Cost and Effectiveness Analysis of the AH-64 and UH-60 On-Board Vibrations Monitoring System

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Abstract—The objectives of our program are to evaluate the cost and effectiveness of the AH-64 (Apache) and UH-60 (Blackhawk) helicopters' on-board Vibration Monitoring (VM) System, to provide an annual cost savings analysis of the Vibration Management Enhancement Program (VMEP) for the AH-64 and UH-60 aircraft fleets, and to initially correlate vibration signals with the ULLS-A (logistics) database to create a Costs Benefits Analysis (CBA) model. Logistics (ULLS-A[1]) and vibration (VMU[2]) data were collected for Blackhawks and Apaches from different establishments (South Carolina Army National Guard, Alabama Army National Guard, deployed units in Kosovo, and Korea), warehoused in our database, and analyzed. In addition, all personnel from these bases were surveyed to examine other non-tangible benefits of the program.

In order to provide a timely and sufficient cost and economic analysis to support the effective allocation and management of resources for Army programs, a CBA model has been developed. Our goal was to develop and maintain cost and economic analyses as effective and efficient tools for decision-making while supporting management decisions by quantifying the resource impact of alternative options. The model utilizes test flight information from the ULLS-A database in order to estimate a cost savings and recovery of the initial cost of the VMU hardware installation and future cost savings for the Apache and Blackhawk helicopters. It includes cost variables such as: test flight hours, hours per flight, cost per flight hour, VMEP investment, number of VMEP helicopters, RT&B flights, and non-RT&B flights. It also includes non-tangible variables such as: availability, morale, safety, operational flight hours gained, premature parts failure, mission aborts, and unscheduled maintenance occurrence.

As of today, our activities have been highlighted by savings in parts cost, operational support, an increase in mission capability rates, a decrease in maintenance, and an increase in total flight time. Other highlights of non-tangible benefits include an increase in confidence for early diagnosis, an increase in attention and performance, an increase in personnel morale, and an increase in safety and sense of safety.

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[1] ULLS-A: Unit Level Logistics Support-Aviation
[2] VMU: Vibration Monitoring Unit
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1. INTRODUCTION

Background

*The AH-64/UH-60, On-Board, Vibration Monitoring (VM) System—*The South Carolina Army National Guard (SCARNG)[3] with input from the US Army and the University of South Carolina has developed an on-board Vibration Monitoring (VM) system that was installed on AH-64 and UH-60 aircraft. The University of South Carolina and SCARNG have established a model to measure the cost effectiveness of the VMEP program. The method and approach of this program are to:

(1) Measure and record in-flight vibrations.

(2) Process vibration data, apply signal analysis methods, and identify "hot-spots."

(3) Fine-tune the track and balance of the aircraft to reduce vibrations.

(4) Identify and address incipient failures through repair and/or replacements.

The goals and objectives of this program were to:

(1) Reduce rotor track and balance maintenance test flights.

(2) Reduce aircraft operation costs.

(3) Increase aircraft availability.

(4) Increase aircraft safety.

VMEP has been mitigated to other Apache Readiness Improvement Program (ARIP) problems, such as:

(1) APU clutch failures (believed to cause fires).

(2) Shaft-driven compressor (SDC) component failures.

(3) Nose gearbox seal failures.

(4) Pitch-change bearing wear.

(5) Tail boom cracking.

(6) Vertical stabilizer ribs cracking.

(7) Engine nacelle bulkhead cracks.

(8) Generator failure due to bearing faults.

(9) Main rotor blade debonding.

Cost and Effectiveness Evaluation of the AH-64/UH-60 On-board Vibrations Monitoring (VM) System—As so well articulated by Dr. Samuel T. Crews (1991), "Many in the helicopter community have long felt that there is a direct relationship between helicopter reliability and maintainability and the level of vibrations allowed on the helicopters. This is a difficult thesis to prove for a number of reasons and skeptics have argued for hard proof that this is indeed true before they would allow significant dollars to be spent on efforts to reduce helicopter vibration." The AH-64/UH-60 On-Board Vibrations Monitoring (VM) System at South Carolina Army National Guard has served as a test-bed on which the vibration-reduction cost and effectiveness have been examined and analyzed.

Concurrent Activities—At present, a number of important projects are directed at reducing the Army aviation costs through improved logistics technology, better data management, and prompt/timely actions. As we embark on Aviation Maintenance Transformation, producing higher operational readiness using fewer, more capable resources (reducing the logistics footprint), connecting the logisticians to an Integrated Enterprise-wide logistics system, provide commanders with relevant maintenance-based readiness information at every level, achieve operating capability by 2011 IAW CSA intent, and shift from preventative and reactive processes to Condition-Based proactive analytical maintenance processes; i.e. Condition Based Maintenance (CBM). Behind homeland security, the next priority for the Commander of the Aviation and Missile Life Cycle Management Command (AMLCMC) is Condition Based Maintenance (CBM). Per the Office of the Secretary of Defense (OSD), CBM is defined as "set of maintenance processes and capabilities derived, in large part, from the real-time assessment of weapon system condition obtained from embedded sensors and/or external tests and measures using portable equipment." Future maintenance action and instructions will be based on aircraft condition and usage data. The AMLCMC is sponsoring a "CBM Proof of Principle" using data from AH-64, UH-60, and CH-47 platforms. The CBM prototype conclusions and recommendations will be delivered by July 2005 with a strategic plan to meet FY11 objectives.

PM Apache along with the UH60 and CH47 PMOs are part of an exciting initiative to transform Army Aviation maintenance. The initiative, Conditioned Based Maintenance (CBM) will use on-board diagnostics and remote prognostics to convert data into maintenance action. Our soldiers might see little change inside their electronic logbooks but the maintenance leaders and logisticians could see dramatic change over the next several years CBM requires at least four kinds of data that stem from Apache systems:

[3] Intelligent Automation Co. (IAC)

(1) Vibration for analysis of dynamic components.
    a) From VMEP (Vibration Maintenance Enhancement Program).

(2) State data for regime recognition, fatigue, and flight visualization.

    a) From the MDR (Maintenance Data Recorder).

(3) Parts tracking and usage history.

    a) From AMATS/CMB (Aviation Maintenance Automated Tracking System/Contact Memory Buttons).

(4) Maintenance activity.

    a) From ELAS (Enhanced Logbook Automation System).

The engineers for the PMs and the CBM working group will undoubtedly find other data requirements as the program evolves.

A maintenance data recorder (MDR)/Longbow integrated maintenance support system (LIMSS) has been developed by the Apache Program Managers Office, in Huntsville, AL. The LIMSS system interfaces recorded faults or exceedances to the IETM and collects maintainer action on the, Maintenance Support Device (MSD), follow-on to the SPORT support computer (rugged PC). Interface from Apache embedded diagnostics systems, to GCSS-A database and electronic logbook are on-going.

Description of Work

Our team at USC and SCARNG have conducted the work that includes but is not limited to data collection, data processing, and data interpretation, in order to evaluate the cost and effectiveness benefits of using the AH-64/UH-60 on-board vibration monitoring system, and has developed a vibration management and health monitoring methodology for military helicopters. This work utilizes: (a) State-of-the-art Vibration Monitoring (VM). (b) Data base management, filtering, and processing software, with special emphasis on that used by SCARNG. (c) Methods of correlation of data base information regarding parts replacement and maintenance man-hour cost between VM equipped helicopters having on-board equipment for vibration recording in comparison with non-VM equipped helicopters. Emphasis was on empirical, statistical, data that clearly identifies positive or negative cost savings and/or a reliability enhancement of the helicopters equipped with the VM device.

A framework of the statistical experiment used to evaluate the cost and effectiveness benefits of using the AH-64/UH-60 on-board vibrations monitoring system, was designed and carried out in order to perform data interpretation.

Costs-Benefits Analysis—The Cost Benefits Analysis (CBA) has been executed in a 3-step procedure:

(1) Define the CBA Objectives. The CBA focused initially on the AH-64 platform, and, after initial trials, were extended to include the UH-60 platforms. The investment efforts were focused mainly at the Unit-Level and below because the costs and benefits were most quantifiable at these levels.

(2) Develop CBA Framework. The VM "building blocks" were considered as investment opportunities. The investment opportunities were analyzed in terms of primary and secondary benefits. For each presumed benefit, a definition and a metric were developed.

(3) Cost estimating and Benefits Analysis. The analysis initially targeted the operating and support (O&S) costs. The O&S costs are a subset of life cycle costs (LCC). We intended to address every aspect of O&S cost in search of major cost drivers. Pursuit of O&S cost reduction is particularly complex because problem areas and potential solutions involve multiple dependent variables. The O&S analysis were guided by the AMCOM document "Reduction of Operating and Support Costs for the US Army Helicopters" of 24 February 1995. In this activity, O&S estimates were developed, benefits were characterized, and impacts were organized. This activity had three levels of depth depending on assignment requirements. The analysis focused on selected VM "building blocks" that had the potential to show investment cost returns. Cost savings and cost avoidances from any source were considered as returns. A project would be successful if the benefits and returns exceed the investment cost. This factor was determined using return-on-investment (ROI) metrics, i.e., the ratio of savings to investment. Savings were represented by returns that are quantified in cost or financial terms.

