ON-BOARD VIBRATIONS AND HEALTH MONITORING SYSTEMS: AN APPROACH TO ACHIEVE CONDITION-BASED MAINTENANCE (CBM)

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ABSTRACT

The objectives of our program are 1) 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), and to initially correlate vibration signals with the ULLS-A (logistics) database to create a Costs Benefits Analysis (CBA) model, 2) to extend our activities in data collection and analysis to achieve the condition-based maintenance (CBM) principles, and 3) to develop diagnosis and prognosis models based on scientific knowledge and laboratory experimentations.

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. 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. Our second objective has begun to extend our On-Board Vibration Monitoring System (VMEP, MSPU, HUMS) activities to meet the objectives and goals of the Condition-Based Maintenance (CBM) concept. At the conclusion of this program we are going to deliver a methodology and the needed technologies for the CBM concept (using logistics (ULLS-A), maintenance (MDR) and vibrations (VMU) databases) to complete a qualified prognosis model(s) and an analytical tool to relate usage and condition indicators to the aforementioned data in order to predict the remaining life as a function of CI's and usage profile; and a simulation model to demonstrate flight regimes and flight profile.

History and Background

1. The On-Board Vibration Monitoring (VM) System:
The specific objectives of this task were to 1) reduce rotor track and balance maintenance test flights, 2) reduce aircraft operation costs, 3) increase aircraft availability, and 4) increase aircraft safety. The University of South Carolina and SCARNG have established a model to measure the cost effectiveness of the VMEP program. VMEP has been mitigated to other Apache Readiness Improvement Program (ARIP) problems, such as APU clutch failures (believed to cause fires), shaft-driven compressor (SDC) component failures, nose gearbox seal failures, pitch-change bearing wear, tail boom cracking, vertical stabilizer ribs cracking, engine nacelle bulkhead cracks, generator failure due to bearing faults, and main rotor blade debonding.

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, and 4) identify and address incipient failures through repair and/or replacements.

2. 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.

2.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 actions (MTBMA), mean time to repair/replacement (MTTR), and operational stability, 3) improved mission completion rates (lower mission abort rates), and 4) improved safety of flight statistics.

2.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 the 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. Cost benefits will also be realized in parts reliability with a resulting extension in parts life (Time before replacement – TBR)

2.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.

2.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.

2.v. 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.

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.

3. Condition-Based Maintenance (CBM) and the On-Board Vibration Monitoring (VM) System:
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; namely 1) vibration for analysis of dynamic components - from VMEP (Vibration Maintenance Enhancement Program), 2) state data for regime recognition, fatigue, and flight visualization - from the MDR (Maintenance Data Recorder), 3) parts tracking and usage history - from AMATS/CMB (Aviation Maintenance Automated Tracking System/Contact Memory Buttons), and maintenance activity – from ELAS (Enhanced Logbook Automation System).

The CBM objectives as cited in several communications [21-26] are to 1) reduce unscheduled maintenance & maintenance workload, 2) decrease maintenance and logistics footprints, 3) perform maintenance only upon evidence of need, 4) improve diagnosis and prognosis capabilities, 5) integrate advanced engineering, maintenance, and information technologies (condition indicators, usage and health indicators, data warehousing and mining), 6) use real-time assessments of material condition obtained from embedded sensors and/or external tests and measurements using portable equipment, and 7) increase Operational Availability.

WORK DESCRIPTION

1. VMEP COST-BENEFIT ANALYSIS

The University of South Carolina’s Department of Mechanical Engineering under several contracts with industry and Government sponsors has been actively involved in studies concerning the diagnosis and prognosis of mechanical systems since 1998. A major part of our investigation started five years ago to evaluate the cost and effectiveness of the AH-64 (Apache) and UH-60 (Blackhawk) helicopters’ on-board Vibration Monitoring (VM) Systems. This will provide an annual cost savings analysis of the Vibration Management Enhancement Program (VMEP) for the AH-64 and UH-60 aircraft fleets, and will correlate vibration signals with the ULLS-A (logistics) database to create a Cost Benefits Analysis (CBA) model. Logistics (ULLS-A) and vibration (VMU) data were collected for Blackhawks and Apaches from different establishments (South Carolina Army National Guard, Alabama Army National Guard, deployed units in Kosovo, Korea, Iraq), warehoused in our database, and analyzed. In addition, all personnel from these bases were surveyed to examine other non-tangible benefits of the program. As of today, three sources of data were used throughout our investigation (the top three barrels in column I in the above figure of the program roadmap).

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 cost savings, 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 part failures, mission aborts, and unscheduled maintenance occurrence.

