DEVELOPING A RELIABILITY INVESTMENT MODEL

PHASE II—BASIC, INTERMEDIATE, AND PRODUCTION AND SUPPORT COST MODELS

REPORT HPT80T1

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Executive Summary

The Director of Operational Test and Evaluation; Deputy Director, Assessments and Support, Systems and Software Engineering; and Deputy Under Secretary of Defense (Logistics and Materiel Readiness) jointly tasked LMI to develop a reliability investment model that would assist with determining the investment in reliability that is needed to achieve a desired improvement in system reliability.[1] This effort required the development of three models:

- A basic model that computes reliability development effort and cost as a function of program size and desired reliability improvement. Use of this model would be suitable, for instance, on the very front end of programs when little is known beyond the desired reliability improvement.
- An intermediate model that computes development effort (and schedule) as a function of program size, desired reliability improvement, and a set of relevant cost drivers.
- A production and support cost model to estimate the delta investment in production (e.g., for retrofit and spare parts) and the change in operations and support cost due to an improvement in reliability.

A detailed model that incorporates the characteristics of the intermediate version with an assessment of the cost drivers' impact on each step (analysis, design, etc.) of the reliability engineering process was not an element of this project, but is the logical extension of this work.

BASIC MODEL

To create the basic model, we developed a cost estimating relationship (CER) by performing regression analysis on data from 17 programs. (As far as we have

[1] Earlier work by LMI provided evidence that such a model was feasible. See *Empirical Relationships between Reliability Investments and Life-Cycle Support Costs*, Report SA701T1, E. Andrew Long et al., June 2007.

been able to determine, this is the first time such a CER has been available.) Required investment increases linearly with average production unit cost (APUC) and a power function of the reliability improvement ratio. APUC is essentially normalizing for program size and complexity. The reliability improvement ratio is (New MTBx − Old MTBx)/Old MTBx:[2]

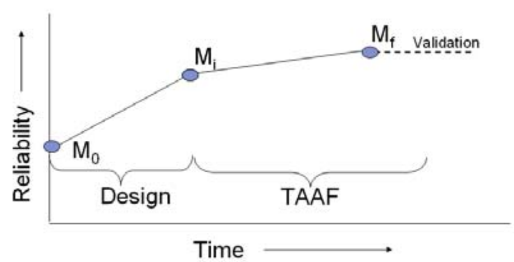
$$Investment = \left(\frac{Reliability\ Improvement\ Ratio}{0.3659} \right)^{2.119} \times APUC\ . \qquad (Eq.\ 1)$$

INTERMEDIATE MODEL

The intermediate model is based on the mathematics that underlie the Army Material System Analysis Agency (AMSAA) Maturity Projection Model (AMPM). Starting from the same premises as the AMPM, LMI rederived the model while incorporating terms representing cost. For development purposes, we divided the reliability engineering process into two periods, as shown in Figure ES-1:

- Design period beginning with Old MTBF (M_0) and producing the initial reliability entering the test, analyze, and fix (TAAF) period (M_i)
- TAAF period, beginning with M_i and ending with the final reliability (M_f).

Figure ES-1. Intermediate Model Concept



TAAF Period

We distinguish between failure modes that management agrees to accept without amelioration, called A-modes, and modes that will be addressed, called B-modes. Our model for the variation of reliability improvement with cost in the TAAF period consists of two equations:

$$\frac{1}{M(\tau)} = \frac{1}{M_A} + \frac{1}{M_0}\left[(1-\mu_{d)}) + \frac{\mu_d}{1+\tau}\right]. \qquad (Eq.\ 2)$$

[2] MTBx can be mean time between failure, mean time between removal, mean time between system abort, mean cycles between removal, or other similar measure relevant to a specific program.

$$\gamma(\tau) = \frac{1}{cv^2}\left[C_0\tau + \mu_b \ln(1+\tau)\right]. \qquad \textit{(Eq. 3)}$$

Equation 2 expresses the system's MTBF $M(\tau)$ at nondimensional time τ with three parameters: M_A, which is the mean time between A-mode failures; M_0, which is the mean time between B-mode failures at the start of TAAF, and μ_d, which is the average value of the reliability improvements made by corrective action, that is, the d_i. M_0 is always known, and is not an adjustable parameter. AMSAA's experience has developed typical values of μ_d, so that this parameter also is often known a priori. The other three cost parameters are cv^2, a measure of the degree to which the initial B-mode failure rates scatter about their mean; C_0, a measure of the cost of operating the TAAF period; and μ_b, the average value of the cost increments incurred by corrective action taken to ameliorate identified B-modes.

Design Period

In the TAAF period, observing a B-mode failure leads to analysis of its causes and "fixing" and, thus, to an increment of cost. Similarly, we believe that in the design period, identifying a potential failure mode by analysis leads to further analysis of how the mode might be eliminated or reduced in rate and to implementation of changes in component design or in operations concept. This belief leads us to a design-period model with the same form as our TAAF-period model. Like the TAAF-period model, our design-period model is expressed in two equations:

$$\frac{1}{M(\tau)} = \frac{1}{M_A^D} + \frac{1}{M_1}\left[(1-\mu_{D)}) + \frac{\mu_D}{1+\tau}\right]. \qquad \textit{(Eq. 4)}$$

$$\gamma(\tau) = \frac{1}{cv_D^2}\left[C_0^D\tau + \mu_B^D \ln(1+\tau)\right]. \qquad \textit{(Eq. 5)}$$

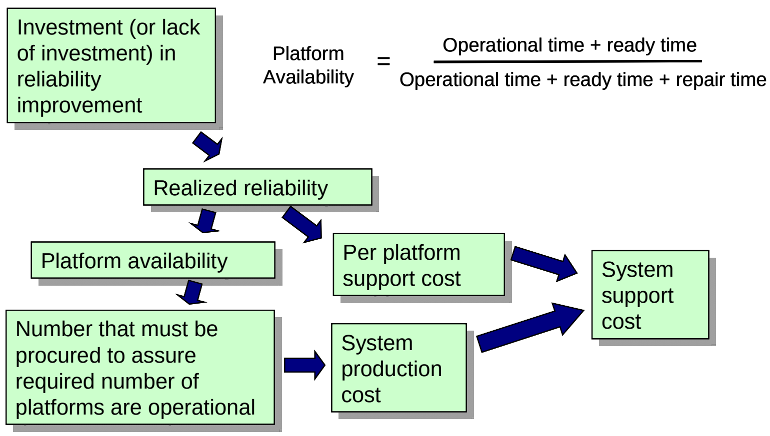
The parameters of the design-period model have the same meanings in relation to the design period and its operations as do the homologous parameters of the TAAF period in relation to the TAAF period and its operations. The parameter M_A^D is the mean time between A-mode failures in the design period. The parameter λ_B^D gives the initial B-mode failure rate at the start of the design period.

The parameter μ_D is the fraction of a B-mode's failure rate eliminated by the design process. Although the homologous TAAF parameter μ_d generally takes values around 70 percent, we believe that μ_D may be significantly larger, approaching 1 in some cases, because of the wider and more fundamental options available for attacking B-modes in the design period. The parameter C_0^D reflects the "burn rate" of engineering labor in the design period; it is equal to the cost of design-period engineering for one mean time between B-mode failures at the start of the design period. The parameter μ_b^D gives the average cost of ameliorating a B-mode failure identified in the design period.

PRODUCTION AND SUPPORT COST MODEL

Changes in reliability, because they affect availability, can influence decisions on the number of platforms that will be required, rather than just the materiel resources required for support. For this reason, we modeled production and support costs as shown in Figure ES-2.

Figure ES-2. Production and Support Cost Modeling Logic



CONCLUSIONS AND RECOMMENDATIONS

We conclude that a strong relationship exists between investment and reliability and that the prospects are good for capturing its predictive properties in a forecasting model. We recommend that more research be performed to mature the basic model. Specifically, continue to make the total number of data points more robust. Also, continue to search for systems that are inconsistent with the described log-log relationship. If found, understand why those systems do not fit the relationship, and determine whether additional parameters would effectively explain and account for any anomalies.

Our design- and TAAF-period models capture the trend of cost as a function of improvement reasonably well, and they treat data consistently. We recommend obtaining data from other reliability programs be used to improve the calibration of our intermediate model and to increase understanding of the relation between reliability improvement and cost in the design period.

Finally, we recommend that a detailed design model be developed to understand how the maturity of reliability engineering affects the efficiency with which an investment in reliability is translated into a reliability improvement.

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Chapter 1

Introduction

The military services need confidence that their systems will not fail during mission execution and, if they do fail, that they can be quickly and economically returned to service. However, test results since the 2001 time frame show that approximately half of DoD's programs are unsuitable at the time of initial operational test and evaluation (IOT&E). The dominant reason is failure to achieve reliability goals. Compared to historical levels, the trend is also adverse: the number of unsuitable programs has increased rather than decreased.

In 2007, the Director of Operational Test and Evaluation (DOT&E) asked LMI to study the cost of not achieving adequate levels of operational suitability by investigating the empirical relationships between reliability investment and life-cycle support costs. An unanticipated outcome of that study was the discovery of what appeared to be a previously unrecognized systematic relationship between investment in reliability and achieved reliability improvement.[1] When we divided the investment in reliability by the average production unit cost (APUC)—essentially normalizing for complexity—and then plotted the logarithm of that ratio against the logarithm of the improvement in reliability, the result was a straight line. As far as we know, this was the first time such a relationship had been discovered.

The 2007 study results were intriguing but were based on data from just six programs, only five of which—Predator unmanned aerial vehicle (UAV), Global Hawk UAV, MH-60S helicopter upgrade, CH-47F helicopter upgrade, and Force XXI Battle Command Brigade and Below (FBCB2)—we analyzed in some detail. Because a relationship defined by five data points is an insufficient basis for cost estimating, DOT&E, along with the Deputy Director of Assessments and Support, Systems and Software Engineering and the Deputy Under Secretary of Defense for Logistics and Materiel Readiness, DUSD(L&MR), asked LMI to build on the 2007 results and develop a reliability investment model that would assist with determining the investment in reliability that is needed to achieve a desired improvement in system reliability. The reliability investment model was to have four components:

- A basic model that computes reliability development effort and cost as a function of program size and desired reliability improvement. Use of this model would be suitable, for instance, on the very front end of programs when little is known beyond the desired reliability improvement.

[1] LMI, *Empirical Relationships between Reliability Investments and Life-Cycle Support Costs*, Report SA701T1, E. Andrew Long et al., June 2007.

- An intermediate model that computes development effort (and schedule) as a function of program size, desired reliability improvement, and a set of relevant cost drivers.
- A production and support cost model to estimate the
  - delta investment in production (for example, for retrofit and spare parts) and
  - change in operations and support (O&S) cost.
- A detailed model that incorporates the characteristics of the intermediate version with an assessment of the cost drivers' impact on each step (analysis, design, and so on) of the reliability engineering process.