Costs-Benefits Models—Costs and benefits are considered at 4 levels: (a) On-Aircraft, (b) At-Aircraft, (c) at Unit-Level, and (d) in the Sustainment Base/Above Unit Level. The costs and benefits for on-aircraft and at-aircraft levels were covered by a HUMS costs-benefits model. The costs and benefits at unit-level and at sustainment base levels were covered by an Activity-Based Costing (ABC) model. The HUMS and ABC model interpenetrate at unit level.

i. On-Aircraft Costs and Benefits
The investment costs occur primarily at the platform level

and consists of the on-board VM equipment. Benefits are delivered to the mission and to the direct support personnel, and may percolate up through successively higher levels of Army personnel. Quantifiable benefits from on-aircraft investments may include:

(1) Reduced flight hour costs and returned maintenance man-hours

(2) Better RAM status: mean time between failures (MTBF), mean time between maintenance action (MTBMA), mean time to repair/replacement (MTTR), Operational stability.

(3) Improved mission completion rates (lower mission abort rates)

(4) Improved safety of flight statistics

Other investments at higher levels may be needed to complete on-aircraft initiatives.

ii. At-Aircraft Costs and Benefits

Investment costs relate to tools designed to improve performance of "hands on" aircraft maintainers. Benefits are delivered initially to hands-on maintainers, and flow up to Army Aviation Logistics network. It is expected that investments will be done in products that complement what is being done at the on-aircraft level. The at-aircraft investment products magnify and complement the on-aircraft investments. A table similar to Table 1 will be compiled to correlation of investment products and perceived benefits for the DAL-P project in the on-aircraft, at-aircraft CBA framework. These benefits begin at platform level and ripple up to the higher levels of Army Aviation organization.

iii. Unit-Level Costs and Benefits

Unit-level costs and benefits are estimated using a combination of HUMS and ABC models. The HUMS model will provide the initial data. The ABC model will provide further estimates of man-hour reductions complementing those estimated by the HUMS model.

Investment costs are related to the tools designed to improve the performance of unit-level maintenance managers. Benefits of the VM system, felt initially by the maintenance managers, will flow up and down through the Army Aviation Logistics network. Investments at the Unit-Level will enable process changes in the way maintenance managers and maintainers do their jobs. Process improvements at the unit level (and below) are fundamental benefits delivered by the VM system. Reduced direct operating costs (DOC), returned man-hours, and higher availability are the results of improved resource utilization.

iv. Above Unit Level and Sustainment Base Costs and Benefits

The investment costs at above unit level and sustainment base framework relate to the VM "building blocks" designed to improve upper elements of Army Aviation Logistics. Benefits are rendered to elements of the sustainment base and to the Operational Army. Benefits will flow down through the Army Aviation Logistics network. Operational commanders will directly benefit from reduced cost, improved availability, and enhanced safety of flight enabled by the VM investments.

Review of Cost-Benefit Analysis Method

Currently, cost-benefit analysis (CBA) is largely used by government agencies. This is mainly due to the strong legislative actions taken by the Reagan and Clinton Administrations that issued Executive Orders endorsing the use of CBA. Executive Order 12886 on Regulatory Planning and Review, signed by President Clinton .on September 30, 1993 requires agencies to perform cost-benefit analysis of proposed and final regulations. It revoked and replaced two executive orders issued under Reagan Administration: Executive Order 12911 requiring Regulatory Impact Assessment and Executive Order 12498 establishing the regulatory planning process. Moreover, the use of CBA by government agencies was enforced by Congress who enacted numerous statutes requiring agencies to perform CBA analyses.

When used by governmental agencies, CBA attempts to measure, over a relevant time period, the change in societal well being resulting from the implementation of a governmental project or the imposition of governmental regulations. It can provide information to decision makers on the merits of the current project or regulation as well as offer a framework for comparing a variety of project or regulatory alternatives. Agencies' project or regulation evaluations are subject to the review of the Office of Management and Budget (OMB). In 1992 OMB issued the Circular No. A-94, which recommends the use of CBA in formal economic analyses of government programs or projects and provides general guidance for conducting CBA Its goal is to "promote efficient resource allocation through well-informed decision-making by the Federal government."

CBA aims to present categories of costs and benefits in terms of dollars (so that the cost-benefit comparison can be performed with a common unit of measurement); therefore, agencies have to define and monetize all categories of costs and benefits determined by the project implementation. Sometimes practical problems appear such as obtaining data, evaluating benefits and costs, etc. Monetization of some benefits categories may be controversial because indirect methods are often employed to estimate a value for goods that are not generally traded in the marketplace (e.g. estimate the monetary value of a reduction in risk of premature mortality). In this sense OMB stipulated, "Analyses should include comprehensive estimates of the expected benefits and costs to society based on established definitions and practices for program and policy evaluation.

Social net benefits, and not the benefits and costs to the Federal Government, should be the basis for evaluating government programs or policies that have effects on private citizens or other levels of government. Both intangible and tangible benefits and costs should be recognized. Costs should reflect the opportunity cost of any resources used, measured by the return to those resources in their most productive application elsewhere"(OMB -A-94).

Despite its recognized merit in providing important information and transparency in the governmental decision-making process, CBA was often criticized, especially by American academics who claim that CBA is an analytical technique that deals only with economic efficiency without considering who receives the benefits and who bears the costs. They also claim that CBA sometimes produces morally unjustified outcomes or it is not correctly used. Yet, it is important to highlight that CBA is a decision procedure or a method for achieving desirable results, and "some decision procedures are more accurate or less costly than others" .As long as it is used in the right way, meaning that under certain conditions agencies may need to modify the traditional approach of CBA, this decision procedure is justified if it is less costly than other procedures (e.g. risk-risk analysis, feasibility based assessment, etc.).

In order to place CBA in context, a good example is the Environmental Protection Agency (EPA) monitoring of drinking water contamination with lead. By law, EPA has to regulate the water cleaning against lead contamination. Therefore, EP A used CBA to evaluate three rules it has previously issued as to lead contamination of water. On the cost side EP A took into consideration the cost of treating contaminated water that enters the distribution system; the cost of maintaining water quality (PH level, temperature, etc.); the cost of replacing lead pipes; the cost of warning the public of high lead levels and informing it of precautions; and the cost of monitoring water quality. These costs were put in balance with the health benefits accrued from avoiding hospitalization and medical treatment of contaminated persons and compensatory costs for lost productivity. After aggregating all these costs and benefits, EP A concluded that the total health benefits from corrosion control alone would be $63.8 billion over a twenty-year period, which vastly exceeded estimated costs of $4.2 billion (Adler and Posner, 1999). Thus, with a large amount of data the CBA analysis was very transparent and convincing so it justified the adopted rule. Yet, without justification, EP A did not include in its final CBA the benefits from reducing lead damage to plumbing components, even if these benefits had been evaluated.

Some remarks have to be made. First, budgetary and time constraints may impede EPA, as well as other governmental agencies, from collecting all the necessary data. Second, when all data are available and easy to collect, agencies should try to monetize all costs and benefits and include them in their final CBA. This helps agencies to clearly present the effects of governmental projects and alert affected groups. Third, CBA is an important way for governmental agencies to defend their projects against critics coming from other agencies, as well as against legal and political challenges from affected groups. Finally, given its relative cheapness and transparency, CBA is considered the best procedure for agencies to use in evaluating their projects. The use of CBA is not limited to governmental agencies. The U.S. Army also employs this technique in estimating whether its projects achieve an improvement in the allocation of resources.

CBA can provide valuable perspectives on the best ways to manage projects concerning the army infrastructure, labor force, capital stock etc. This approach is consistent with the Department of Defense and Army guidance and with the Army Regulation 11-18 establishing responsibilities and policy for the Army's Cost and Economic Analysis Program.

For the design and manufacturing of the helicopter AH-64D Apache Longbow, Boeing Helicopter of Mesa, Arizona put up a multidisciplinary team focused on meeting the Army's cost and performance requirements. This Integrated Product Development (IPD) team incorporated a manufacturing engineer, a design engineer, a tool engineer, a stress engineer, and later on a material process engineer, purchasing personnel, and an industrial engineer who was called in to perform a CBA. During the project development, the team used the costing software Design for Manufacture and Assembly (DFMA) that provided "a means of before-and-after comparison -not only against the previous models [six Apache Prototypes] but for individual redesign ideas that are part of the iterative process" (parker, 1997). Thus through continuous CBA the best alternative was chosen and the new Apache Longbow innovative production strategies not only proved better performance and quality, but also brought savings of $1.3 billion over the life of the program.