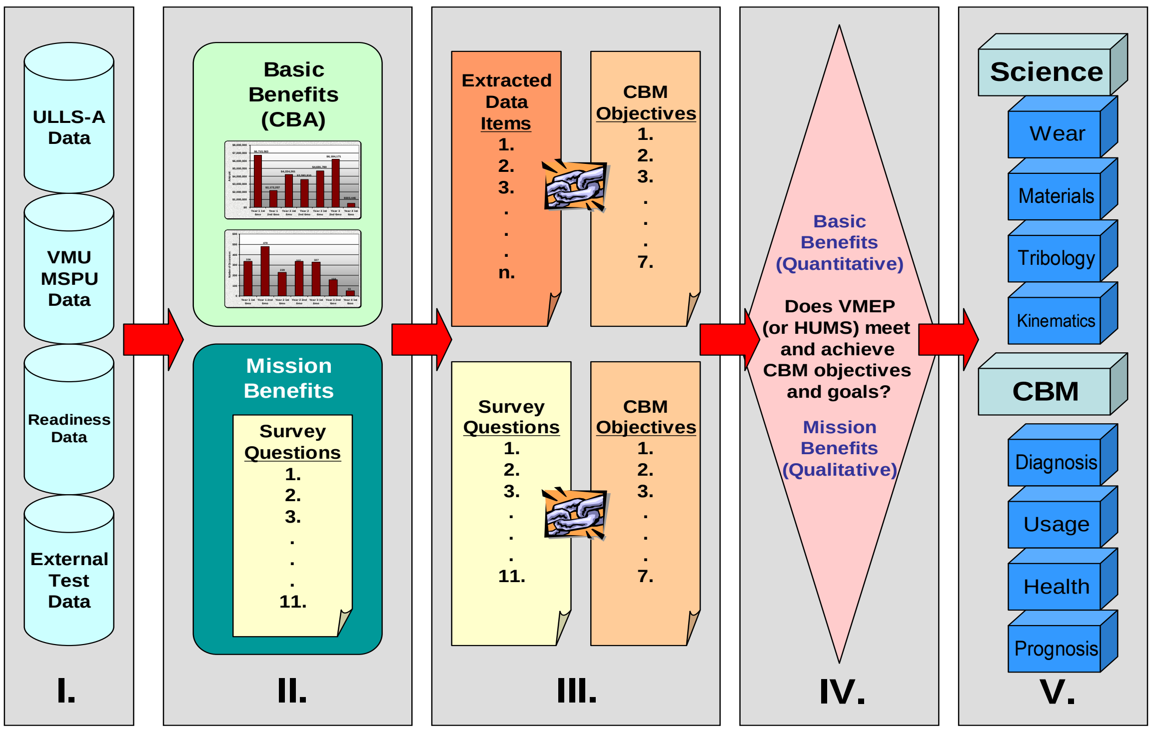


Figure 1 - Program Roadmap

As of today, our activities (Column I, II, and III in Figure 1 above of the program roadmap) 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, attention and performance, personnel morale, actual safety and sense of safety.

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.

Our team at USC and SCARNG has 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.

1.1. 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.

1.2. Data Collected and Associated Benefits

a) 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 1) part S/N and cost, 2) man-hour for installation and troubleshooting, test-flight hours for confirmation or operational crew hours, identify if part is related or not to vibration (a tire – *no*; an on-board computer – *yes*; a hydraulic pump – *maybe*), and 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.

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.

Figure 2 shows the aircraft tracking as of July 2005 with the number of ULLS-A and vibrations data records.

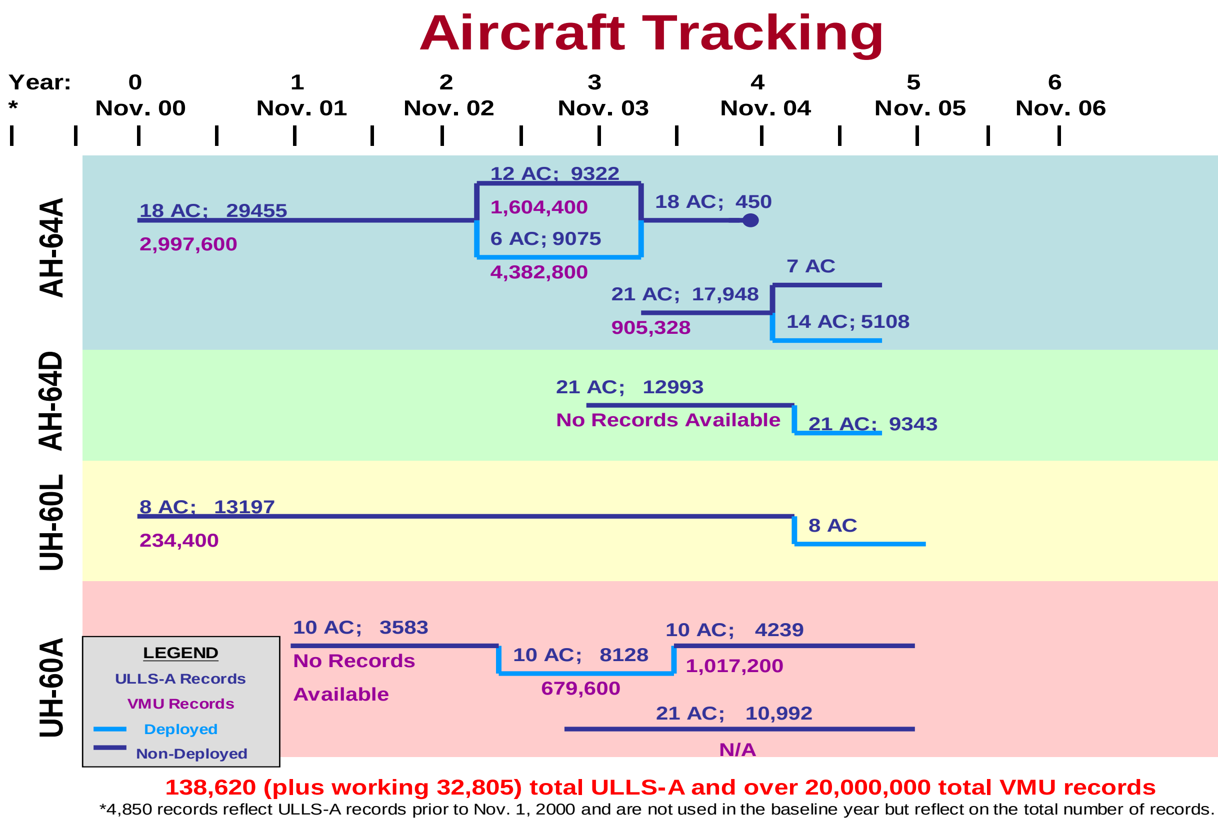


Figure 2 - Aircraft Tracking and ULLS-A/Vibrations Data records

b) 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.