Development of the basic, intermediate, and production and support cost models constitute Phase II (the 2007 study being Phase I). Development of the detailed model, notionally Phase III, is beyond the scope of this study, although we recommend an approach in Chapter 5.

Many organizations and individuals contributed to the research described in this report. Appendix A lists them. Without their gracious cooperation and assistance, we could not have conducted this research.

PHASE II STUDY APPROACH

Basic Model

To create the basic model, we built onto the work we did in Phase I to develop a cost estimating relationship (CER) by performing regression analysis on data from 17 programs. As far as we have been able to determine, this is probably the first time such a CER has been available.

Intermediate Model

The intermediate model is based on the mathematics that underlie the Army Material System Analysis Agency (AMSAA) Maturity Projection Model (AMPM). Starting from the same premises as the AMPM, LMI rederived the basic model while incorporating terms representing cost. For purposes of development, we divided the reliability engineering process into three periods:

- A design period beginning with the old mean time between failures (MTBF)—M_0—and producing the initial reliability (M_i).
- A test, analyze, and fix (TAAF) period, beginning with M_i and ending with the final reliability (M_f).

- A validation period that included sufficient testing to provide a desired degree of confidence that the required M_f had been achieved. Calibration to empirical data was outside the scope of the Phase II study.

Production and Support Cost Model

Development of a model to account for production and support costs was neither necessary nor planned because the Cost Analysis Strategy Assessment (CASA) model we used during this phase already provides a suitable, generic platform for capturing such costs. Rather, our approach was to look beyond simple production and support cost accounting and develop an overall estimating method that accommodates the following:

- Effect of reliability on platform availability and, hence, the number of platforms needed to provide a desired degree of target coverage (or other suitable measure)
- Effect of reliability on support cost per platform
- Multiplier effect of low reliability increasing both the number of platforms required and the support cost per platform.

LIMITATIONS

The primary limitations of this study relate to data. Most significantly, unless reliability growth is part of the management strategy, many programs do not separately account for the costs of reliability and maintainability (R&M) improvement efforts. In the case of the basic model, for which we had data from a wide variety of ground and aircraft systems, we relied heavily on program offices for reliability data and, to some extent, for budget data. In all cases, we used what amounts to secondary sources for reliability data: reliability values (for example, MTBF) before and after reliability efforts that had been determined by others. We did not have access to raw data. However, we were careful to use only empirical data, in other words, data that had resulted from tests or that had been recorded in services' operational data systems.

For the intermediate model, we had a mix of actual and estimated values. For the design period, we had both actual and estimated values from a relatively wide variety of systems. For the TAAF period, we had estimated values only, although the estimates had been developed by highly knowledgeable subject matter experts (SMEs); in addition, the values were for ground systems only. Because the underlying data set for the intermediate model is not as rich in variety as the data set for the basic model and because it includes estimated values, additional replication of the intermediate results would be prudent.

REPORT ORGANIZATION

The remainder of this report is organized as follows:

- Chapter 2 describes our approach to developing the basic model and presents the resulting CER, including statistical properties.
- Chapter 3 describes our mathematical approach to developing the intermediate model, both the design and TAAF periods. It also contains the results of fitting the developed mathematical expressions to data.
- In Chapter 4, we describe the production and support cost model construct using, as an example, a hypothetical UAV.
- Chapter 5 recommends an approach to the detailed model.
- Chapter 6 offers conclusions and recommendations.

The appendixes contain supporting detail.

Chapter 2
Basic Model

The purpose of developing the basic model was threefold: collect additional data, determine if we could replicate the relationship we found in Phase I, and develop it into a cost estimating relationship with acceptable statistical properties. The task order required us to base the CER on a minimum of 16 individual projects as data points. This chapter describes our approach to developing the basic model and presents the resulting CER, including statistical properties. It also notes caveats and limitations and recommends areas for further research.

MODELING APPROACH

We were able to obtain data on 17 projects, including the 5 from the Phase I study. Consistent with the approach we took in the 2007 study, the data had to meet certain criteria:

- Reliability data had to come from actual test data or from military service R&M databases, meaning that we would not use estimates of anticipated improvement.
- Investment data had to come from military service budget exhibits or from internal budget information supplied by program offices. In addition, the investments had to precede or coincide with the period during which reliability improved.
- APUC data had to come from program offices, Selected Acquisition Reports (SARs), commercial parts databases, or service budget exhibits.

In the following subsections, we describe the sources of our data. Appendix B contains detailed information on each data point. If data came from a source other than the cognizant program office or required reduction of more detailed data that had been provided by a program office, we sent the data we used to the program office for its review. When we could not, for various reasons, validate data through a program office, we determined reasonableness by comparing the data to data from other sources before using them.

Reliability Data

As noted above, we used only field or test reliability values; we did not report estimates or similar values not verified through field or test experience. Generally, we obtained reliability data from system program offices, which, in turn, obtained the data from their contractors or the military services' maintenance databases.

Initial Apache line replaceable unit (LRU) reliability data, for instance, came from a Lockheed Martin analysis of Army repair and maintenance data in the Army's Unit Level Logistics System—Aviation. The achieved reliability figure for the Apache LRUs was based on field maintenance data collected during FY00–FY01. As another example, in the case of the C-17 On-Board Inert Gas Generation System (OBIGGS) data, a contractor–Air Force team used Air Force maintenance databases and internal Boeing tools to determine both initial and achieved reliabilities.

Investment Data

We collected investment data by fiscal year from service budget exhibits. Because the investment dollars are from a number of different fiscal years, we expressed the investments in FY03 dollars for consistency with the Phase I report. The exception was when the data were from a previously published report and were expressed in terms of a different fiscal year. To facilitate comparison to the original report, they are expressed here in terms of the same fiscal year as found in the report from which they came.

In some cases, we also cross-checked investment data against information on www.globalsecurity.org. We used this source primarily for validation and not as the sole source of investment data. For three programs (C-17, MV-22, and F-22), we obtained investment data from an Institute for Defense Analyses (IDA) presentation at the 2008 DoD Cost Analysis Symposium (DoDCAS).[1] We took special effort to ensure that investments for other purposes were not commingled with those for improving reliability, and we did not use data that we had reason to believe involved such commingling.

Average Production Unit Cost

We typically computed the APUC from procurement data in service budget documentation. Exceptions were the C-17 OBIGGS 1.1, Apache, and F100 engine nozzle. For OBIGGS 1.1, APUC data came from contractual documents between Boeing and the Air Force, which we then verified with the program office by e-mail and telephone. In the cases of the Apache LRU and F100 engine nozzle, we initially obtained the APUCs from the program offices and then cross-checked them against Defense Logistics Agency (DLA) procurement information for those national stock numbers (NSNs) in the LogiQuest database management system.

For the C-17, MV-22, and F-22, we obtained the APUC from the Unit Cost Report section in the December 31, 2006, SAR for each of the systems.

[1] Tzee-Nan Lo et al., Institute for Defense Analyses, "Cost of Unsuitability" (presentation, DoD Cost Analysis Symposium, February 21, 2008), http://www.dodcas.org/DoDCAS2008presentations/T1/T1S5b_Lo.pdf.

Table 2-1 identifies the programs we researched as part of this study effort and the ones for which we obtained data.

Table 2-1. Programs Contacted for Data

Program	Provided data?	Used in model?
A-10 global positioning system (GPS)	Yes[a,b]	Yes
AH-64 pump	Yes[a,b]	Yes
ALR-69	No	No
Apache LRUs (3)	Yes[c]	Yes
APG-63 radar	Yes	Yes[d]
C-130 Avionics Modernization Program (AMP)	No	No
C-17 aircraft	No	Yes[e]
C-17 OBIGGS (1.1 and II)	Yes	Yes
C-5 AMP	No	No
C-5 Reliability Enhancement and Reengineering Program	No	No
CH-47F aircraft	No	Yes[f]
Expeditionary Fighting Vehicle (EFV)	No	No
F100 engine exhaust nozzle divergent seals	Yes	Yes
F-22 aircraft	No	Yes[e]
FBCB2	Yes	Yes[f]
Global Hawk	Yes	Yes[f]
H-1 upgrade	No	No
H-60 Blackhawk	No	No
Heavy Expanded Mobility Tactical Truck (HEMTT)	No	No
M1 Abrams	No	No
MH-60S	Yes	Yes[f]
MV-22	No	Yes[e]
Predator	Yes	Yes[f]
Stryker Mobile Gun System (MGS)	Yes	No
Universal Exciter Upgrade (UEU)	Yes	No

[a] Investment and APUC data for the A-10 GPS and AH-64 pump are in FY95 dollars.

[b] LMI, *Using Technology to Reduce Cost of Ownership,* Volume 2, Report LG404RD4, Donald W. Hutcheson et al., April 1996.

[c] Provided data for three Apache LRUs.

[d] Provided data for APG-63 (V) 0, 1, and 3; (V) 0 and (V) 3 were not used due to data problems.

[e] Tzee-Nan Lo et al., Institute for Defense Analyses, "Cost of Unsuitability" (presentation, DoD Cost Analysis Symposium, February 21, 2008).

[f] Data used in original model.

RESULTS

In developing the CER, we normalized investment in reliability by dividing it by the APUC. Reliability improvement is expressed as (New MTBx − Old MTBx)/Old MTBx. We use the convention "MTBx" because different programs have different measures of reliability (such as mean time between failure, mean time between demand, and so on). Within programs, we used consistent measures; across programs, it was neither practical nor necessary. We tabulated the data from our different sources in an Excel spreadsheet and performed a regression using JMP statistical analysis software.

Table 2-2 contains the data points used in the basic model. Figure 2-1 displays the regression results with a 95 percent confidence interval. As was the case in the Phase I study, a strong relationship continues to be evident between investment and reliability improvement over a fairly wide range of values for equipment complexity and reliability improvement. The R^2 is 0.81.