2. VMEP COST-BENEFIT ANALYSIS

Data Collected

ULLS-A and Vibration Data—The Unit Level Logistics Support – Aviation (ULLS-A) system was used to track parts and man-hour usage. The elements to be tracked include, but not restricted to, the following:

(1) Part S/N and cost.

(2) Man-hour for installation and troubleshooting.

(3) Test-flight hours for confirmation or operational crew hours.

(4) Identify if part is related or not to vibration (a tire – *no*; an on-board computer – *yes*; a hydraulic pump – *maybe*).

(5) Tear-down analysis results, when available. ("Might have operated another maintenance period" or "It is surprising that it lasted that long").

The VM data has also been tracked using the ULLS-A maintenance database. In order to achieve this, the ULLS-A configuration has been reprogrammed to include VM events/data.

Data from the ULLS-A database has been transferred electronically to USC computer. To achieve this, USC has a dedicated computer workstation with a data transfer/translation algorithm. USC has maintained a long-term database of the selected ULLS-A data items, thus overcoming the 6-month limitation of the ULLS-A system.

ULLS-A and vibration data were collected for Apache and Blackhawk aircrafts since 2000. In 2000, we started with 18 Apaches and 8 Blackhawks from the South Carolina Army National Guard (SCARNG). At present, we are collecting data for over 100 aircrafts (AH-64 and UH-60) from SCARNG, Alabama Army National Guard (ALARNG), Kosovo, Korea, and Iraq.

Note: In Year 3, eight Apaches and ten Blackhawks were deployed to Kosovo. All aircraft have returned. Additionally, data has been collected for the first six months of Year 4 for the Apache aircraft from Korea (21 Apache) to SCARNG. Also, ULLS-A data from January 2003 has been collected. This gives us a baseline of 12 months for all aircrafts.

Survey Data—All personnel from the South Carolina Army National Guard and Alabama Army National Guard were surveyed (deployed and non-deployed personnel) for the purpose of analyzing the non-tangible benefits of the program.

Costs Benefits Analysis Model and Results—USC has been receiving desensitized vibration data (VMU) for the last three years and maintenance data (ULLS-A) for the last four years. This data is being appended to the database and uploaded to the USC secured server and is being used to update the CBA records, investigate the O&S analysis, and investigate safety and benefits.

i. Basic Benefits

In order to provide a timely and sufficient cost and economic analysis to support the effective allocation and management of resources for Army programs, a CBA model has been developed. Our goal was to develop and maintain cost and economic analyses as effective and efficient tools for decision-making while supporting management decisions by quantifying the resource impact of alternative options. In our model as with any good cost model; as a program matures and more information becomes available, the cost estimate grows in complexity and detail.

In developing our model, we investigated other models such as the Galorath SEER-H model and the Cost Analysis Strategy Assessment (CASA) model to estimate operating and support (O&S) cost.

Our model utilizes the test flight data from the ULLS-A database in order to estimate a cost savings and recovery of the initial cost of the VMU hardware installation and future cost savings for the Apache and Blackhawk helicopters. Our model includes cost variables such as: test flight hours, hours per flight, cost per flight hour, VMEP investment, and number of VMEP helicopters, RT&B flights, non-RT&B flights.

The ULLS-A data that was used in developing our model is presented in Tables 1 and 2. Table 1 shows the flight hour record and associated faults for DA 2408-12, DA 2408-13, and DCR. Table 2 shows the ULLS-A field name and description.

Table 1 - ULLS-A Data (Dash 12, Dash 13, DCR)

Flight Hour Record	Faults	Document Control Register
DA 2408-12	**DA 2408-13**	**DCR**
REC_ID	REC_ID	REC_ID
UNIT_ID	UNIT_ID	UNIT_ID
EVENT_DATE	EVENT_DATE	EVENT_DATE
ENENT_TIME	FAULTDAT	DTE_COMP
VMU	FAULTNO	DTE_ESTB
FLT_DATE	SS	NIIN
TIME_DPT	FAULT	NOMEN
FLT_NO	CORRDATE	EX_PRICE
MSNSYMB	ACTION	QTY_REC
DATE_AR	OHM	
TIME_ARVL	VMU	
TOT_HRFL	FAILCODE	

TOT_LNDS	AC_MODL	
HIT_1	RTB	
HIT_2	AAAR	
LOAD2	PPF	
LOADE	SCH_UNSCH	
OAT	ABORTS	
AC_MODL	MTF	
	CORROSN	
	REMARKS	

Table 2 - ULLS-A Field Name and Description

	Field Name	Description	From
1	RECORD_ID	RECORD NUMBER	Derived
2	UNIT_ID	UNIT IDENTIFICATION	Assigned
3	EVENT_DATE	EVENT DATE	Matching Field for VMU Data
4	EVENT_TIME	EVENT TIME	Matching Field for VMU Data
5	VMU	VMU INSTALLED ON THE AIRFRAME	Look up from Aircraft Database
6	AC_MODL	AIRFRAME MODEL	Look up from Aircraft Database
7	UIC	UNIT ID CODE	Look up from Aircraft Database
8	HIGH_UIC	NEXT HIGHER UIC	Look up from Aircraft Database
9	HIHI_UIC	2ND HIGHER UIC	Look up from Aircraft Database
From DA 2408-13 Database			
10	WUC	WORK UNIT CODE	
11	SYSCODE	SYSTEM CODE	
12	FAULTDAT	FAULT DATE	
13	FAULTNO	FAULT NUMBER	
14	SS	FAULT STATUS SYMBOL	
15	FAULT	WRITE-UP AGAINST THE AIRFRAME	
16	CORRDATE	DATE OF CORRECTIVE ACTION	
17	ACTION	ACTION TAKEN TO CLEAR A FAULT	
18	OMH	ORGANIZATIONAL MANHOURS	
From DA 2408-12 Database			
19	FLT_DATE	MAINTENANCE TEST FLIGHT DATE	
20	TIME_DPT	TIME OF MTF	
21	FLT_NO	MTF NUMBER	
22	MSNSYMB	FLIGHT MISSION SYMBOL	
23	DATE_AR	END DATE OF THE MTF	
24	TIME_ARVL	END TIME OF THE MTF	
25	TOT_HRFL	TOTAL FLIGHT TIME LOGGED	
26	TOT_LNDS	TOTAL NUMBER OF LANDINGS FOR THE FLIGHT	
27	HIT_1	#1 ENGINE HEALTH INDICATOR CHECK	
28	HIT_2	#2 ENGINE HEALTH INDICATOR CHECK	
29	LOADI	INTERNAL LOAD	
30	LOADE	EXTERNAL LOAD	
31	OAT	OUTSIDE AIR TEMPERATURE	
From Document Control Register (DCR)			
32	DTE_COMP	DATE PARTS ARE RECEIVED	
33	DTE_ESTB	DATE PARTS REQUEST ARE INITIATED	
34	NIIN	FEDERAL PART NUMBER	
35	NOMEN	PART NAME	
36	EX_PRICE	COST OF PARTS ORDERED	
37	QTY_REC	QUANTITY RECEIVED	
38	TBO_CD	INDICATES TIME BETWEEN OVERHAULS	Look up from TBO Chart
39	RM	PARTS REPAIRED AT MSAVCRAD	Look up from RM/RR Chart
40	TADS	INDICATES A TADS/PNVS PARTS	Look up from TADS/Pnvs Chart

Table 2 - ULLS-A Field Name and Description (continued)

From 2410 Database			
41	A410_CNTL	PART INSTALLATION / REMOVAL INFORMATION	
42	ACDRMVL	DATE OF PART REMOVAL	
43	ACDTINST	DATE OF PART INSTALLATION	
44	PN	PART NUMBER	
45	PSERNO	PART SERIAL NUMBER	
46	TSN	PART TIME SINCE NEW	
47	TSO	PART TIME SINCE OVERHAUL	
48	FAILCODE	FAILURE CODE	
49	REASON	REASON FOR REMOVAL	
From Vibration Database			
50	ENT_DATE	ENTRY DATE FOR VIBRATION CHECK	
51	ENT_TIME	ENTRY TIME FOR VIBRATION CHECK	
52	LAT_READ	LATERAL VIBRATION READING	
53	LON_READ	LONGITUDINAL READING	
54	SFTNOMEN	SHAFT NOMENCLATURE	
55	VER_READ	VERTICAL VIBRATION READING	
From Manual Cataloging of Faults			
56	RTB	ROTOR TRACK AND BALANCE	
57	AAAR	AFTER ACTION REPORT	
58	PPF	PREMATURE PART FAILURE	
59	SCH_UNSCH	SCHEDULED OR UNSCHELDULED MAINTNEANCE	
60	ABORTS	MISSION ABORTS	
61	MTF	MAINTENANCE TEST FLIGHTS	
62	CORROSN	CORROSION FAULTS	
63	REMARKS	REMARKS	
64	COMPONENT	COMPONENT INVOLVED	