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. We were able to extract all 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.

2. Condition-Based Maintenance (CBM) Program

A major task of our activities was to connect our cost-benefits and mission-benefits analyses with the condition-based maintenance (CBM) objectives through five steps procedure below. Steps 1 and 2 were fully implemented for the data we collected to date, step 3 is partially carried out, and steps 4 and 5 will be carried out using our new test stand.

1. Quantitatively operationalize the CBM objectives through our ongoing quantitative ULLS-A and vibrations data that we are collecting, analyzing, and processing for the last six years. The most obvious outcome of these activities is the cost benefits and mission benefits models. Other ongoing activities will include value engineering process of the system in meeting CBM objectives.
2. Qualitatively operationalize the CBM objectives through our ongoing activities of surveying engineers, pilots, maintainers, and crew chiefs on the non-tangible and mission benefits of the VMEP system (safety, morale, mission capabilities, confidence on the system, and system liability).
3. Combine the qualitative and quantitative measures from (1) and (2) above to validate that the VMEP system can meet CBM objectives. This task is particularly important in what is needed to develop a new paradigm shift for maintenance training. The combined measures will also be presented and evaluated mathematically, parametrically, and mechanistically as diagnosis models of components or systems. Such models will include and encapsulate, among other data collected, the flight regimes and flight profiles. A simulation model will be created to help the users practicing these tools virtually prior to implementations.
4. The On-Board Vibrations Monitoring System (VMU) has been successful in identifying faults by the exceedance values of the Condition Indicators (CIs). Since the VMU systems are installed on existing aircraft, usage history and remaining life are still undetermined. The goal of the test stand is to provide data and algorithms for usage and remaining life for new and existing parts. Components and parts that show excessive vibrations will be removed from the aircraft. These parts will be inspected and the fault will be recorded. The part will be placed in the test stand and run until final failure. At the present time several components have been removed from aircraft due to excessive vibrations and are available for immediate testing. They include APU clutch, hanger bearing, two nose gear boxes (en route from Iraq) and four IGB assemblies. This data will be used to develop prognosis algorithms that correlate known faults with CIs. When the CIs are fully refined and validated this sensor information will be integrated into the CBM framework that will be used to predict the overall health and the remaining life of components or systems.
5. All collected data will be interrogated and validated in the laboratory using our **Helicopter Drive Component Test Stand.** The test stand will be used to refine and improve our prognosis models by examining bearings, shafts and gears in order to correlate their conditions with the associated parameters both from new and existing components or operational aircrafts. Parameters to be monitored include, but are not limited to: wear, friction, oil condition, metals in oil, temperature, other tribological factors, vibration, condition indicators, and loading conditions and profiles.

Results And Discussion

Highlights of results and benefits are presented in Figures 4 through Figure 9 for AH64. Similar results were obtained for UH-60 aircrafts with similar highlights of results and benefits. For example, 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. The program elements are schematically shown in Figure 3.

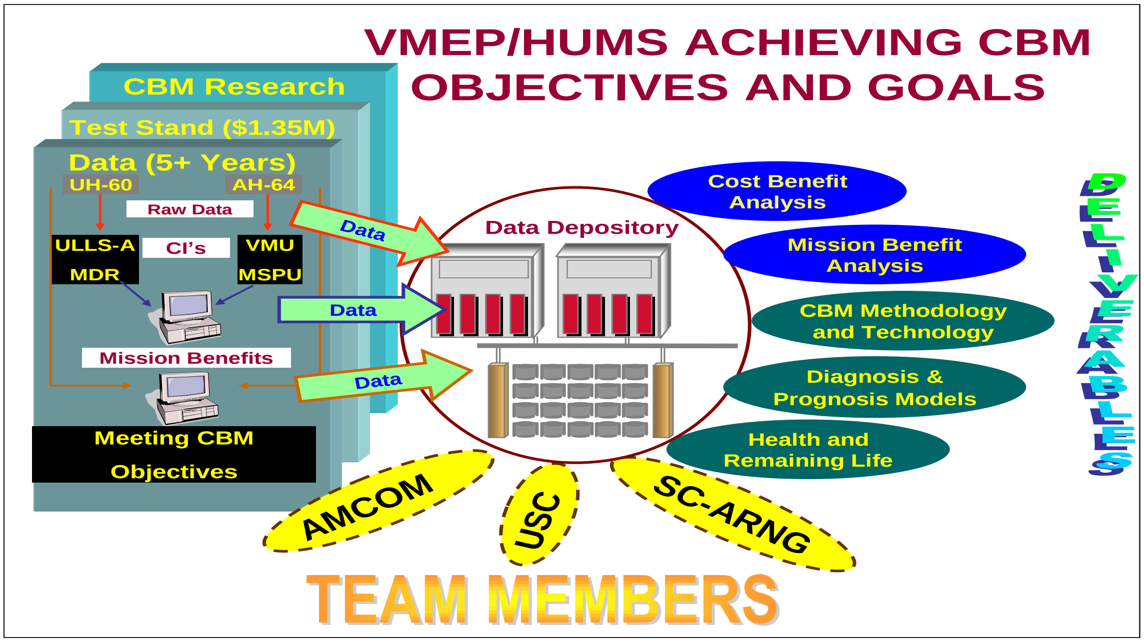


Figure 3 - Program Elements

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.