Table 2-2. Reliability and Investment Data Summary: Basic Model

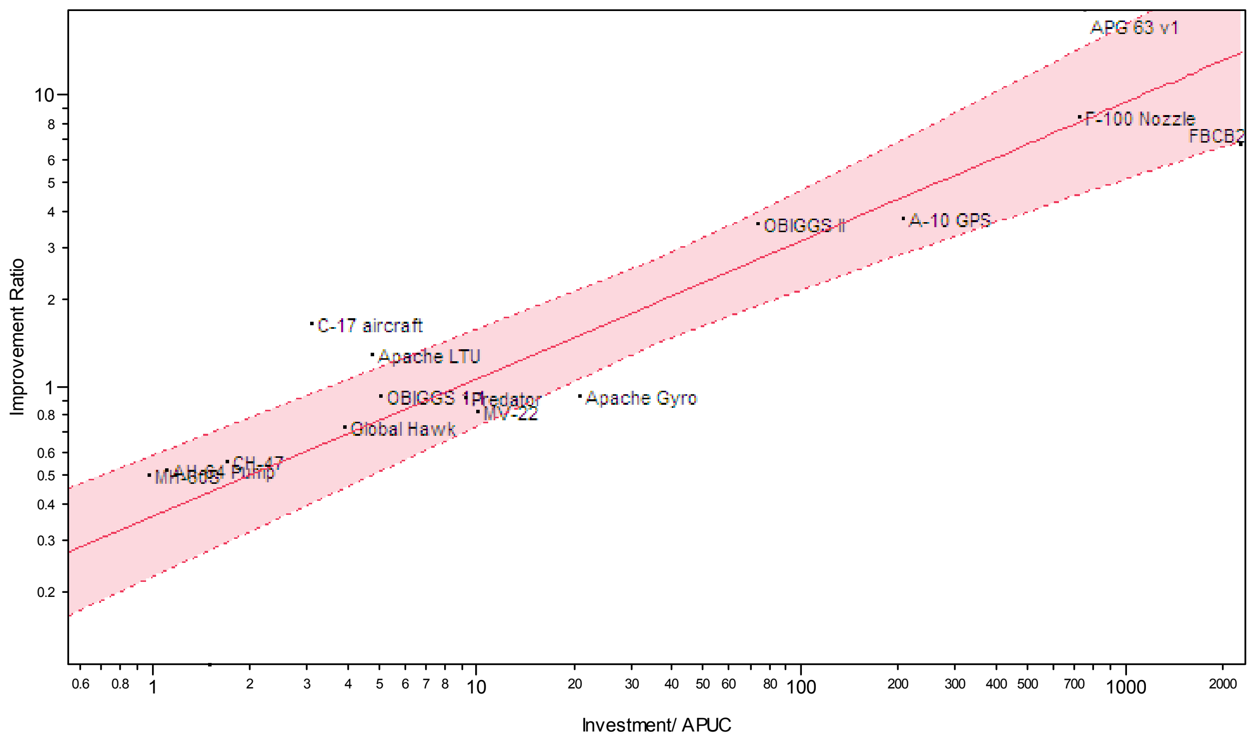
Program	Initial reliability (MTBx)	Achieved reliability (MTBx)	Investment (FY03 $M)	APUC (FY03 $M)	Ln improvement ratio	Ln (investment/ APUC)
A-10 GPS	415.00	1,975.00	6.50[a]	0.0316[b]	1.32	5.33
AH-64 pump	1.52	2.31	0.23[b]	0.20[b]	−0.65	0.11
Apache gyro	800.00	1,550.00	0.44	0.0212	−0.06	3.04
Apache LTU	700.00	1,600.00	0.39	0.0810	0.25	1.57
Apache TNP	111.00	130.00	0.25	0.4710	−1.77	−0.63
APG 63 v1	12.90	264.00	238.83	0.32	2.97	6.62
C-17 aircraft	0.41	1.09	807.69	260.51	0.51	1.13
CH-47	30.00	46.70	39.59	23.13	−0.59	0.54
F100 nozzle	700.00	6,582.00	0.70	0.000966	2.13	6.58
F-22	0.71	0.79	275.00	182.92	−2.18	0.41
FBCB2	47.00	364.00	87.39	0.0387	1.91	7.72
Global Hawk	67.66	117.07	121.93	31.20	−0.31	1.36
MH-60S	2.40	3.60	6.56	6.70	−0.69	−0.02
MV-22	0.91	1.66	807.70	79.90	−0.19	2.31
OBIGGS 1.1	65.00	126.00	5.62	1.11	−0.06	1.62
OBIGGS II	65.00	299.00	82.00	1.11	1.28	4.30
Predator	40.00	77.00	39.13	4.20	−0.08	2.23

Note: Ln = natural logarithm; LTU = Laser Transceiver Unit; and TNP = TVS/NSA/PTUR, where TVS = Television Sensor, NSA = Night Sensor Assembly, and PTUR = Pilotage Sensor Turret Assembly.

[a] Investment and APUC data for the A-10 GPS and the AH-64 pump are in FY95 dollars.

[b] Tzee-Nan Lo et al., Institute for Defense Analyses, "Cost of Unsuitability" (presentation, DoD Cost Analysis Symposium, February 21, 2008).

Figure 2-1. Regression of 17 Data Points



CAVEATS AND LIMITATIONS

The following are caveats and limitations related to our basic model:

- When a budget exhibit or other document described an investment as having the purpose of improving reliability, we assumed that it actually was used for this purpose. We did not audit budget data or take other extraordinary measures to verify the ultimate nature or use of funds.
- Similarly, we treated as valid the reliability data our sources provided. We did not seek or analyze raw data directly obtained from service data systems.
- The basic model describes a general relationship between investment and reliability growth. It is insensitive to variables such as the quality of reliability engineering applied to a program. Nor does it distinguish between reliability improvement that results from redesign (with or without technology insertion) and reliability improvement that results from TAAF efforts. Moreover, the current model reveals nothing about the design techniques that contributed to the realized improvements.
- Aviation systems dominate our sample for developing the CER. It is possible that the CER could change if we considered data from additional ground systems or from naval systems.

Recommendations for Follow-on Research

The basic model would benefit from the following additional research:

- Fill in equipment gaps by including data from more ground systems and from naval systems
- Continue to make the total number of data points more robust
- Continue to search for systems that are inconsistent with the described log-log relationship; understand why those systems do not fit the relationship if found; and, at the risk of a more complicated CER, determine whether additional parameters would effectively explain and account for any anomalies.

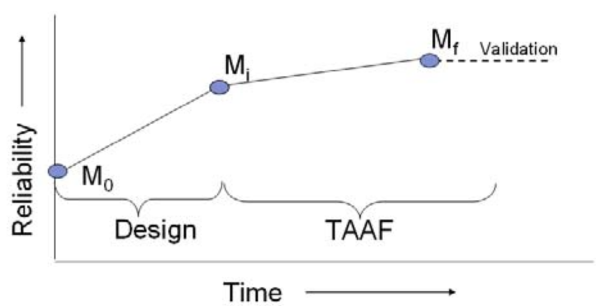
Chapter 3
Intermediate Model

The purpose of developing the intermediate model was to compute development effort and schedule as a function of program size, desired reliability improvement, and a set of relevant cost drivers. Specifically, starting from the same premises as the AMPM, LMI rederived the basic model while incorporating terms representing cost. We divided the reliability engineering process into three periods: design, TAAF, and validation. This chapter describes our approach to developing the intermediate model and presents the resulting CERs. It also notes caveats and limitations and recommends areas for further research. Appendixes C and D contain mathematical details of the AMPM development and of our addition of a cost model to it.

Modeling Approach

Figure 3-1 shows the basic approach to our intermediate model. A reliability improvement project begins with a system reliability measured by M_0, MTBF measured at time zero or at the start of the design phase. A design period—which incorporates tasks laid out in Military Standard (MIL-STD) 785B ("Reliability Program for Systems and Equipment, Development and Production") and possibly adds such steps as physics-of-failure (PoF) studies, highly accelerated life testing (HALT) exercises, and durability analyses—improves reliability to an initial MTBF, M_i. A TAAF period then improves reliability to M_f, the final MTBF.

Figure 3-1. Intermediate Model Concept



The figure also shows the very important validation period. This period confirms, with assigned confidence γ, that MTBF is not less than a goal value, M_g. It is not sufficient for the design and TAAF periods of a reliability improvement program to have generated MTBF $M_f \geq M_g$, where M_g is the goal of the program. Rather, the program must give an assigned confidence that the system's MTBF, M, is not less than M_g. This means that some reliability testing must take place, even if M_i, the system's estimated reliability at the end of the design period, is not less than M_g. However, such a model was not part of our present task. We look forward to developing and calibrating a model of the validation period in subsequent work.

The intermediate model comprises two submodels: design period and TAAF period. It is intuitive that greater success in the design period will reduce the required effort in the TAAF period. In mathematical form, the model makes explicit the relationship between the two investments by estimating the costs and benefits of efforts occurring in both periods. Specifically, we introduce a cost model to the AMPM.[1] By identifying analogies between TAAF processes and processes in the design period, we then developed a cost model of the design period.

RESULTS

Chronologically, the periods of a reliability improvement program happen in the sequence shown in Figure 3-1. However, since the design-period model uses concepts from the TAAF-period model, we begin with a discussion of the TAAF-period model, including an explanation of how we introduced cost to the AMPM. We then address the design-period model. Finally, we provide a summary description of the intermediate model.

TAAF Period

DEVELOPMENT OF THE MODEL: INTRODUCING COST TO THE AMPM

We start by characterizing failure modes into A- and B-modes. An A-mode is defined as one in which no corrective action will be performed; management has chosen not to address the failure for technical, financial, or other reasons. Conversely, a B-mode is one in which corrective action will be taken. However, not all corrective actions will be fully effective: after corrective action, the failure rate of a B-mode will be reduced, but not necessarily reduced to zero.

Since A-mode failures, by definition, are not eliminated, the failure rate attributable to them will not be affected. Thus, estimating the effectiveness and cost of reliability improvement in the design period is the same as estimating the number of B-mode failures removed, their corresponding failure rates, and the cost of the design effort to remove them.

Development of the AMPM proceeds by assuming a certain statistical model for the set of B-modes present in the system before the TAAF period begins. Next, the development assumes that mitigation of the *i*th B-mode failure reduces the failure rate by a factor d_i. Building on these bases and considering expected values of the system's B-mode failure rates, the AMPM generates an expression for the expected B-mode failure rates at a given time.

[1] U.S. Army Materiel Systems Analysis Activity, *AMSAA Reliability Growth Guide*, Technical Report TR-652, 2000.

We introduced cost to the AMPM using two assumptions:

- The cost of operating the TAAF period increases proportionally to the time in that period.
- Corrective action taken to mitigate the *i*th observed B-mode failure adds an incremental cost b_i.

Making the same expected-value analyses that lead to the AMPM itself, we developed a model for the variation of the cost of the TAAF period with time. In developing the model, we also considered AMSAA's experience with the AMPM. Specifically, AMSAA found that, in many cases, the AMPM takes a limiting form when the number of initial B-modes is very large.[2]

Our model for the variation of reliability improvement with cost in the TAAF period consists of two equations:

$$\frac{1}{M(\tau)} = \frac{1}{M_A} + \frac{1}{M_0}\left[(1-\mu_{d)}) + \frac{\mu_d}{1+\tau}\right]. \qquad \textit{(Eq. 3-1)}$$

$$\gamma(\tau) = \frac{1}{cv^2}\left[C_0\tau + \mu_b \ln(1+\tau)\right]. \qquad \textit{(Eq. 3-2)}$$

Equation 3-1 expresses the system's MTBF $M(\tau)$ at nondimensional time τ with three parameters: M_A, which is the mean time between A-mode failures; M_0, which is the mean time between B-mode failures at the start of TAAF, and μ_d, which is the average value of the reliability improvements made by corrective action, that is, the d_i. M_0 is always known, and it is not an adjustable parameter. AMSAA's experience has developed typical values of μ_d, so that this parameter also is often known a priori.