Highlights of results and benefits are presented in Figures 1 through Figure 7 for AH64. Similar results were obtained for UH-60 aircrafts with similar highlights of results and benefits. For exemplification, we have chosen a six-year period of analysis. Actual cost data has been collected for estimating the costs and savings of each of the two project alternatives (baseline and VMEP) for each future year of analysis. The baseline costs have remained the same throughout the six-year period, where as the VMEP values are determined by a 3% decrease after the first year and a 3% decrease each subsequent year thereafter. This rate was determined comparing initial VMEP data with the baseline data. The cost of the process at SCARNG between November of 2000 and October of 2001 for the AH-64 provides the baseline for the CBA. Data acquired for November of 2001 through October of 2002, was used to project the cost for the VMEP alternative. November of 2001 was chosen due to all of the VMU's being installed and operational by this date. It also includes non-tangible variables such as: availability, morale, safety, operational flight hours' gain, premature parts failure, mission aborts, and unscheduled maintenance occurrence. In our case, benefits take the form of tangible and non-tangible benefits. Therefore, we first analyze the savings of the VMEP alternative by comparing the costs in the two cases. Then we discuss the non-tangible benefits of the VMEP alternative and their implications.

Non-tangible benefits have been or will be analyzed in our model. These values are based on information and surveys from the base and are used to show the non-tangible benefits that arise from the use of VMEP. Again, the idea is that with the implementation of the VMEP program whether or not the fleet will see an increase in aircraft availability, safety, and operational flight hours along with a decrease in premature parts failure, mission aborts, and unscheduled maintenance occurrences.

ii. Mission and Non-Tangible Benefits

A long term goal was to evaluate other benefits such as the mission and non-tangible benefits as a function of real cost and saving. Several brainstorm sessions were conducted in order to carry out such a task. The brainstorming team consisted of academicians from engineering and business, practitioners, maintainers, designers, and users. Tables 3 and 4 show an outcome of such sessions. It shows the components of the cost benefits analysis that consist of basic and mission benefits with variables impacting them. Some of the variables are readily available from the collected data while others are still needed.