Measuring Non-Tangible Mission Benefits

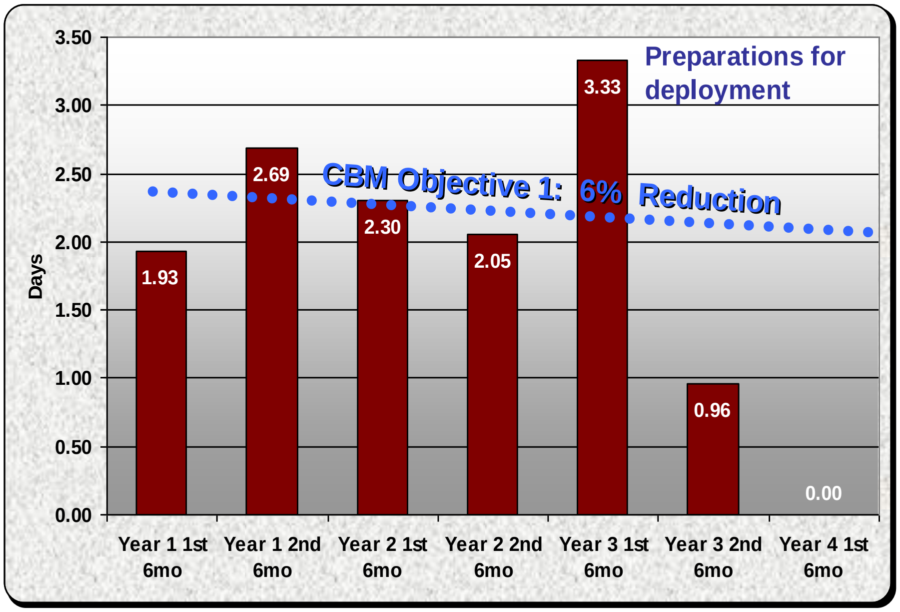
Our original brainstorming sessions identified two categories of benefits, basic and mission, which are important areas to "measure" VMEP outcomes in a comprehensive cost and benefit model. Mission benefits, the "soft" benefit area, were conceived to comprise four areas: Operational Readiness, Morale,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

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. Indicators of improvement in operational readiness, safety, morale and performance were noticeable. The results suggested solid improvement in these mission benefit areas over the time since VMEP was introduced into this unit's aircraft.

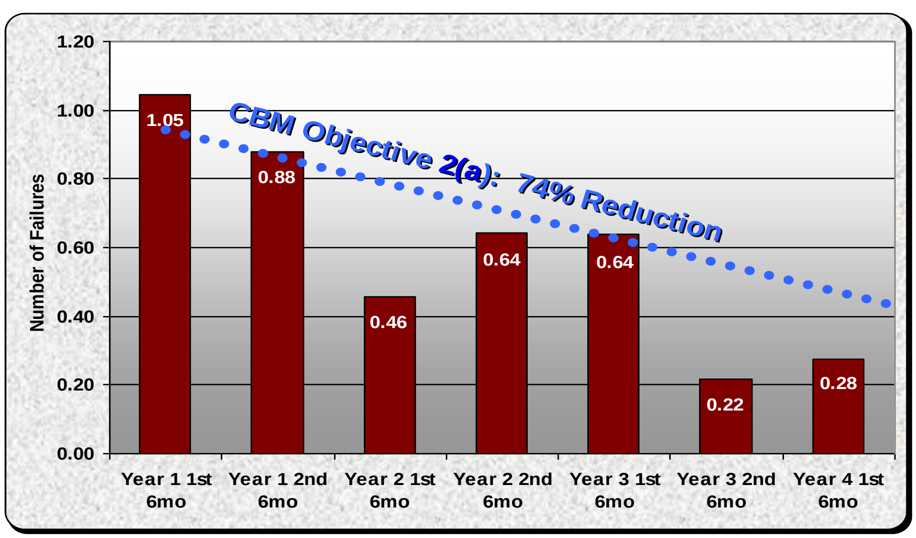
CBM Objective 1: Reduce Unscheduled Maintenance & Maintenance Workload



Days Pending Repair per 100 Flight Hours (AH64)

Figure 4 – Total Parts Cost, AH-64

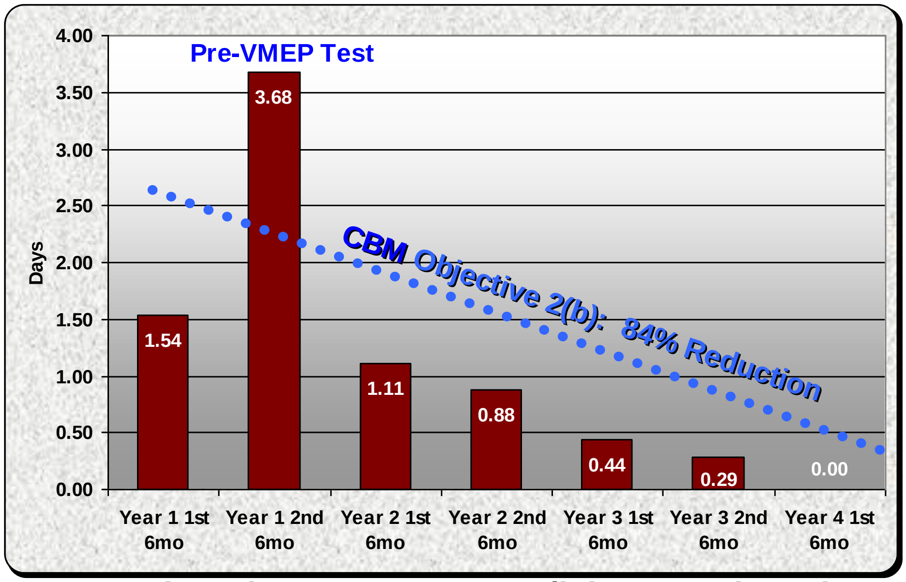
CBM Objective 2: Decreased Maintenance & Logistics Footprints