Our cost model has three additional cost parameters:

- cv^2—a measure of the degree to which the initial B-mode failure rates scatter about their mean. As we explain in Appendix D, we believe that this parameter is a measure of the "goodness" of the processes that generated the original MTBF M_0.
- C_0—a measure of the cost of operating the TAAF period; it is equal to the cost of operating the TAAF period for the time M_0.
- μ_b—the average value of the cost increments incurred by corrective action taken to ameliorate identified B-modes.

Equations 3-1 and 3-2 express cost γ and MTBF M as functions of a nondimensional time τ. Because Equation 3-2 expresses γ as a monotone increasing

[2] See Note 1.

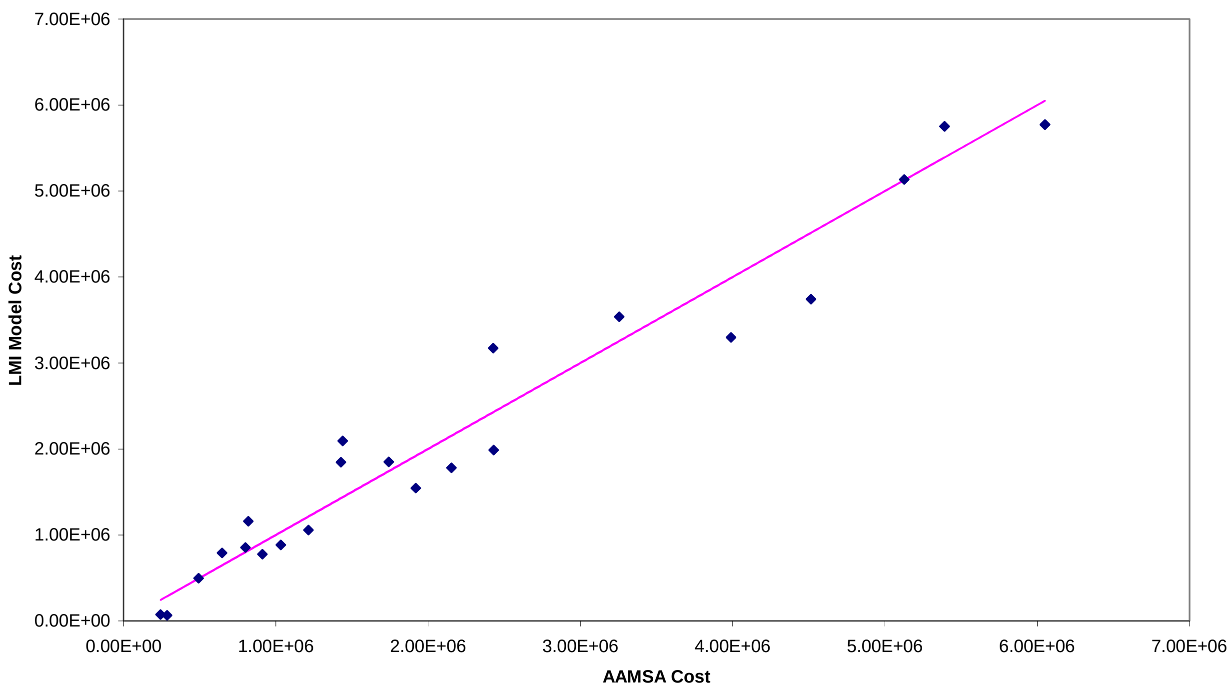
function of τ, that equation can, in principle, be solved for τ as a function of γ. Substituting that function for τ in Equation 3-2 would then express M as a function of γ. Because there seems to be no way to express that function as a simple combination of well-known functions, we have used Equations 3-1 and 3-2 as two parametric equations defining M as a function of γ.

Initial Calibration of the TAAF-Period Model

So that we could calibrate our TAAF-period model, AMSAA personnel obligingly gave us data for the cost of TAAF periods for 26 cases involving eight platforms. Rather than observations, the data represent AMSAA's estimates, based on experience, of the costs and improvements to be expected for the 26 cases.

When calibrating our TAAF model, we assumed that M_A was sufficiently large that its reciprocal could be neglected. We then used Equation 3-1 to express τ as a function of the given values M_0 and M_1. Then, the cost γ is determined by the value of τ and the two parameters C_0/cv^2 and μ_b/cv^2. We adjusted the values of those parameters to minimize the mean average deviation of the model's predicted costs from AMSAA's costs. The result was a mean average deviation of 19 percent, a value that is considered good for cost models. Figure 3-2 compares the model costs and the AMSAA costs.

Figure 3-2. Comparison of Model Costs and AMSAA Costs



Design Period

DEVELOPMENT OF THE MODEL

We believe that identifying and mitigating B-modes in the design period results from a process whose behavior and cost act very much like those of the TAAF period. Specifically, we believe that in the design period, engineering labor applied to PoF analyses, HALT exercises, and durability studies plays a role similar to test operations in the TAAF period.

In the TAAF period, observing a B-mode failure leads to analysis of its causes and “fixing” and, thus, to an increment of cost. Similarly, we believe that in the design period, identifying a potential failure mode by analysis leads to further analysis of how the mode might be eliminated or reduced in rate and to implementation of changes in component design or in operations concept. This belief leads us to a design-period model with the same form as our TAAF-period model. Like the TAAF-period model, our design-period model is expressed in two equations:

$$\frac{1}{M(\tau)} = \frac{1}{M_A^D} + \frac{1}{M_1}\left[(1-\mu_{D)}) + \frac{\mu_D}{1+\tau}\right]. \qquad \textit{(Eq. 3-3)}$$

$$\gamma(\tau) = \frac{1}{cv_D^2}\left[C_0^D\tau + \mu_B^D \ln(1+\tau)\right]. \qquad \textit{(Eq. 3-4)}$$

The parameters of the design-period model have the same meanings in relation to the design period and its operations as do the homologous parameters of the TAAF period in relation to the TAAF period and its operations.

The parameter M_A^D is the mean time between A-mode failures in the design period. The parameter λ_B^D gives the initial B-mode failure rate at the start of the design period.

The parameter μ_D is the fraction of a B-mode’s failure rate eliminated by the design process. Although the homologous TAAF parameter μ_d generally takes values around 70 percent, we believe that μ_D may be significantly larger, approaching 1 in some cases, because of the wider and more fundamental options available for attacking B-modes in the design period.

The parameter C_0^D reflects the “burn rate” of engineering labor in the design period; it is equal to the cost of design-period engineering for one mean time between B-mode failures at the start of the design period. The parameter μ_b^D gives the average cost of ameliorating a B-mode failure identified in the design period.

INITIAL CALIBRATION OF THE DESIGN PERIOD MODEL

To calibrate the design-period model, we obtained data on reliability improvement in the design period, and their associated costs, for efforts on two fundamentally different platforms: U.S. Marine Corps EFV, and tri-service air-to-air missile AIM-9X. Discussions with engineers in the EFV and AIM-9X programs led us to conclude that it would be reasonable to make an initial calibration of our design-period model using data on the relation between reliability improvement and cost for certain components of those two platforms.[3]

For this initial calibration, we used a set of 14 data points, 13 for EFV and one for AIM-9X. We were given dollar costs for materials used in the proactive work of the design period, but only engineering hours for the engineering labor. We priced engineering hours at $150 per hour, which we found to be at the higher end of the GSA rates for systems engineers.

We modeled our model's parameters in this way: We set $\lambda_A = 0$ and $\mu_D = 1$, on the grounds that A-modes were not significant in the design-period cases considered and that all the failures associated with a B-mode identified in the design period would be eliminated by redesign.

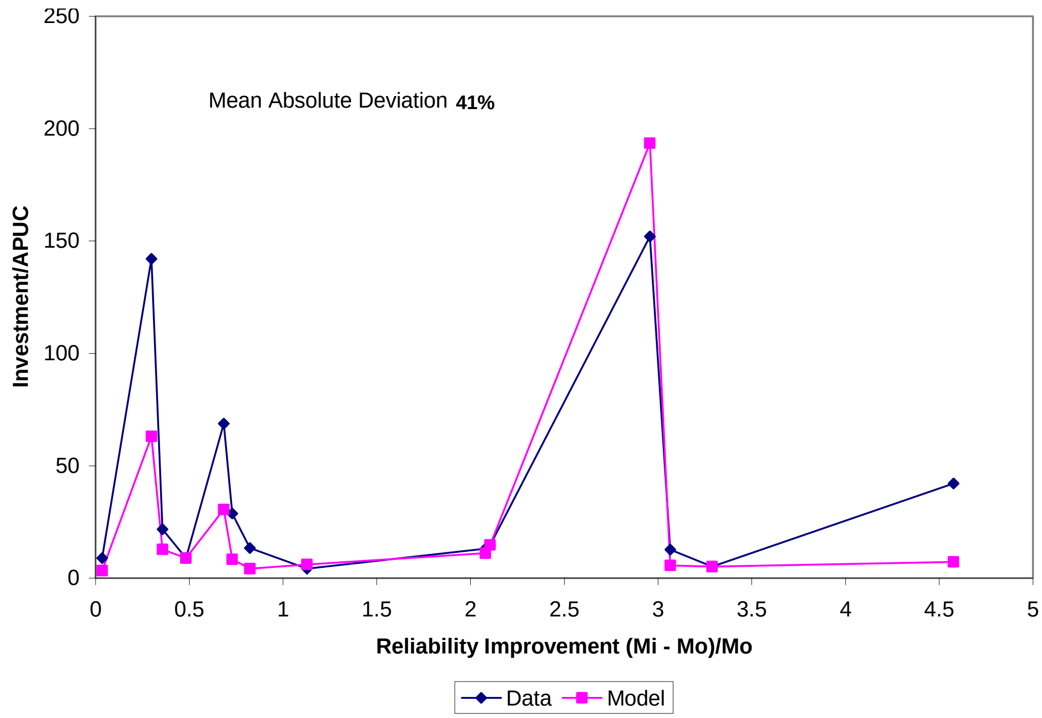
We allowed C_0^D to be an adjustable parameter. We modeled μ_D as proportional to a power of each component's APUC and took the constant of proportionality and the power as two adjustable parameters.

We modeled cv^2 as taking one of four discrete values. We expect that the "goodness" of initial systems will generally be adequately described by such small sets of values.

Thus we had seven adjustable parameters. We adjusted them to minimize the mean absolute deviation of the model's costs from the observed costs. Figure 3-3 shows the result, displaying cost as a function of relative improvement.