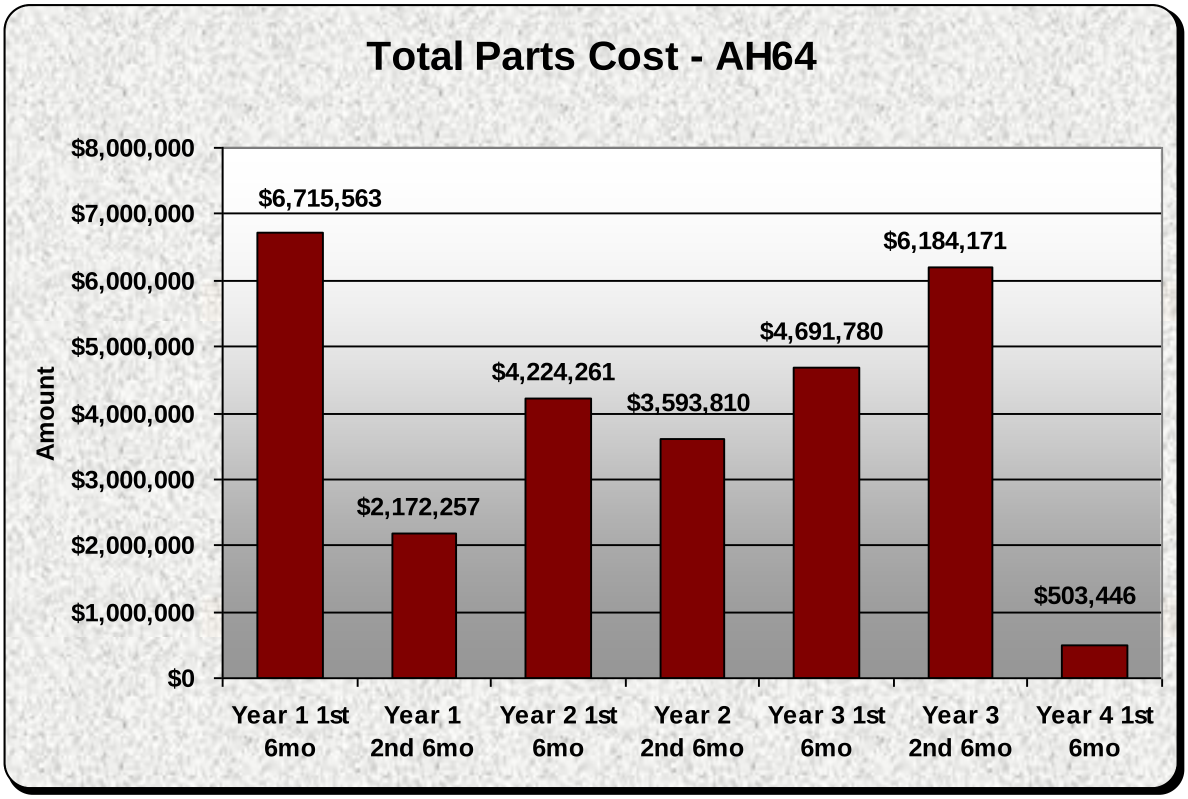

Figure 1 – Total Parts Cost, AH-64

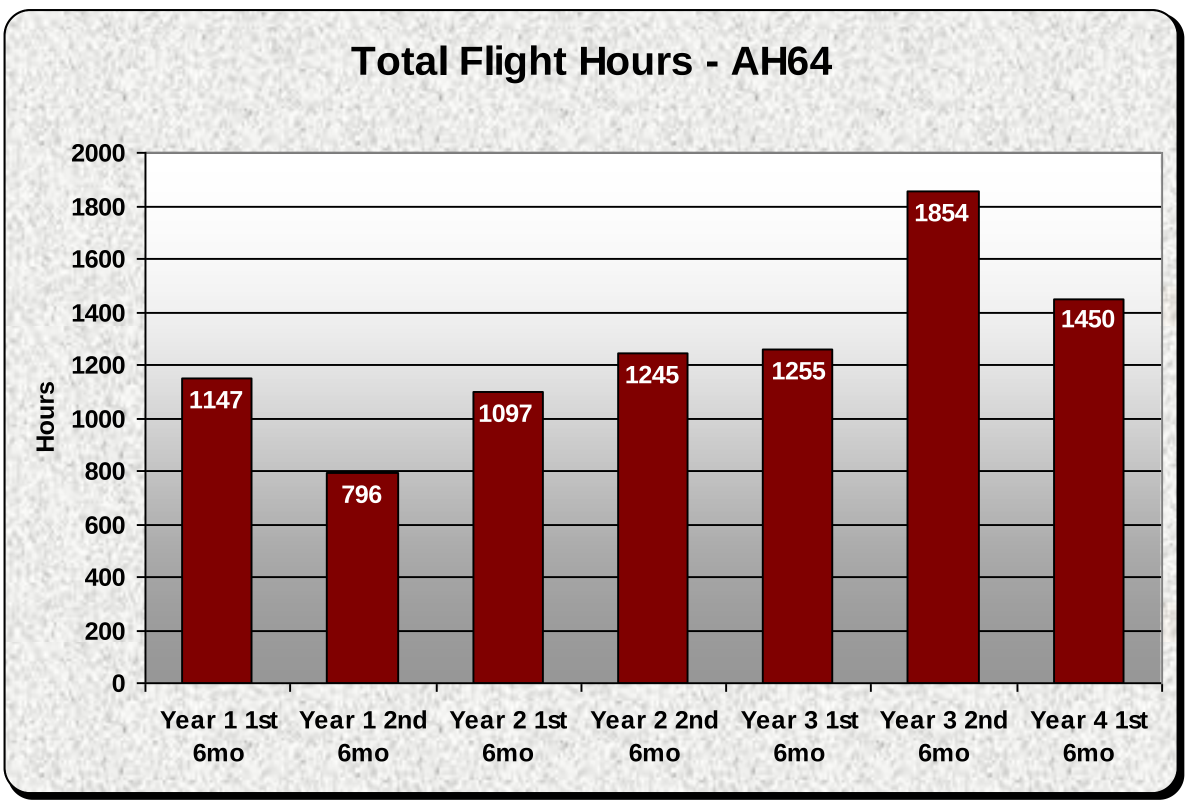

Figure 2 – Total Maintenance Test Flight Hours, AH-64

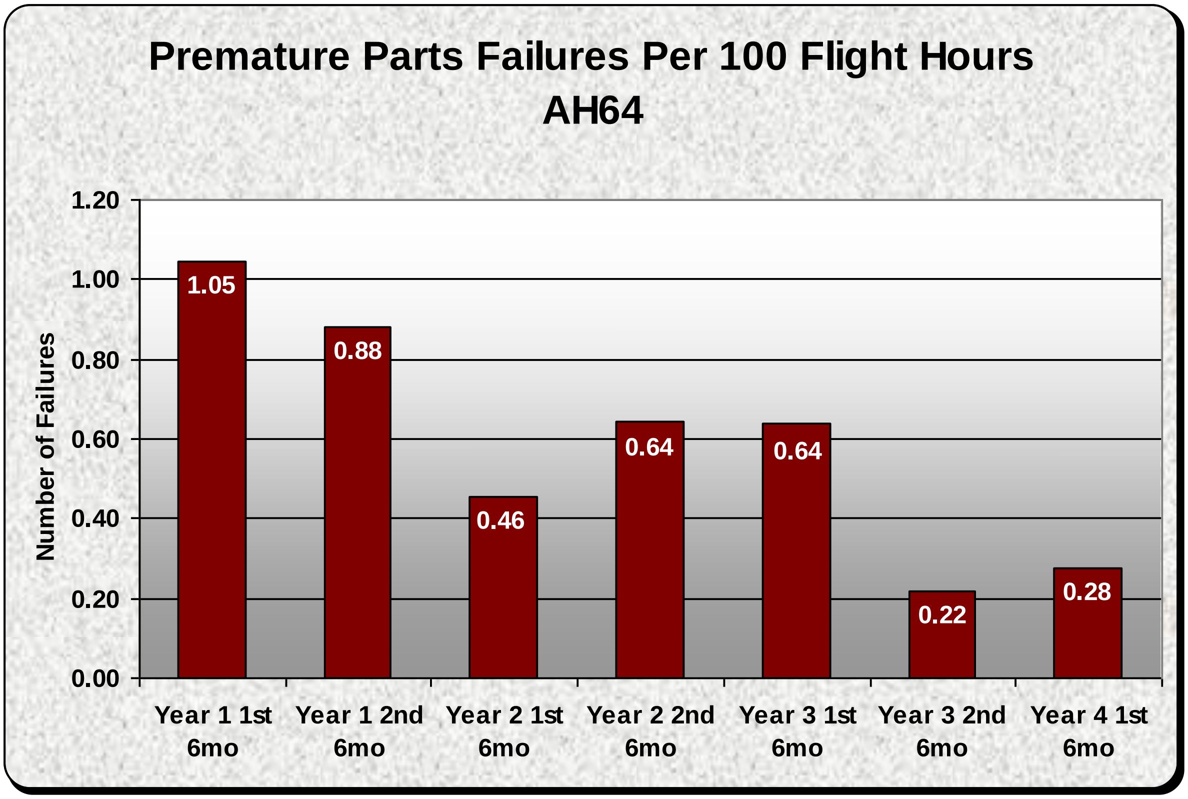

Figure 3 – Premature Parts Failures per 100 Flight Hours, AH-64

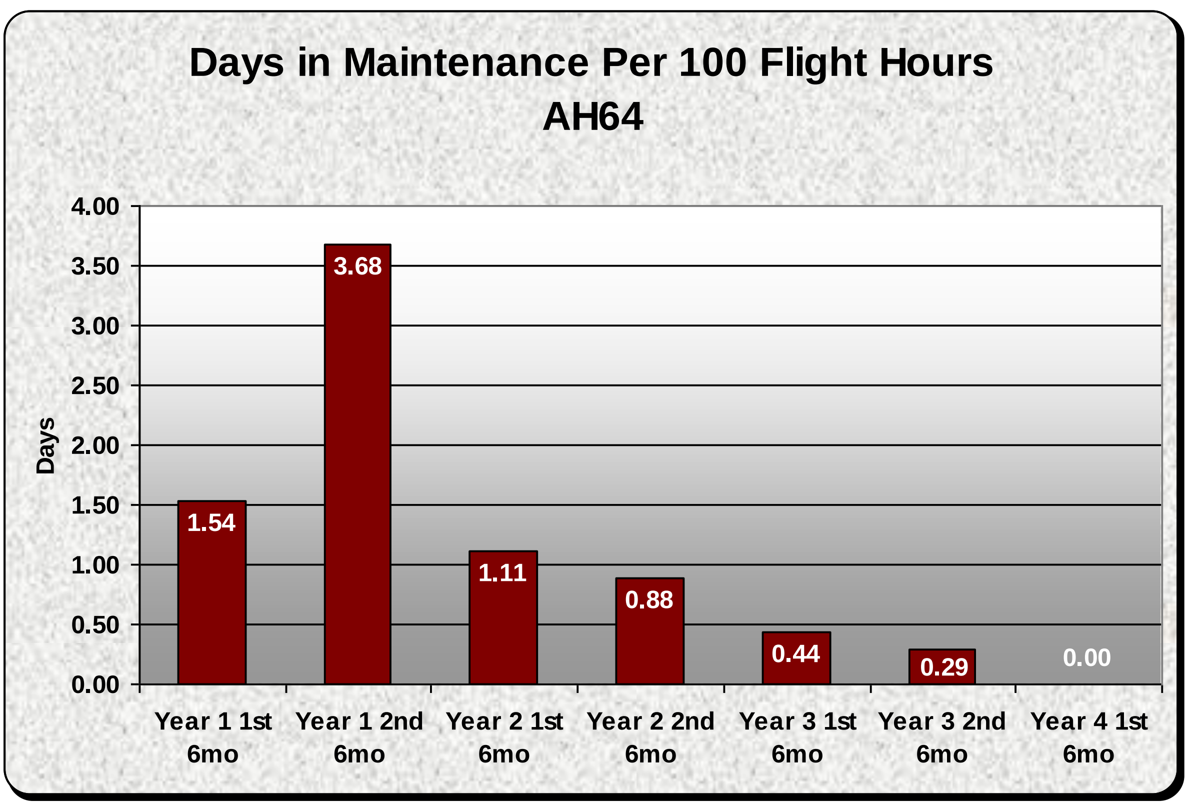

Figure 4 – Days in Maintenance per 100 Flight Hours, AH-64

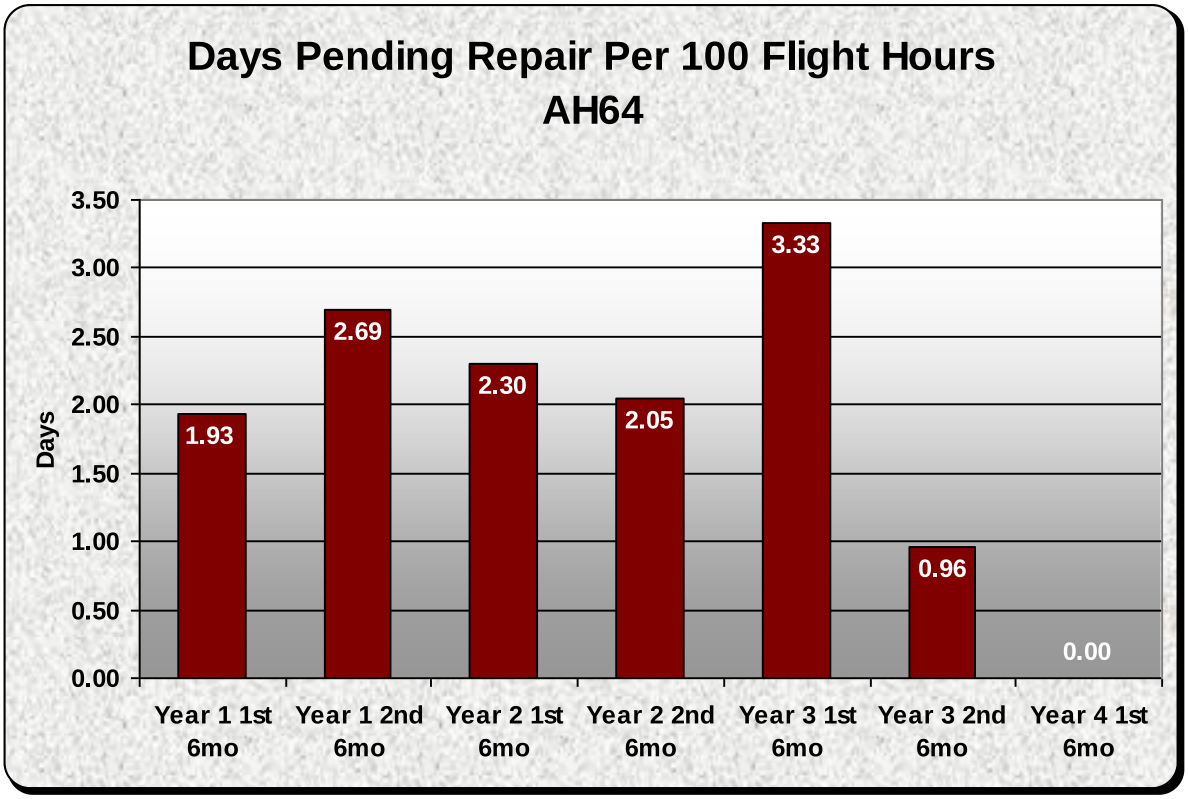

Figure 5 – Days Pending Repair or Part, AH-64

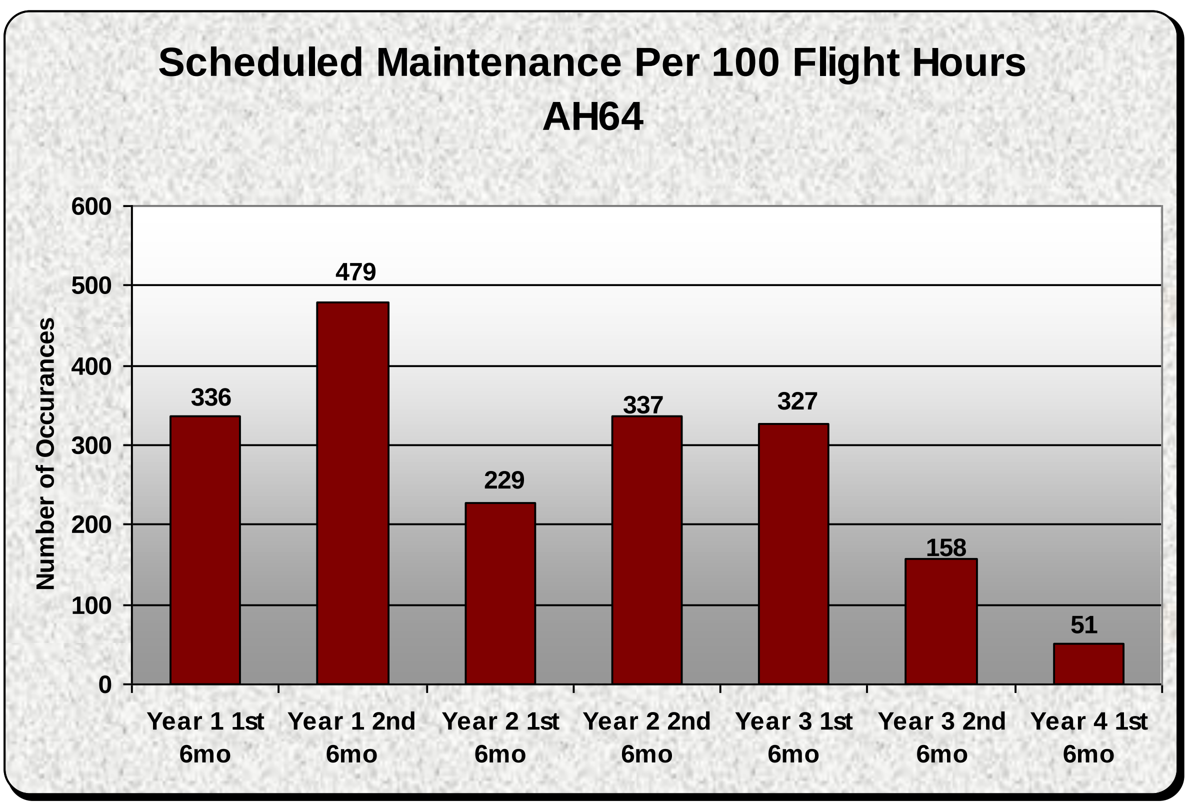

Figure 6 – Scheduled Maintenance, AH-64

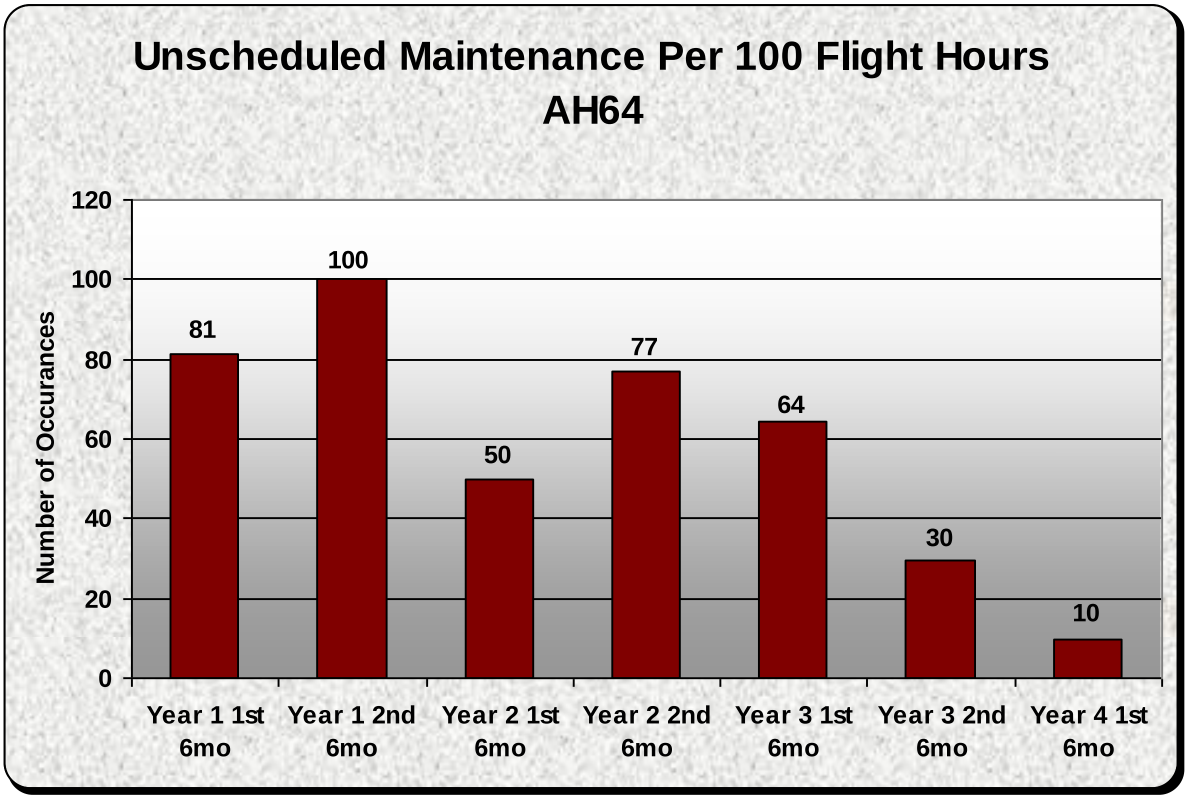

Figure 7 – Unscheduled Maintenance, AH-64

<u>*ii.a. Measuring Non-Tangible Mission Benefits*</u>

Our original brainstorming sessions identified two categories of benefits, basic and mission, which are important areas to "measure" VMEP outcomes in a comprehensive cost and benefit model. Mission benefits, the "soft" benefit area, were conceived to comprise four areas: Operational Readiness, Morale, Performance, and Safety. We next committed to six steps through which our team would eventually be able to quantify and subsequently "measure" the non-tangible mission benefits achieved using the VMEP program. The first three steps are described below and the last three steps are presented later in the paper.

Step 1. Our research team, crew chiefs, and pilots reviewed various iterations of a set of questions designed to address aspects of operational readiness, morale, performance and safety as they related to operating and maintaining Blackhawk and Apache helicopters. Numerous questions and items were suggested; and, through a series of review, discussion and reaction iterations, narrowed down to four items that addressed each of the four non-tangible mission benefit areas. Anchor points for each were created using a seven-point Likert Scale.

Step 2. A questionnaire containing these sixteen items along with addition background questions was designed and pre-tested on a small group of crew members, crew chiefs, and helicopter pilots. Feedback about question wording and anchors was used to design a revised questionnaire. The revised questionnaire was pre-tested once again and a final, questionnaire created to use in surveying various units in the National Guard and Regular Army that fly and maintain Blackhawk and Apache helicopters around the world.

Step 3A. The questionnaire was administered to a SC National Guard unit at McEntire in Spring, 2003. The results were received and tabulated. The responses were used to check the questionnaire items' reliability and validity.

Findings from the survey regarding the four non-tangible mission benefit areas were reported in the June 2004 VM System Interim Report. Indicators of improvement in operational readiness, safety, morale and performance were reported in that report. The results suggested solid improvement in these mission benefit areas over the time since VMEP was introduced into this unit's aircraft.

Step 3B. The questionnaire was administered to an Alabama Army National Guard unit deployed in Kosovo in the Summer, 2004. The results were recently received and tabulated. The responses were again used to check the questionnaire items' reliability and validity.