Premature Part Failures per 100 Flight Hours (AH64)

Figure 5 – Total Maintenance Test Flight Hours, AH-64

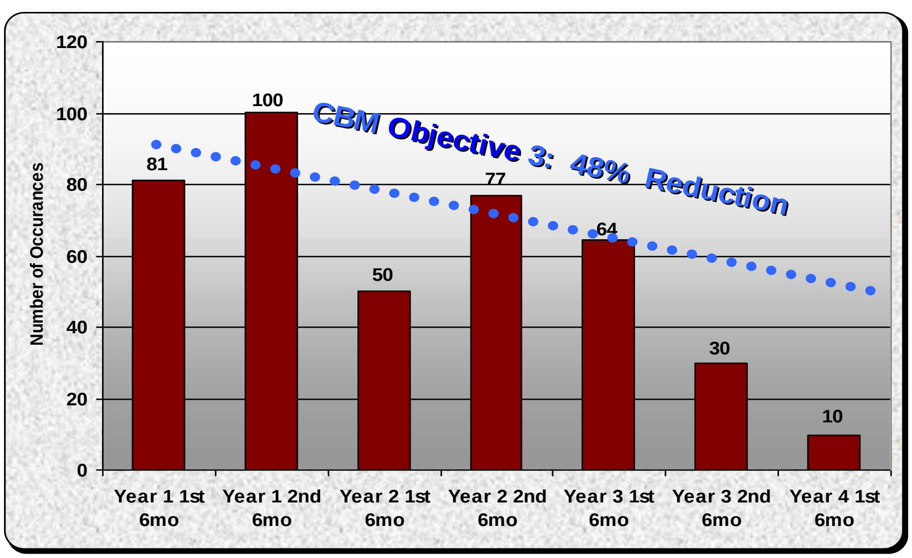
CBM Objective 2: Decreased Maintenance & Logistics Footprints



Days in Maintenance per 100 Flight Hours (AH64)

Figure 6 – Premature Parts Failures per 100 Flight Hours, AH-64

CBM Objective 3: Perform Maintenance Only Upon Evidence of Need



Unscheduled Maintenance per 100 Flight Hours (AH64)