[3] The best kind of data for calibration would cover reliability improvements and associated costs for complete programs. Time and funding constraints precluded us from getting a large enough set of such data to do reasonable calibration.

Figure 3-3. Initial Calibration of Design Period Model



We are cautiously encouraged by this result. The model captures the trend of cost as a function of improvement reasonably well, and it treats data from two distinct platforms consistently (the AIM-9X datum, the second point from the right in Figure 3-3 is not an outlier but happens to be one of the best-fit points).

Summary

The A-mode/B-mode scheme is well developed, and we used it as the basis for modeling the design and TAAF periods. Our design- and TAAF-period models capture the trend of cost as a function of improvement reasonably well, and they treat data consistently. We look forward to obtaining data from other reliability programs that we can use to improve the calibration of our intermediate model and to increase our understanding of the relation between reliability improvement and cost in the design period.

Caveats and Limitations

The following are caveats and limitations related to the intermediate model:

- Data for the design-period model are actual values but were taken from just two systems.
- Data for the TAAF-period model are SME estimates from ground systems only.

- The underlying data set for the intermediate model is not rich in variety and includes estimated values.

RECOMMENDATIONS FOR FOLLOW-ON RESEARCH

Additional validation of the design- and TAAF-period model is needed. This will require data from other reliability programs to improve the calibration of our model and to increase our understanding of the relation between reliability improvement and cost in the design period. Also, as mentioned earlier, modeling the cost of a validation period is needed to give an assigned confidence that the system's MTBF goal has actually been achieved.

Chapter 4

Production and Support Cost Model

This chapter discusses the model relating investment in reliability to expected changes in production and support costs. The chapter begins by addressing the form of the model. It then uses an example application to illustrate the use of the CASA model to estimate support costs. The last section addresses the data needed to run the CASA model. The mathematics that drive this model is described in Appendix E.

FORM OF THE MODEL

It is generally understood that support cost is a function of

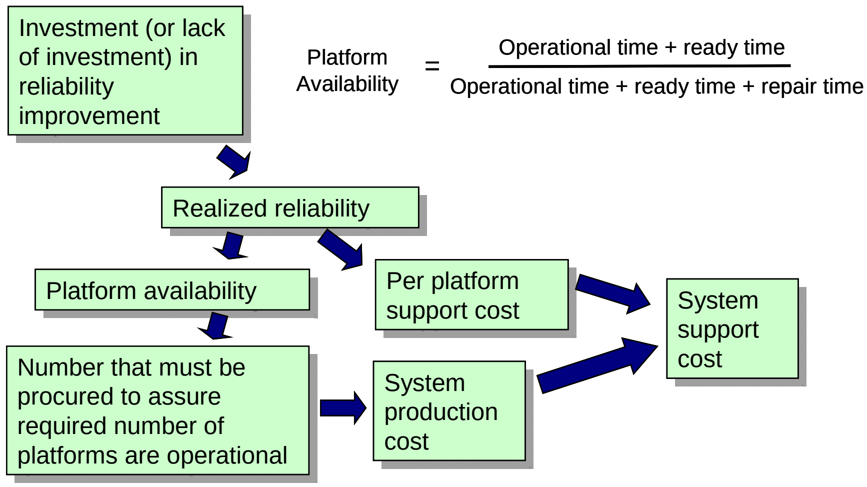
- usage (especially density and OPTEMPO);
- product design (particularly production unit cost, reliability, and maintainability); and
- process design (in particular as it determines cycle time).

Changes in reliability, because they affect availability, can influence decisions on the number of platforms that will be required, rather than just the materiel resources required for support. For this reason, we recommend modeling production and support costs following the logic in Figure 4-1. The following are the main points to be drawn from this figure:

- Investment in reliability, or the lack of it, will determine realized reliability.
- Reliability affects both platform availability and support cost per platform.
- Platform availability determines the number of platforms that will be required to accomplish anticipated missions and, hence, the number of platforms that will need to be procured. We realize that factors such as lethality and survivability also factor into decisions regarding the needed number of platforms, but for this discussion, we are concentrating on the effects of reliability.
- The number of platforms that are procured obviously has a major impact on procurement cost. In combination with the support cost per platform, the number of platforms will also drive downstream support costs. Hence, reliability will have a multiplier effect on life-cycle costs—first as it

influences the number of platforms procured, and second as it influences support cost per platform.

Figure 4-1. Production and Support Cost Modeling Logic



To quantify the relationship between reliability investment and long-term costs, three models are required:

- A model that relates investment in reliability to a change in realized reliability. Either our basic or intermediate model can be used for this purpose. From a data standpoint, the basic model is the most mature.
- A model that estimates, with the required confidence (for example, 95 percent), the number of platforms required to ensure that sufficient numbers are available when needed. The form of this model will depend on the specifics of the platform and mission.
- A model that, given a level of reliability and other essential factors, estimates support costs. We have used the CASA model for this purpose because it is well suited for this application and is generic enough to be applicable to a wide scope of platforms. Other models are also available.

EXAMPLE APPLICATION USING THE CASA MODEL

Our example is based on a notional unmanned aerial vehicle. For this example, we have defined UAV platform availability as

(operational time + ready time)/(operational time + ready time + repair time).

Repair time includes time spent waiting for parts.

Using the example of the notional UAV, we developed a dynamic algorithm to estimate the number of UAVs required to ensure, with confidence, the availability of sufficient numbers when needed. In principle, similar logic would apply to most systems.[1]

Our example is based on the following assumptions, which are realistic for a medium-sized, fixed-wing UAV:

- The baseline MTBF is 40 hours.
- The mean time to repair (MTTR) is 10 hours.
- The production unit cost is $4 million.

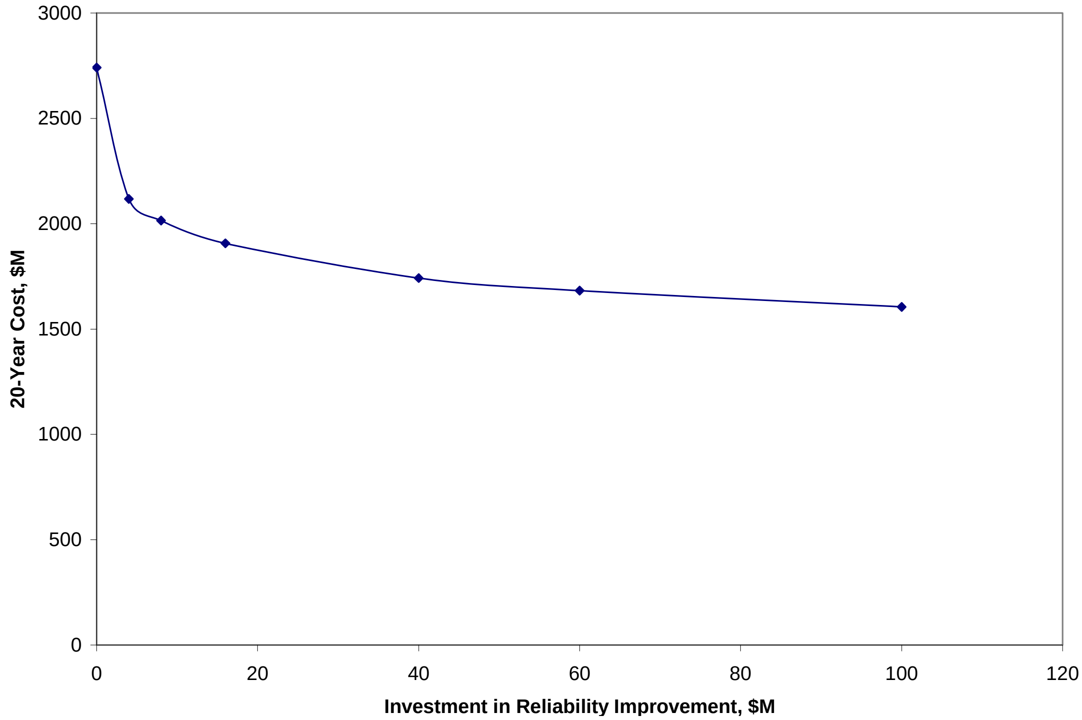
With those assumptions, we used the basic model to relate investment in reliability to achieved reliability, and we used the dynamic model to determine how many UAVs would have to be procured to ensure that 100 are available at a 95 percent confidence level. We then translated that into total cost using the CASA model. (In this specific case, we regressed the support cost output from the CASA model against a range of reliability values and then used the result of the regression to estimate support cost as a function of reliability. We calculated production cost directly from the number of UAVs.) Total cost comprised the investment in reliability plus the cost to produce the required number of UAVs plus 20 years of support for each UAV.

Figure 4-2 shows example results. In this particular case, relatively modest investments in reliability relative to production unit cost produce large reductions in total cost. Beyond a 5:1 ratio of investment to production unit cost, the return on investment gradually decreases. Over the range of investments shown on the figure, there is always a return on investment. However, the curve will bend back up when investments in reliability do not return savings of at least 1:1. We did not examine investment beyond $100 million because investments this large are outside our empirical observations. The behavior shown in Figure 4-2 is specific to this example. Even in this case, a different confidence level will shift the curve up or down. Other cases may or may not look like this example, depending on the specifics of the applications.

In addition to estimating support costs, the CASA model will also capture production costs. Appendix F contains an overview of the CASA model. The reader is referred to that appendix and the documentation included with CASA for more information on the model.

[1] The mathematics behind this example application and Visual Basic code implementing the mathematics can be obtained from Dr. David Lee, one of the authors.

Figure 4-2. Effect of Reliability Investment on Support Cost



DATA REQUIRED TO RUN THE CASA MODEL

The CASA model can represent systems to any level of detail desired. We found that representing major subsystems and their major components was sufficient. That is, we collected data for the first and second levels of indenture under a system itself. In addition to fleet size and OPTEMPO data, platform-specific data are needed. Table 4-1 shows the minimum platform-specific data.

Table 4-1. Platform-Specific Data Required for CASA Modeling

Item	MTBx (hours)	Fail rate (per hour)	PUC ($K)	Weight (pounds)	MTTR (Level 1)	RTOK	MTTR (Level 2)	Cost/repair ($K)
System								
Subsystem 1								
Component 1a								
Component 1b								
Subsystem 2								
Component 2a								
Component 2b								

Chapter 5
Approach to Detailed Model

The basic model describes a general relationship between investment and improved reliability. The model is insensitive to variables such as the quality of reliability engineering applied to a program. Moreover, it does not distinguish between reliability improvement that results from redesign (with or without technology insertion) and reliability improvement that results from TAAF.

The intermediate model improves on the basic model by distinguishing between improvement achieved during initial design and improvement achieved through TAAF and by relating the cost of improvement to the rate of removal of B-modes in both cases. However, the intermediate model is still insensitive to variation in the quality of reliability engineering applied to a program.