Surveys were completed by 35 SCARNG and by 22 ALARNG helicopter personnel. Sixteen questions were asked which compared their feelings when they took the survey and how they felt two years ago. Twelve general questions on the survey pertained to safety, performance, morale, and mission capability without mentioning VMEP specifically. Four questions specifically referred to the VMEP system. All questions were scored on a scale of one to seven, where one is the lowest and seven is the highest, or most confident, score. A general overview of the results is presented below in Table 5.

Table 3 - Components of the Cost Benefits Analysis: Basic Benefits

Benefits	Variables	Measured			
		Available	**From**	**Needed**	**From**
Operational Costs ($$)	Supply management Spares and repair parts Consumables Maintenance tasks undertaken Training/ sustainment Maintenance test flight hours	Top 10 Cost Drivers Cost of each test flight Cost of each RT&B flight Reduction in demand on supply chain* Cost per maintenance test flight with fuel included * *Watch out for a drop in demand and supply per year.*	DCR: EX_PRICE DA 2408-12: TOT_HRFL DA 2408-12: TOT_HRFL DCR: NIN, QTY_REC DA 2408-12: TOT_HRFL	Need indicator of training costs and sustainment costs where time/money spent on training maintenance folks for skills (i.e. rotor blades, classes, etc.)	Army Aviation Support Facility
Availability (Time)	Maintenance Time Supply	Days available to fly Days in maintenance Days pending repair or part	SCARNG DA 2408-13: FAULTDAT - CORRDATE DCR: DTE_COMP – DTE_ESTB	Total flight hours Fully mission capable Partial mission capable	SCARNG SCARNG SCARNG
Maintenance Man Hours per Flight Hour (Man Power)	Scheduled Unscheduled	Number of test flights (iterations, time, etc.) Number of RT&B test flights versus non-RT&B test flights Number of incidents of good parts swapped out while trouble-shooting. PPF (Premature Parts Failure) Days in maintenance (scheduled and unscheduled)	DA 2408-12: FLT_DATE, FLT_NO Manual Input: Query of RTB field Manual Input: TS (926 Failure Code) Manual Input: PPF SCARNG	Time between unscheduled maintenance	Manual Input: SCH_UNSCH

Table 4 - Components of the Cost Benefits Analysis: Mission Benefits

	Variables	Measured		
		Available	From	• Corresponding Survey Questions
Operational Readiness	Supply management Spares and repair parts Consumables Maintenance tasks undertaken Training / sustainment Maintenance test flight hours	AAAR from safety officer (aborted missions) *currently not considered in evaluation.* VMEP Survey respondents	Manual Input: AAAR Manual Input: VMEP Survey	I am extremely confident in early diagnosis of potential mechanical problems and parts failures. My crew and I concentrate on mission goals I spend more in-flight time concentrating on my mission than on sensing aircraft performance indicators. While in flight, being able to check VMU status increases my confidence
Morale	Pilot/Co-Pilot perspective Crew Chief/Gunner perspective	Flight hours VMEP survey respondents	Operational Flight Hours Maintenance Flight Hours Manual Input: VMEP Survey	My morale and that of my crew is excellent. Flight crew morale is enhanced by an effective maintenance program I prefer to be responsible for detecting potential causes of aircraft failure or the need for maintenance. VMEP equipped aircraft improve morale and performance.
Performance	Gunnery scores Pilot/Co-Pilot perspective Crew Chief/Gunner perspective	Pilot vibration sensing VMEP Survey respondents	Manual Input: VMEP Survey	I feel greater pressure to be sensitive to vibration and other symptoms of potential mechanical problems. Confidence in maintenance improves performance. My gunnery performance in each of the weapon system tables is very strong and consistent.
Safety	Scheduled maintenance Unscheduled maintenance Personnel confidence in troubleshooting Personnel confidence in overall flight performance	Number of test flights Number of RT&B test Premature Parts Failure VMEP Survey respondents	DA 2408-12: FLT_DATE, FLT_NO Manual Input: Query of RTB field Manual Input: PPF Manual Input: VMEP Survey	I believe my aircraft is safe to operate. There is a greater margin of safety after maintenance has been performed. There is a greater margin of safety with VMEP installed. My aircraft always operates as it is supposed to.

Table 5 – Summary of Survey Results, VMEP Impact Over Two Years

Area	SCARNG	ALARNG
Safety	+ 16%	+ 16%
Sense of Safety	+ 30%	+ 11%
Performance	+ 21%	+ 28%
Mission	+ 18%	+ 15%
Morale	+ 11%	+ 19%
Confidence	+ 20%	+ 27%
Morale & Performance	+ 35%	+ 27%
Ease of Troubleshooting	+ 32%	Strongly Agreed

Based on these results, we have concluded that VMEP:

(1) Increases confidence in early diagnosis.

(2) Increases confidence.

(3) Increases attention to and concentration on mission and performance.

(4) Increases morale.

(5) Increases the sense of safety.

(6) Improves performance.

Findings from the survey regarding the four non-tangible mission benefit areas are reported in the October 2004 VM System Interim Report. Indicators of improvement in operational readiness, safety, morale and performance similar to the earlier survey were reported. The results suggested solid improvement in these mission benefit areas over the time since VMEP was introduced into this unit's aircraft much like those found in the earlier survey with the SC National Guard Unit.

Consistency in answers across both surveys support the reliability and validity of the questionnaire and individual items on the questionnaire. Step 3B will be an ongoing research process as numerous other National Guard and regular army units deploy the VMEP system and agree to participate in answering the questionnaire. This will allow us to compare results across a wide variety of unit situations, deployments and characteristics increasing the validity of our non-tangible outcome indicators and our ability to move toward extrapolating quantifiable benefits from these perceptual measures.

Below are some testimonials from the surveys returned by South Carolina Army National Guard and by Alabama Army National Guard.

SCARNG:

- "I feel the aircrews within the state are not fully aware of the capabilities of VMEP and emerging technologies that will enhance aircraft readiness, maintenance and safety."
- "I can see an improvement in the reliability of our aircraft. Precautionary landings [PLs] used to be a common problem. I have had only one PL in the last two years [knock on wood]!"
- "VMEP is a good tool."
- "The VMEP system works very well. I look forward to establishing consistent vibration parameters that can be worked out at the facility without having to download & shoot across the country"
- "Properly employed, it's a fantastic program!"
- "These AH-64 Apaches are almost 20 yrs old. We need to have some early warning system of possible problems. VMEP should be a requirement in every Apache"
- "I can tell a definite change in the way our aircraft fly since installation of VMEP. The blade tracking is greatly improved resulting in an airframe that flies smoothly in all phases of flight. This allows crews to concentrate on mission tasks and training with fewer distractions."

ALARNG:

- "I think VMEP is a great diagnostic tool to help improve the performance of Army airframes."
- "The aircraft seem to fly much smoother with the ability to continually monitor and adjust or correct for vibrations."
- "The Basic Rotor Smoothing experience with VMEP took considerably less time and provided a greater level of accuracy in performing this task."
- "During operations I have used VMEP as well as AVA, Chadwick and several other systems extensively working for Sikorsky. VMEP potential BY FAR exceeds the potential of these other systems."

3. Program Highlights & Success Stories

Program Highlights

As of today, our activities have been highlighted by the following results and benefits:

(1) Savings in parts costs: $1.4 million.

(2) Savings in parts cost and operation support: $2.1 million.

(3) Increased mission capable rates through a decrease in maintenance test flights and an increase in total flight time.

(4) Improved safety, sense of safety, morale, and performance.

Success Stories

So far, the VMEP program has received a lot of attention and has had several success stories. Among these stories for the program, two stories were selected; aft hanger bearing and Auxiliary Power Unit (APU) clutch.

Aft Hanger Bearing—In September of 2003 we (McEntire Army National Guard) observed the aft hanger bearing of one of our Apaches beginning to approach the yellow caution limit. By late October, the vibration level had crossed into yellow and appeared to be increasing at an accelerating rate.

An aircraft inspection did not reveal any abnormalities. Production Control assigned a work order and the hanger bearing was replaced on October 23, 2003. After replacement, the vibration level returned to normal for the aft hanger bearing.

Once removed, the hanger bearing was inspected and the failed notation checked. While rotating the bearing, a rough spot could be felt.