Figure 7 – Days in Maintenance per 100 Flight Hours, AH-64

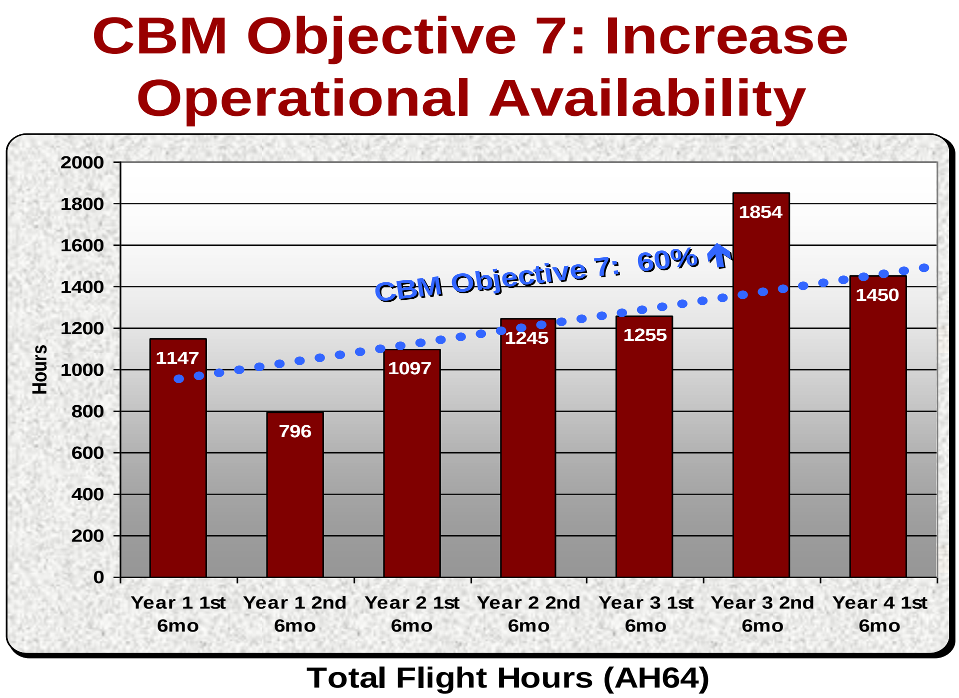


Figure 8 – Days Pending Repair or Part, AH-64

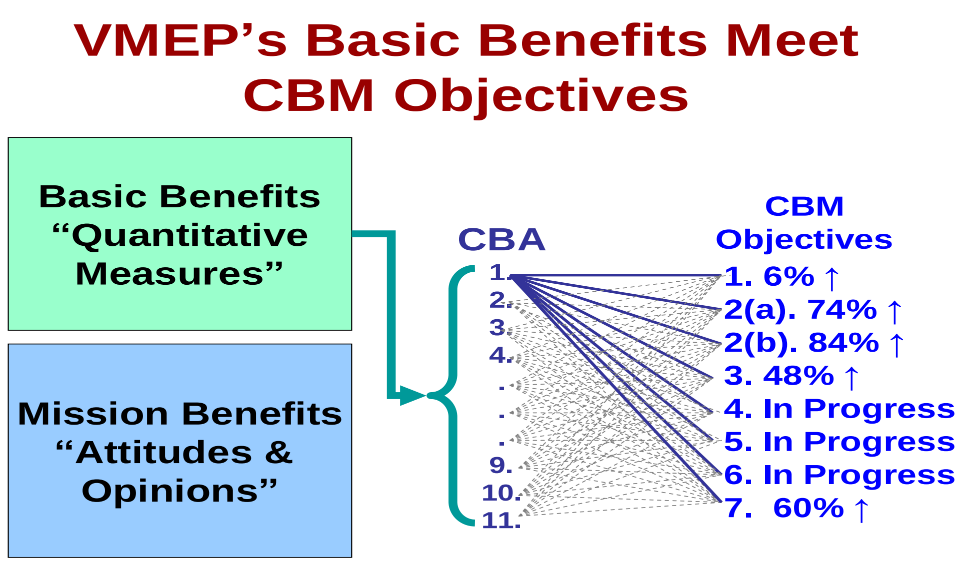


Figure 9 - VMEP Basic Benefits Meets CBM Objectives

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 Figure 10.

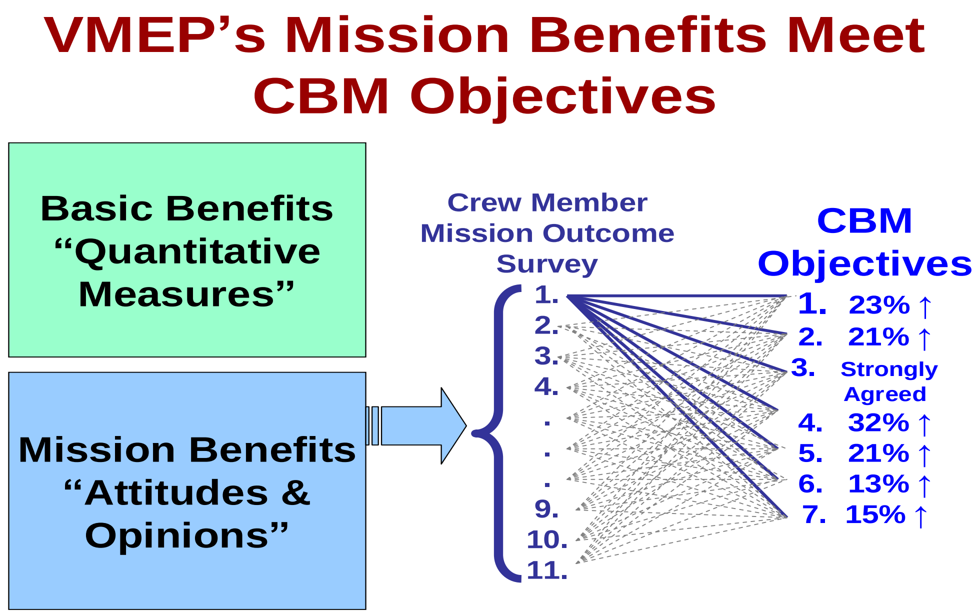


Figure 10 - Mission Benefits Meets CBM Objectives

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, and 6) improves performance. Additionally Figure 9 shows that the VMEP vision benefits meet most of the CBM objectives.

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 Testimonials:
"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 Testimonials:
"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."

PROGRAM HIGHLIGHTS AND 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, and 5) meeting CBM objectives.

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.

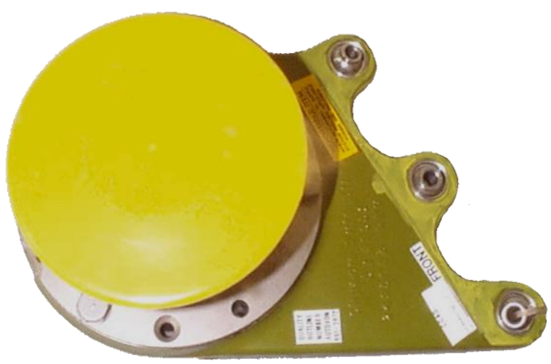


Figure 11 – Aft Hanger Bearing

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.

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.

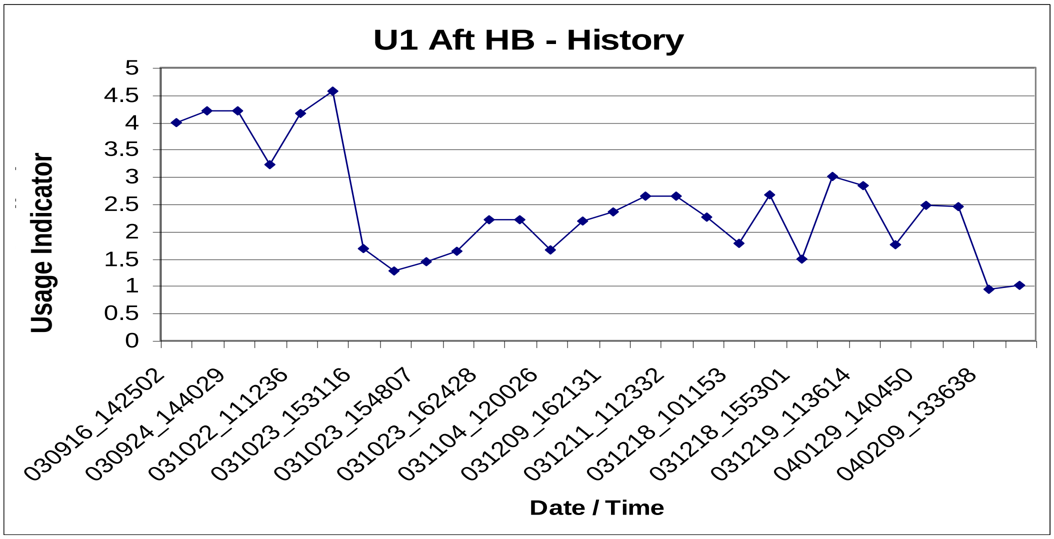


Figure 9 – If we plot the data points relating to sequence 29 where we saw a high reading over time, we can see that there was an unusually high spike on about 10/22/03. There were leading indicators in the trend line leading up to this point that shows an increase in the amount of vibration. We can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

Figure 12 – 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, is measured every time a plot presses the "DO" button.