It is a common-sense observation that different firms (and different projects) vary in the quality of their engineering, including reliability engineering. Therefore, there is a fairly obvious need to understand how the maturity of reliability engineering affects the efficiency with which an investment in reliability is translated into a reliability improvement. This chapter proposes an approach to developing a detailed model for gaining that understanding.

Our recommended approach to the detailed model has the following aspects:

- *Retain as a central feature the A-mode, B-mode paradigm that underpins the intermediate model.* Although not all organizations have reliability estimating and tracking methods based on this paradigm, just about all organizations that we contacted understood the basics after even a short discussion. Further, it appears that for some large (but not precisely known) number of organizations, it is possible to translate from current methods into the A-mode, B-mode scheme. Over time, as more and more organizations use the A-mode, B-mode paradigm as a basis for their reliability planning and measurement, we would expect the obvious: it will become easier to use it for estimating costs.

- *Develop more robust data sets for the design and TAAF periods.* The sets of data underlying the design- and TAAF-period models are, in part, based on estimates rather than results and do not represent a sufficient cross-section of technologies or types of systems.

- *Obtain design and TAAF period data from the same programs.* A limitation of the analysis presented in this report is that design-period and TAAF-period data were not obtained from the same programs. Although we have “stitched” the data together statistically, it will be much more satisfying to know that we have data that represent both the design and TAAF periods for the same programs.

- *Implement a method for assessing the maturing of organizations and projects from the perspective of reliability engineering.* Based on research performed in conjunction with this study, three potential approaches are available: a maturity model developed by Sanjay Tiku, the Tiku model with tailoring, and the AMSAA reliability scorecard. A discussion of each follows:

  - The first alternative would be to use Sanjay Tiku's dissertation "Reliability Capability Evaluation for Electronics Manufacturers" as a basis for evaluating reliability maturity. Research we performed as part of the present study has convinced us that Dr. Tiku's model is encompassing in scope, not necessarily limited to electronics despite the title, and that it would be straightforward to tailor the model to the DoD environment. However, it is also clear that application of this model requires in-depth knowledge of an organization's reliability methods. Evaluation based on secondary sources such as plans or other evaluations is not adequate and will result in naïve results. An advantage of this approach is that the Tiku model was validated statistically through a broad survey of electronics manufacturers.

  - We believe that all but proactive tasks of the Tiku model are captured in the canceled MIL-STD-785B ("Reliability Program for Systems and Equipment, Development and Production"), that this standard is still generally followed, and that reliability growth during engineering design depends on the proactive tasks. Therefore, it may be reasonable to tailor the model by limiting evaluation to proactive tasks, although in-depth knowledge will still be needed. Only additional research can answer that question.

  - AMSAA's reliability scorecard is based on the Tiku maturity model, related models by Raytheon and Alion Science and Technology Corporation, and "Standard for Organizational Reliability Capability" (standard P1624 drafted by the Institute of Electrical and Electronics Engineers). When this report was written, the scorecard had been circulated for comment but was not yet refined or stable. The scorecard has the potential advantages of being simpler than the Tiku model and being developed specifically for DoD application. As a result, when implemented, users will already be familiar with its characteristics. Still, there is probably no substitute for in-depth knowledge of an organization.

For this study, the reliability design engineering task framework (Appendix G) assumes the second approach: tailor the Tiku model. Additional research is needed to determine if this approach (or combination of approaches) will be best.

Chapter 6
Conclusions and Recommendations

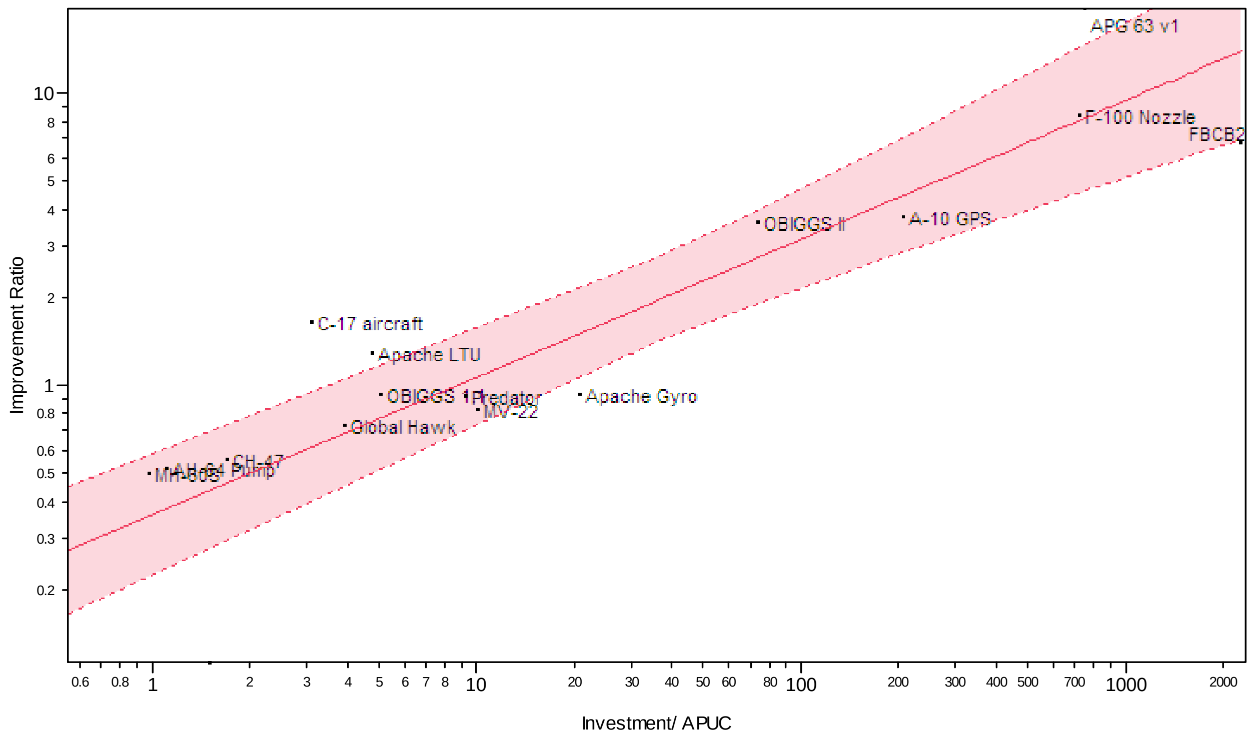
In this chapter, we present the conclusions we've drawn from our research to date and recommend an approach for using these conclusions going forward.

CONCLUSIONS

Basic Model

The basic model describes a general relationship between investment and improved reliability. Figure 6-1 shows that relationship. The required investment increases linearly with APUC and a power function of the reliability improvement ratio. The explanatory power of the CER is quite high, and the CER appears to be valid across technologies, across different types of weapon systems, and across a wide range of complexity, from components to subsystems to complete platforms. The programs in the sample range from the early 1980s until 2001. The reliability data are from either test or service reliability management systems, and cost data are from service budget submissions or other related sources.

Figure 6-1. Basic Model CER



The model is insensitive to variables such as the quality of reliability engineering applied to a program. Moreover, it does not distinguish between reliability improvement from redesign (with or without technology insertion) and reliability improvement from TAAF.

From our basic model research, we concluded that a strong relationship exists between investment and reliability and that the prospects are good for capturing its predictive properties in a forecasting model.

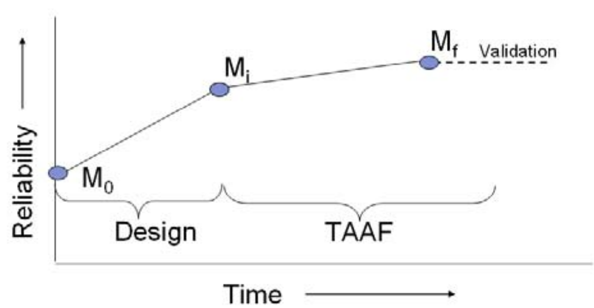
Intermediate Model

The intermediate model improves on the basic model by distinguishing between improvement achieved during initial design and improvement achieved through TAAF and by relating the cost of improvement to the rate of removal of B-modes in both cases. However, the intermediate model is still insensitive to variation in the quality of reliability engineering applied to a program. Different firms (and different projects) vary in the quality of their engineering, including reliability engineering. Therefore, there is a fairly obvious need to understand how the maturity of reliability engineering affects the efficiency with which an investment in reliability is translated into a reliability improvement.

The intermediate model is based on the mathematics that underlie the AMPM. Starting from the same premises as the AMPM, LMI rederived the basic model, incorporating terms representing cost. For purposes of development, we divided the reliability engineering process into two sequential periods:

- A design period beginning with a starting or old MTBF (M_0) and ending with M_i, the initial reliability entering the TAAF period
- A TAAF period, beginning with M_i and ending with the final reliability, M_f, as shown in Figure 6-2.

Figure 6-2. Chronology of the Intermediate Model



We address the design and TAAF periods below. We begin with the TAAF period because the design-period model uses concepts from the TAAF-period model.

TAAF PERIOD

The A-mode, B-mode scheme is well developed for representing growth in the TAAF period, and we used it as the basis for modeling this period. Recall that A-mode failures are those that management agrees to accept without any mitigation, while B-mode failures are those that *will* be addressed.

Our model for the variation of reliability improvement with cost in the TAAF period consists of two equations:

$$\frac{1}{M(\tau)} = \frac{1}{M_A} + \frac{1}{M_0}\left[(1-\mu_{d}) + \frac{\mu_d}{1+\tau}\right]. \qquad \textit{(Eq. 6-1)}$$

$$\gamma(\tau) = \frac{1}{cv^2}\left[C_0\tau + \mu_b \ln(1+\tau)\right]. \qquad \textit{(Eq. 6-2)}$$

Equation 6-1 expresses the system's MTBF $M(\tau)$ at nondimensional time τ with three parameters: M_A, which is the mean time between A-mode failures; M_0, which is the mean time between B-mode failures at the start of TAAF, and μ_d, which is the average value of the reliability improvements made by corrective action; in other words, the d_i. M_0 is always known and is not an adjustable parameter. AMSAA has developed typical values of μ_d, so this parameter also is often known a priori.

Our cost model has three additional cost parameters:

- cv^2—a measure of the degree to which the initial B-mode failure rates scatter about their mean. We believe that this parameter is a measure of the "goodness" of the processes that generated the original MTBF M_0.
- C_0—a measure of the cost of operating the TAAF period; it is equal to the cost of operating the TAAF period for the time M_0.
- μ_b—the average value of the cost increments incurred by corrective action taken to ameliorate identified B-modes.