Figure 8 – Aft Hanger Bearing

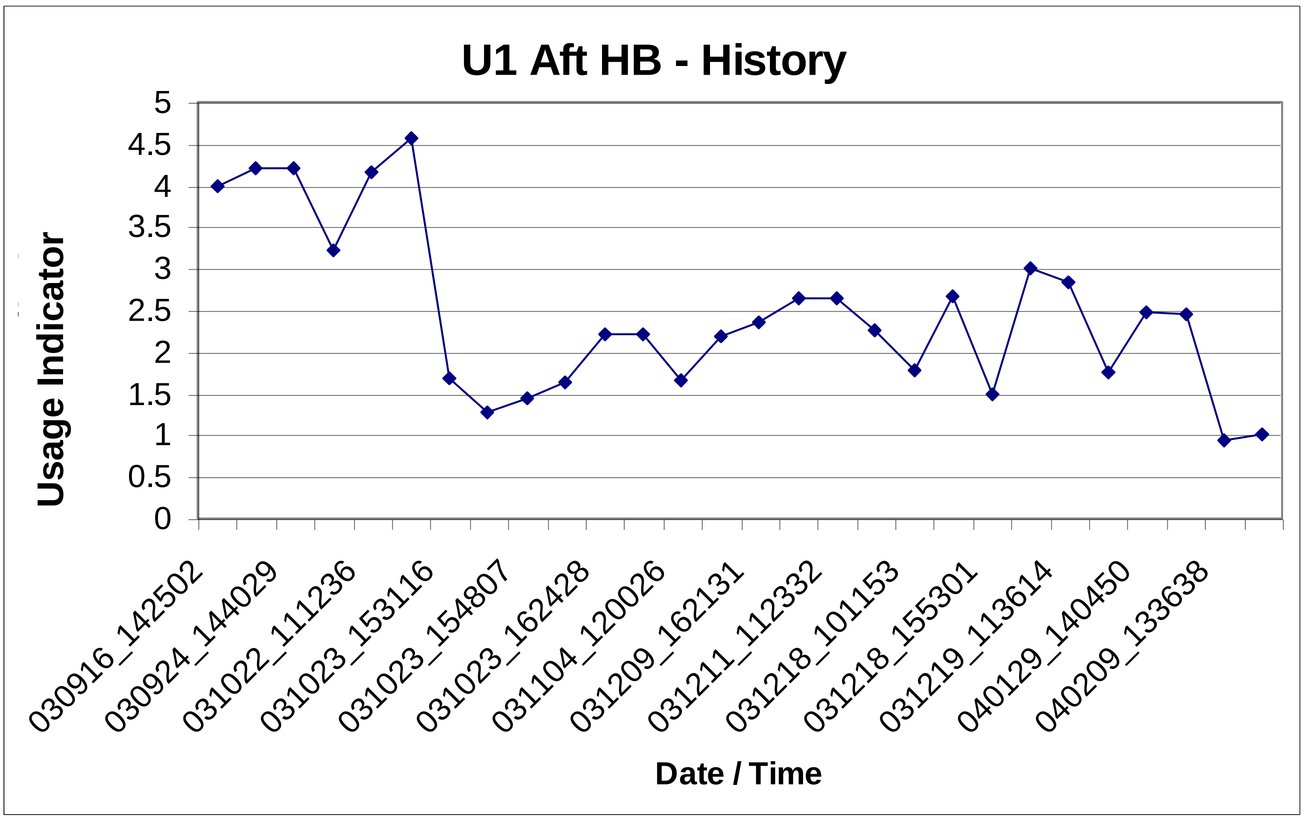

Figure 9 – If we plot the data points relating to sequence 29 where we saw a high reading over time, we can see that there was an unusually high spike on about 10/22/03. There were leading indicators in the trend line leading up to this point that shows an increase in the amount of vibration. We can suppose and verify that after 10/23/03 that the Aft HB was replaced due to the immediate trend of decreasing vibration.

APU Clutch—Over $100,000,000 was lost in late 2003 due to the failure of three APU clutches. VMEP would have alerted the crew chief that the vibration level of the clutch was approaching critical levels. The Aviation Engineering Directorate (AED) used the three years of APU clutch data from the South Carolina Apaches to help determine the maximum safe vibration level for APU clutches.

Figure 10 – APU Clutch

A procedure using the AVA was then established to measure the APU clutch vibration level every 50 hours. With VMEP, this measurement, along with most rotating components, are measured every time a plot presses the “DO” button.

4. PROGRAM DIRECTIONS & FUTURE WORK

Program Directions

Our ongoing activities are being performed along four main directions, namely:

(1) Refine / improve the CBA model based on the cost benefits basic and mission analysis.

current and future responses to questions about non-tangible benefits.

Step 3. Here we essentially repeat the process going back to Step 3B as well as continuously considering the questionnaire items and any needed adjustment in them. The purpose in repeating the process is first to bring more units into the population of pilots and crew chiefs assessed with regard to mission benefits of the VMEP system; and second to have a continuing reassessment from units already responding to the questionnaire to monitor ongoing mission benefits over time within individual units across similar and different mission situations.

(2) Extend data collection and data analysis to other military establishments.

The following three steps are to find ways to quantify and subsequently “measure” non-tangible benefits in order to include such benefits in the cost and benefits model.

Step 1. Our next step will be to conduct focus groups with crew chiefs, and focus groups with pilots the purpose of which will be to identify quantifiable indicators associated with the Likert scale anchor points on each of the four questions across the four non-tangible mission benefit areas. The purpose of this step will be to engage people directly involved in using and maintaining these aircraft and most responsible for mission objectives to discuss and shape measurable indicators in areas like safety, operational readiness, morale and performance - what is the tangible payoff of higher morale, better safety, etc. We will conduct several focus groups within each group across guard and regular army settings to again achieve diversity in our input and as a result greater reliability and hopefully validity in the attributions we eventually make.

Step 2. Take the input from our focus groups, and with our research team and army advisory group agree upon measurable financial, time and other outcome “results” associated with Likert scale outcomes in the four non-tangible benefit areas. Our objective will be to quantify, financially, whenever possible and credible, measures or multipliers we can apply to questionnaire answers in these areas. If we are not satisfied with the credibility and validity of the attempt to attach financial indicators, we will adopt a more academic research approach and create a “normalized” score for non-tangible benefits, much like the BCS creates a scoring system to rate football teams, and we will use it to “measure and quantify” in a meaningful way concurrent and future responses to questions about non-tangible benefits.

(3) Develop a unique, high fidelity laboratory test stand facility for physics-based diagnosis and prognosis purposes.

(4) Develop a complete and smart reliability model based on 1, 2, and 3 above in order to improve system’s integrity, functionality, and qualification.

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BIOGRAPHIES

***Abdel-Moez E. Bayoumi**, Ph.D., is a Professor and Department Chair of Mechanical Engineering at the University of South Carolina, Columbia. He has over 25 years of teaching and research experience. Before joining USC, he was a Professor of Mechanical and Aerospace Engineering at North Carolina State University, 1996 – 1998, an engineering project manager at Hewlett-Packard Company, 1993 – 1995, and a Professor of Mechanical and Materials Engineering at Washington State University 1983 –1993. He has been actively involved in developing strong programs in mechanical systems for both teaching and research. His research activities have been focused in mechanical behavior of materials, diagnosis and prognosis of mechanical systems, mechanical design, design for manufacturability, concurrent engineering, mechatronics, non-destructive testing of materials, product qualifications, and integrity.*

***William Ranson**, PhD., has over thirty years teaching experience. Dr. Ranson is Professor of Mechanical Engineering at the University of South Carolina College of Engineering and Information Technology. He has published over sixty papers and supervised twenty doctoral and forty five masters students. He has provided technology-enabled learning to over 1500 engineers working in over fifty corporations. He developed one of the three initial University Extension programs in the field of manufacturing, the purpose of which is to technology-enable manufacturing supply chains for world-class competition. He has developed training programs in the use of information technology in manufacturing. He has co-developed a curriculum in manufacturing which uses information technology as an enabler to achieve world-class competitiveness.*

***Colonel Lester D. Eisner** is currently serving as the Director of Aviation and Safety for the South Carolina Army National Guard. He was commissioned into the U.S. Army in 1976. He has served in various key staff and command positions including battalion and brigade command. Colonel Eisner has logged over 5000 flight hours in various U.S. Army aircraft, including the UH-60 and AH-64A. He is a graduate of the U.S. Army War College. Colonel Eisner serves as the director of the Vibration Management Enhancement Program (VMEP).*

***Chief Warrant Officer Five Lemuell Grant** graduated from Georgia State University with a B.S in Criminal Justice. Presently, Mr. Grant is the State Army Aviation Maintenance Officer for the South Carolina Army National Guard. He has 38 years of Army aviation experience beginning in 1966. During his career, he has flown over 7500 hours while serving in Vietnam, Operation Desert Shield and Operation Joint Endeavor. Currently he is an Apache Maintenance Test Flight Examiner but is also qualified in the Blackhawk, Huey and several other retired army helicopters. During his military service he has twice been awarded the Distinguished Flying Cross, the Bronze Star, and 56 Air Medals. His career has centered on helicopter maintenance. He has co-authored seven articles referencing helicopter vibrations and aircraft health monitoring systems. He began the VMEP development in 1984.*