Main Rotor Swashplate Bearing

- AH-64A Main SP at caution consistently starting Nov 2003; *Swashplate single point-of-failure*
- SP CI abnormal compared to all other VMEP-equipped A/C; *Over caution, but not growing significantly*
- SP passed standard inspection per TM 1-1520-238-23, paragraph 1.137; *"Spin & feel for roughness" test subjective*
- Data reviewed via iMDS website during caution/exceedance limits review *(Large peak in spectral data for aircraft, Sidebands spaced at intervals corresponding to bearing fault frequencies)*
- Suspected bad swashplate bearing
- Raw vibration data was acquired Apr 04 and SP was received May 04 before aircraft was turned-in for D model conversion
- SP disassembled by PIF per DMWR Aug 04
- Corrosion pitting, broken cage & blackened grease discovered
- Additional algorithms developed from raw data and implemented into VMEP for release Sep 04

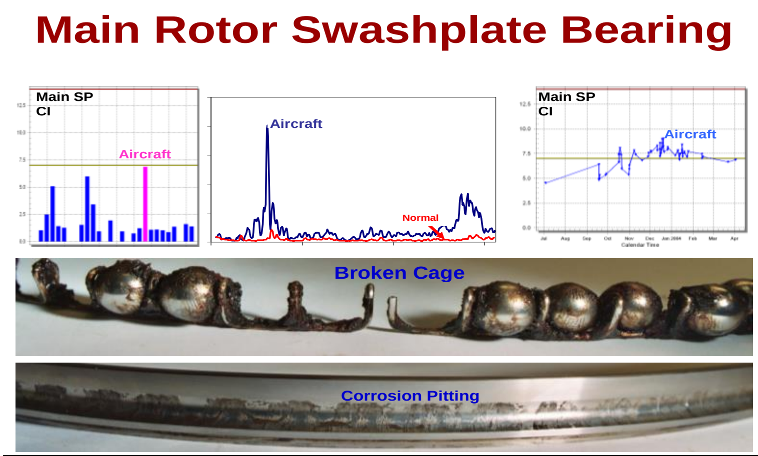


Figure 13 – APU Clutch

<u>Program Long-Term Anticipated Deliverables</u>:

1. ***A METHODOLOGY*** and technology that implements the CBM concept using logistics (ULLS-A) data, maintenance (MDR) data, vibrations (VMU) data, and helicopter test stand as well as other laboratory data.
2. Accurate ***PROGNOSIS MODELS*** that relate usage and health indicators (CI's) with ULLS-A, MDR, and VMU data creating algorithms that predict the remaining life as a function of CI's and usage profile.
3. ***A SIMULATION MODEL*** of flight regimes and profiles.

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BIOGRAPHIES

Abdel-Moez E. Bayoumi*, Ph.D., has over 25 years teaching and research experience. Dr. Bayoumi is Professor of Mechanical Engineering at the University of South Carolina College of Engineering and Information Technology. Before joining USC, he was a Professor of Mechanical and Aerospace Engineering at North Carolina State University, a project manager at Hewlett-Packard Company, and Professor of Mechanical and Materials Engineering at Washington State University. 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, and NDE. He has published over 100 papers and supervised twelve doctoral and thirty masters' students.*

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 in over fifty corporations. He developed one of the three initial University Extension programs in the field of manufacturing 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).*

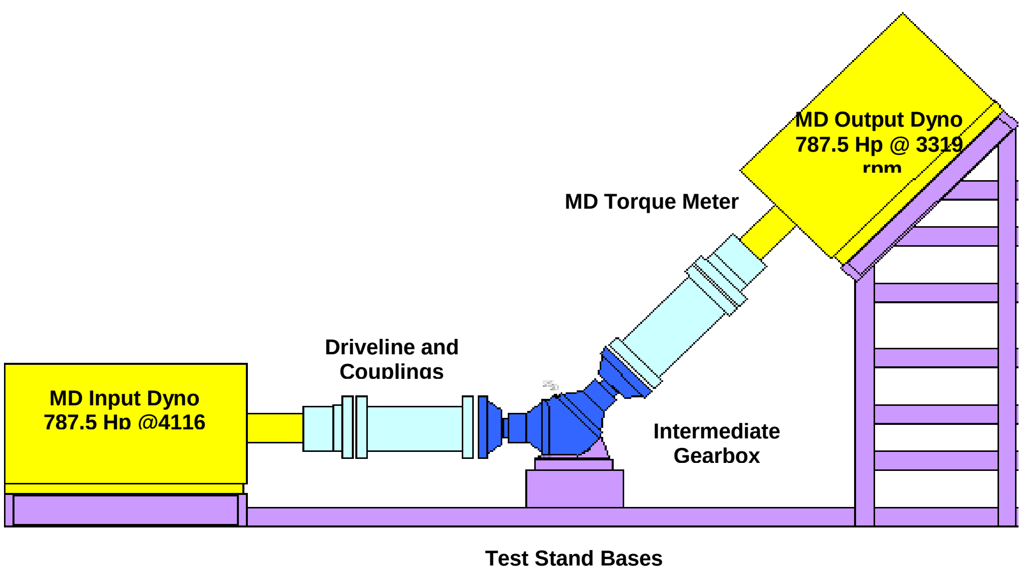
Chief Warrant Officer Five Lemuell Grant *graduated from Georgia State University with a B.S in Criminal Justice. Presently, Mr. Grant is the State Army Aviation Maintenance Officer for the SC-ANG. He has 38 years of Army aviation experience beginning in 1966. During his career, he has flown over 7500 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.*