There are two important caveats regarding this result. First, although the data are from multiple platforms, they are from a single program and a single service. Second, and probably more important, in contrast to the basic model in which we used demonstrated reliability values, the data in this instance are estimated costs and estimated reliability improvements. Thus, additional validation of the TAAF period model is needed.

Design Period

In the TAAF period, observing a B-mode failure leads to analysis of its causes and "fixing" and, thus, to an increment of cost. Similarly, we believe that in the design period, identifying a potential failure mode by analysis leads to further analysis of how the mode might be eliminated or reduced in rate and to implementation of changes in component design or in operations concept. This belief leads us to a design-period model with the same form as our TAAF-period model. Like the TAAF-period model, our design-period model is expressed in two equations:

$$\frac{1}{M(\tau)} = \frac{1}{M_A^D} + \frac{1}{M_1}\left[(1-\mu_{D)}) + \frac{\mu_D}{1+\tau}\right]. \qquad \textit{(Eq. 6-3)}$$

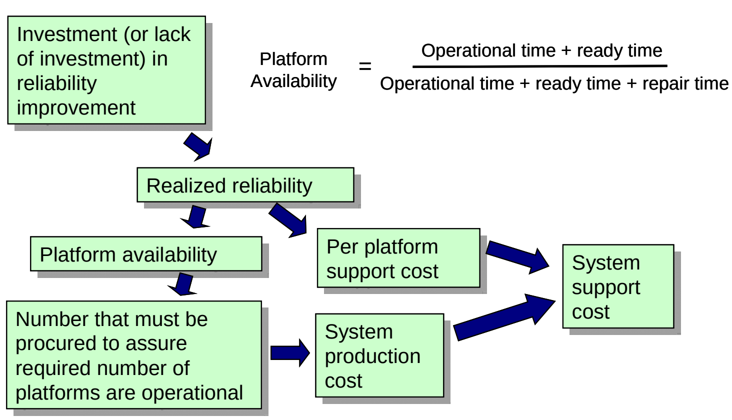
$$\gamma(\tau) = \frac{1}{cv_D^2}\left[C_0^D\tau + \mu_B^D \ln(1+\tau)\right]. \qquad \textit{(Eq. 6-4)}$$

The parameters of the design-period model have the same meanings in relation to the design period and its operations as do the homologous parameters of the TAAF period in relation to the TAAF period and its operations. The parameter M_A^D is the mean time between A-mode failures in the design period. The parameter λ_B^D gives the initial B-mode failure rate at the start of the design period. The parameter μ_D is the fraction of a B-mode's failure rate eliminated by the design process. The model captures the trend of cost as a function of improvement reasonably well, and it treats data from two distinct platforms consistently.

Production and Support Cost Model

Changes in reliability, because they affect availability, can influence decisions on the number of platforms that will be required, rather than just the materiel resources required for support. For this reason, we developed a production and support cost model, shown in Figure 6-3.

Figure 6-3. Production and Support Cost Model



The main points of this model are as follows:

- Investment in reliability, or the lack of it, will determine realized reliability.
- Reliability affects both platform availability and support cost per platform.
- Platform availability determines the number of platforms required to accomplish anticipated missions and, hence, the number of platforms that must be procured.
- The number of platforms that are procured obviously has a major impact on procurement cost. In combination with the support cost per platform, the number of platforms will also drive downstream support costs. Hence, reliability will have a multiplier effect on life-cycle costs—first as it influences the number of platforms procured, and second as it influences support cost per platform.

Three models are required to quantify the relationship between reliability investment and long-term costs:

- A model that relates investment in reliability to a change in realized reliability. For this study, either the basic or intermediate model can be used.
- A model that estimates the number of platforms required to ensure, with some required confidence (for example, 95 percent) that sufficient numbers are available when needed. The form of this model will depend on the specifics of the platform and mission. For this study, we developed a dynamic system model to estimate the number of systems required to ensure, with specified confidence, the availability of sufficient numbers when needed. In principle, similar logic would apply to most systems.
- A model that, given a level of reliability and other essential factors, estimates support costs. We used the CASA model for this purpose, because it is well suited for this application and is generic enough to be applicable to a wide scope of platforms.

Research Recommendations

We recommend that the following research be performed to mature the basic model:

- Continue to make the total number of data points more robust. In particular, fill in equipment gaps by including data from more ground systems and from naval systems.

- Continue to search for systems that are inconsistent with the described log-log relationship. If found, understand why those systems do not fit the relationship, and determine whether additional parameters would effectively explain and account for any anomalies.

We recommend that further replications of the intermediate model be performed using actual values from a variety of data sources. For the design period, we had both actual and estimated values from two systems, but for the TAAF period, we had only estimated values, developed by knowledgeable subject matter experts, for ground systems. We recommend obtaining design- and TAAF-period data from the same programs and from as large a variety of programs as is feasible.

Finally, we recommend that a detailed design model be developed to understand how the maturity of reliability engineering affects the efficiency with which an investment in reliability is translated into a reliability improvement. This requires implementing a method for assessing the maturing of organizations and projects from the perspective of reliability engineering. Based on research performed in conjunction with this study, three potential approaches are available: a maturity model developed by Sanjay Tiku, the Tiku model with tailoring, and the AMSAA reliability scorecard. For this study, the reliability design engineering task framework used the second approach: tailor the Tiku model. However, additional research is needed to determine if this approach (or a combination of approaches) would be best.

POTENTIAL MODEL APPLICATIONS

Our research and resulting insights point to ways that these models may be used. We contend that these tools can be useful in a number of ways at all stages of system acquisition.

During the requirements definition/concept refinement phase, the dynamic/ support model could be useful for justifying reliability requirements and the rationale for the system or product, based on expected investment, operational availability (within a confidence percentage), and life-cycle costs. This assumes one can reasonably define the following:

- Expected failure modes and mechanisms
- Failure definition and scoring criteria
- User and environmental profile that defines the system/product’s life cycle (including operating and non-operating environments (including storage), expected operating and non-operating times, etc.).
- Performance requirements and specifications, system/product engineering plans, operational concepts, maintenance concepts, and logistics support.

During the active design/technology development phase, the model may be used to plan or check that resources are allocated correctly. We must, again, assume that one can reasonably define the following:

- Existing system/product designs that will be used and corresponding reliability data
- Refined reliability model of the system/product, including reliability allocations to lower indenture levels
- Refined user and environmental loads that the system/product is expected to encounter during the life cycle
- Initial estimates of loads that subordinate assemblies and components will experience during the life cycle
- Engineering analysis and test data identifying the system/product failure modes and distributions that will result from the life-cycle loads that will be imposed on assemblies and components
- Data verifying the mitigation of these failure modes.

Given some understanding of these parameters, the intermediate model in its current state could be used to get a ballpark estimate of the cost and reliability growth based on program plans to ameliorate B-mode failures during the design and TAAF periods.

The Dynamic/support Model could be used to predict operational effectiveness and LCC deltas based on predicted M_f and estimated cost of reliability improvement. In this way, optimal reliability investments—for example, maximum return on investment for a given confidence in a specified operational effectiveness—could be estimated.

Finally, after fielding, these models may tell us something about how much we could expect from an investment in reliability growth, e.g., for follow-on acquisition increments. Since at this stage, undoubtedly, much more will be known about the system or program in place (the environmental loads and stresses, empirical data on failure modes, etc.), the intermediate and detailed models may be used to assist in programming new or product-improved systems.

In sum, these models will significantly increase system developer predictive capability and confidence as programs establish reliability processes in compliance with “Reliability Program Standard for Systems Design, Development, and Manufacturing,” Standard 0009 issued by the Government Electronics and Information Technology Association.

Appendix A
Sources of Data and Assistance

Since the inception of this study in late 2007, many organizations and individuals have contributed to the research described in this report. Without their gracious cooperation and assistance, we could not have conducted this research. This appendix lists them. Tables A-1 and A-2 list the programs, organized by type of data (basic model data and intermediate model data) and then alphabetically. We acknowledge that any misunderstanding of data or opinion is our responsibility alone.

A-1.Basic Model Data

Program	Source/Contact
A-10 GPS	LMI, Using Technology to Reduce Cost of Ownership, Volume 2, Appendix G, Report LG404RD4, Donald W. Hutcheson et al., April 1996.
AH-64 Pump	LMI, *Using Technology to Reduce Cost of Ownership*, Volume 2, Appendix I, Report LG404RD4, Donald W. Hutcheson et al., April 1996.
ALR-69	Jonathan S. Gates, ALR-69 Lead Engineer 542 CBSG/GBECB 460 Richard Ray Boulevard, Suite 200 Robins Air Force Base, GA 31098-1813
Apache	John Lund, Apache Program Management Office ATTN: Roy Longino Log Modernization Office, SFAE-AV-AAH-LM Building 5681, Redstone Arsenal Huntsville, AL 35898-5000
APG-63 Radar	Major Kris Ecker, F-15 PEM SAF/AQPB 1060 Air Force Pentagon Washington, DC 20330
C-17 Aircraft	Tzee-Nan Lo et al., Institute for Defense Analyses 4850 Mark Center Drive Alexandria, VA 22311
C-17 OBIGGS (1.1 and II)	Tom Condron, 516 AESG 2590 Loop Road West, Wright-Patterson Air Force Base, OH 45433-7142 John W. Stewart, On Board Inert Gas Generating System (OBIGGS) Engineer, Fuel System Engineer, C-17 System Group (516th AESG) Wright-Patterson Air Force Base, OH 45433 John T. Watson Jr., Senior Principal Engineer–Technical Lead, C-17 Reliability, Maintainability and Availability Group, Boeing IDS Long Beach–Global Mobility Systems, Building 78, 2nd Floor, Post 6A/2–M/C C078-0535

A-1.Basic Model Data

Program	Source/Contact
CH-47F Aircraft	Gina Kleinkauf, PMA-299 Senior Analyst, HH-60H NALDA LMDSS Aircraft Verified Failure and BCM Report, e-mails to Andy Long, LMI, 2007. Tom Snow, Avion, Inc., Integrated Logistics, Huntsville, AL
F-22 Aircraft	Tzee-Nan Lo et al., *Cost of Unsuitability* Institute for Defense Analyses 4850 Mark Center Drive Alexandria, VA 22311
F-100 Engine Nozzle	David Jay, AFRL/RZT; 577 Aeronautical Systems Group (577 AESG/YN) 2145 Monahan Way Wright-Patterson Air Force Base, OH 45433-7017
FBCB2	FY 2004 DOTE Report, Force XXI Battle Command, Brigade and Below/Blue Force Tracker (FBCB2/BFT) Block I, Summary. TRADOC, Combat Development Engineering, FDSC for FBCB2 BFT System, December 2003. COL Brett Weaver, TSM Force XXI (FBCB2), Force XXI Battle Command Brigade and Below (FBCB2), Computer Set, Digital, January 25, 2005. Institute for Defense Analyses, Operational Evaluation Division.
Global Hawk	Institute for Defense Analyses, *Unmanned Aerial Vehicle Operational Test and Evaluation Lessons Learned*, 1999. Major Martin J. O’Grady, 303 AESG/PM Wright-Patterson Air Force Base, OH 45433 Northrop Grumman Corporation, Global Hawk Reliability Program, Product Support–Reliability Engineering Palmdale, CA
MH-60S	CAPT Paul Grosklags USN, Commander Naval Air Systems Command PMA 299, 47123 Buse Road Patuxent River, MD 20670-1547
MV-22	Tzee-Nan Lo et al., *Cost of Unsuitability*, Institute for Defense Analyses 4850 Mark Center Drive Alexandria, VA 22311
Predator	Major Michael Lock, Air Combat Command, MQ-1 Branch Chief Langley Air Force Base, VA