APPENDICES

APPENDIX A
USC HELICOPTER DRIVE COMPONENT TEST STAND

A Helicopter Drive Component Test Stand was designed and configured for the development of comprehensive diagnosis algorithms and prognosis models, and in order to meet/achieve the CBM objectives. It is being built to test the intermediate gear box (IGB) components and assembly of the S-70 tail rotor drive. This test stand was designed to be affordable and practical for multiple purposes. We currently have four used IGB assemblies, the drive shafts, and the ability to obtain more assemblies and components rejected during future overhauls. A schematic of the USC test stand is shown below. Additionally, the department of Mechanical Engineering at the University of South Carolina has state-of-the-art metrology, imaging, sensing, materials characterization, and tribology laboratories that will be utilized throughout this program of research.

USC Helicopter Drive Component Test Stand



Schematic of the USC Helicopter Drive Component Test Stand

APPENDIX B
IMPORTANT DEFINITIONS

Condition Based Maintenance:
Condition-Based Maintenance (CBM) is the nomenclature assigned to a maintenance process that is based upon the electronically determined condition of a component, sub-system or system.

Condition:
Condition is based upon electronic measurements that can be related to condition without the need to disassembly and inspect through conventional means.

Objectives of Conditions-Based Maintenance (CBM):

1. Reduce unscheduled maintenance and maintenance workload.
2. Decrease maintenance and logistics footprints.
3. Perform and integrate advanced engineering, maintenance, and information technologies.
4. Maintenance only upon evidence of need.
5. Improve diagnosis and prognosis capabilities.
6. Use real-time assessments of material condition obtained from embedded sensors and/or external tests and measurements using portable equipment.
7. Increase operational availability.

Condition Indicators (CI):
Condition indicator algorithms come in many varieties and capabilities. These condition indicators are in turn used to develop Health Indicators (HI).

Ideal Condition Indicator (ICI):
The Ideal Condition Indicator emulates the fault. That is, if it were possible to measure the physical distortion (crack or other evidence of damage) the fault would grow in an exponential way that could be characterized as time to double amplitude, with amplitude being both ICI and the physical dimension of the fault.

Health Indicator (HI):
The Health Indicator (HI) is a non-dimensional metric that is constructed (calculated) by the manipulation of related condition indicators (the output of condition algorithms). The time history of a perfect HI would identically track (match) the time history of the related ICI.

Low Power Mechanical Wear:
Certain types of faults can develop as the result of extended low power operations. It was also determined that summing the operating time at or below 40% of takeoff power would provide a suitable usage metric for predicting faults or for correlating usage to certain types of faults (for Reliability Centered Maintenance (RCM) analysis and long lead logistics planning).

Diagnosis:
Faults in bearings, gears and shafts can be detected. These detections are reported as magnitudes. Faulted shafts are the easiest to detect, and bearing faults are the most difficult.

Prognosis:
When it is possible to detect an increase in the magnitude of a detection algorithm output as a function of a tangible usage metric, it is possible to predict the useful service life remaining. This prediction is known as prognosis. A tangible usage metric is that usage metric that relates most directly to the loads and cycles causing the fault (or incipient fault) to propagate. In the case of a helicopter power train, there are many potential metrics:

- Flight time
- Operating time (running time)
- Power spectrum
- Time integral of applied power (throughput power)
- Time integral of applied power normalized for the system S-N Characteristic (Normalized Throughput Power.)

Normalized Power:
Power normalized for the damage factor applicable to a given power train.

Usage of Mechanical Systems:
Usage is defined as time integral of the power applied to the mechanical system. This usage is also known as generic system usage.

Normalized Throughput Power (NTP):
When corrected for the generic system usage factor, this usage is referred to as the “Normalized Throughput Power (NTP)”. It may be more correct to recognize that some assemblies are subject to an assembly unique usage factor schedule (or characteristic).

In addition, the NTP term is used to track how demanding the usage has been over time. This usage will allow the Reliability Center Management (RCM) analysis to compare the usage experienced by individual aircraft in a fleet and predict the need for compensatory engineering and logistical actions.

If the increase is significant and can be correlated to the Normalized Throughput Power Hour, a fault exists. If a number of detection algorithms see the same fault, the potential threat to airworthiness is further verified.

Observed Usage vs. Reported Usage:
Observed usage refers to data automatically recorded or automatically derived from time histories. Reported usage refers to manually observed and reported data.

Usage Tracking:
Observed usage is accumulated for all flights to allow historical analysis of usage for the subject aircraft and for the relevant fleet.

Simulation Program:
The simulation program is a program to simulate the propagation of a mechanical fault in a typical rotorcraft power train. This program will be written to provide engineers and logisticians a simple tool to use to generate time histories of a variety of mechanical faults as they progress from an incipient stage to the point where corrective maintenance is required before the next flight.

Flight Profile:
A flight profile is a series of ground and flight phases (or events). The simulation program is limited to the simulation of mechanical power train health during flight operations and ground operations when the rotor is turning. The analyst (user) will be able to create flight profiles or use an existing flight profiles. For the purposes of this simulation, the program needs to know the sequence of the various phases and the time spent in each phase.

Flight Phase:
A flight phase is a portion of a flight profile: take-off, cruise, climb, landing, etc.