A-1.Basic Model Data

Program	Source/Contact
UEU	Kimberly Horn Naval Surface Warfare Center, 300 Highway 361 Crane, IN 47522-5001

Table A-2. Intermediate Model Data

Program	Source/Contact
APG-63	Major Kris Ecker, F-15 PEM SAF/AQPB, 1060 Air Force Pentagon Washington, DC 20330
C-17 OBIGGS	Thomas Condron 516 AESG, 2590 Loop Road West Wright-Patterson Air Force Base, OH 45433-7142
Cobra Judy	Steve Caldwell, Systems Planning and Analysis 80 M Street, Suite 430 Washington, DC 20003
EFV	Andrea Costanzo, CRE, Program Manager Advanced Amphibious Assault RAM Chief SE Directorate 14041 Worth Avenue, Woodbridge, VA 22192
F100 Nozzle	David Jay AFRL/RZT 577 Aeronautical Systems Group (577 AESG/YN), 2145 Monahan Way Wright-Patterson Air Force Base, OH 45433-7017
FCS	Mel Downes, Chief, FCS Support Cell C/O QE&SA Dir. U.S. Army RDECOM-ARDEC Picatinny, NJ 07806-5000
NAVAIR Programs: P-8A, EA-18G, AMRAAM, JASSM, E-2D, H-1, TOMAHAWK	Andrew Monje, Head Reliability and Maintainability Engineering Division Naval Air Systems Command, Code AIR-4.1.10 22347 Cedar Point Road Patuxent River, MD 20670
Stryker MGS	Dr. Dmitry Tananko, Manager Reliability and Robust Engineering GD Land Systems 38500 Mound Road Sterling Heights, MI 48310-3200

Appendix B
Data for the Basic Model

For our basic model, we obtained data on 17 projects. This appendix contains an overview of each program, along with details about each program's reliability improvement, achieved reliability, reliability investment, and average production unit cost.

PROGRAM NAME: AN/APG-63(V)1 RADAR

Military service: Air Force (AF)
Contractor: Boeing (F-15 integration) Raytheon (AN/APG radar)
Time frame of data: FY70 to FY08

Program Overview

The AN/APG-63 radar is an all-weather multimode radar. The APG-63 radar combines long-range acquisition and attack capabilities with automatic features to provide the information and computations needed during air-to-air and air-to-surface combat. The APG-63 has been operational since 1973. In 1979, it was the first airborne radar to incorporate a software programmable signal processor. The APG-63 V(0) is no longer in production but remains in service. Almost 1,000 APG-63 V(0)s had been delivered when production ended in 1986.[1]

Reliability Improvement

The APG-63 V(0) radar had an average mean time between failure (MTBF) of 12.9 hours based on field data.[2] APG-63 V(0) LRUs became increasingly difficult to support both in the field and at the depot. Individual parts became increasingly unavailable from any source. Continuing reliability deterioration also affected sustainment, particularly during deployment, as well as the Air Combat Command's ability to implement two-level maintenance. In addition, the APG-63 V(0) radar had virtually no remaining processing and memory capacity to accommodate software upgrades to counter evolving threats.[3,4,5] The AN/APG-63(V)1 radar is a reliability/maintainability upgrade of the (V)0, including state-of-the-art

[1] Global Security, http://www.globalsecurity.org/military/systems/aircraft/f-15-design.htm.

[2] Major Kris Ecker, F-15 PEM, SAF/AQPB (Pentagon), attachment to e-mail to Bill Esmann, LMI, March 3, 2008.

[3] See Note 1.

[4] See Note 2.

[5] Battlefield On-Line, http://www.bf2online.com/modules/wfsection/article.php?articleid=16, March 4, 2008.

hardware with significant growth opportunities to address user requirements. Based on field data, it provides an increase in radar reliability,[6] while increasing system capacity for growth.[7]

Timeline	Thru FY94	FY95	FY96	FY97	FY98	FY99	FY01-08
Investment (FY03 $M)							
R&M	15.20	59.60	58.50	70.60	34.50	0.43	
Cumulative	15.20	74.80	133.30	203.90	238.40	238.83	
MTBF (hours)	12.9						264.0

Achieved Reliability

The initial reliability data for the APG(V)0 were collected during its lifetime. The achieved reliability for the APG(V)1 is 264 hours, based on field data accumulated between April 2001 and February 2008.[8]

Reliability Investment

The sources of APG(V)1 reliability investment data are research, development, test, and evaluation (RDT&E) and Aircraft Modification—Air Force DoD budget materials for FY99 and FY00. The total reliability investment to develop the (V)1 is $238.8 million in FY03 dollars.[9,10]

Average Production Unit Cost

For the APUC of APG 63(V)0, we obtained an FY99 unit price of $348,000 from a database management tool called LogiQuest.[11] We adjusted this price to FY03 dollars using FY06 DoD Green Book escalators. The resulting APUC is $0.319 million in FY03 dollars.

[6] See Note 2.

[7] See Note 5.

[8] Major Kris Ecker, SAF/AQPB, attachment to email to Bill Esmann, LMI, March 7, 2008.

[9] Supporting Data for Fiscal Year 1999 Amended Budget Estimates, Research, Development, Test and Evaluation, Descriptive Summaries 2/1/1998, Volumes I, II, and III.

[10] Modification of Aircraft, Exhibit P3A (PE 0207130F) APG-63V(1) Upgrade, February 15, 2000.

[11] TerraBase Corp., LogiQuest, Version 1.78, FLIS data view.

PROGRAM NAME: F100 ENGINE EXHAUST NOZZLE DIVERGENT SEALS

Military service: Air Force
Contractor: Snecma U.S.
Time frame of data: FY04–FY08

Program Overview

The F100 engine powering both the F-15 and F-16 aircraft has a design life of 4,300 total accumulated cycles (TACs) and is scheduled to remain in service beyond 2015. Metal exhaust nozzle divergent seals, a critical engine component, are lasting an average of 700 TACs in engine hot spots. These seals degrade as the engines accumulate TACs. Replacement of metallic seals with a ceramic matrix composite (CMC) divergent seal has demonstrated an extension of engine life. This reliability improvement completes ground and flight testing to qualify CMC divergent seals as the full-life preferred spares for the F100 nozzle. Testing is conducted at Mountain Home AFB, ID, and McIntire AFB, SC.[12]

Reliability Improvement

In normal operation, the individual seals are flown to failure. Each seal is replaced as necessary. (The divergent seal is a line replaceable unit, or LRU.) The metallic seals in the engine hot spots deteriorate faster than seals in other locations and typically last about 700 TACs. The metallic seals in locations other than hot spots last about 2,000 TACs or longer, while the CMC seals in either hot spots or other locations survived 6,582 TACs during accelerated mission testing (AMT).[13] The lack of any degradation in the ground-tested hardware run to 1.5 times the design life prompted the start of a field service evaluation. Starting in July 2005, a total of 8 CMC divergent seals began flying at an operational base on two F-16 aircraft. In February 2006, 20 additional CMC divergent seals began flying on F-15 aircraft at a second operational base. Flight testing continued through March 2008 when the project ended.[14]

Timeline	FY03	FY04	FY05	FY06	FY07	FY08
Investment (FY03 $M)						
R&M [a]	0	0.000	0.698	1.113	0.240	0.170
Cumulative		0.000	**0.698**	1.811	2.051	2.221
TACS (cycles)	700		6,582			
TAC = Total Accumulated Cycles						

[12] Department of Defense, *Annual Report to Congress on Defense Acquisition Challenge Program for FY 2006*, June 2007, p. 19.

[13] David Jay, 577 AESG/YN, e-mail to Bill Esmann, LMI, March 11, 2008.

[14] OSD RDT&E Project Justification (R2a Exhibit), PE0604051D8Z, February 2007, pp. 9–10.

Achieved Reliability

Metallic divergent seals are lasting an average of 600 TACs as reported by polls of the field. Two prototype seals run on AMT engines have run well past 4,300 TACs, and some CMC seals in hot spots on field service evaluation engines have accumulated about 1,000 TACs. The lack of any degradation in the ground-tested hardware run to 1.5 times the design life prompted the start of a field service evaluation. During AMT, the ceramic seals achieved 6,582 TACs.[15] Starting in July 2005, a total of 8 CMC divergent seals began flying at an operation base on two F-16 aircraft. In February 2006, 20 additional CMC divergent seals began flying on F-15 aircraft at a second operational base.[16] Flight testing continued through March 2008 when the project ended.

Reliability Investment

The total RDT&E investment is $2.22 million in FY03 dollars.[17] However, 6,582 TACs were achieved by June 2005[18] after the first $0.698 million investment, which is the value we used.

Average Production Unit Cost

We obtained the NSN for the metallic nozzle from the program office and looked up the cost in FEDLOG on October 1, 2007. The FY07 APUC is $0.001053 million. The FY03 APUC is $0.000966 million in FY03 dollars.[19]

PROGRAM NAME: APACHE RATE GYRO CIRCUIT CARD ASSEMBLY (GYRO LRU)

Military service: Army
Contractor: Lockheed Martin (LM)
Time frame of data: FY91–FY01

Program Overview

This case is one of three engineering change proposals (ECPs) identified and researched in 1990–1991 and developed in 1991–1992. All three engineering changes were implemented on components of the TADS/PNVS sensor system on the Apache attack helicopter (AH-64A and 64D models). Development work on the Modernized-TADS/PNVS (M-TADS/PNVS) started in 2001 and was not con-

[15] See Note 14.
[16] See Note 13.
[17] See Notes 13 and 14.
[18] See Note 13.
[19] See Note 11.

nected to these prior ECPs. This change involves relocating the anti-ice circuit card assembly to prevent resistor impact damage on gyro assemblies during TADS Day Sensor Shroud maintenance.[20]

Reliability Improvement

Problems associated with all the Apache gyros were recognized in 1990 based on analysis of repair and maintenance data for the prior 2-year period. This analysis, as well as follow-on research and development, was funded by LM internally. Research into the physical root cause of each problem was conducted in 1990–1991. Engineering fixes for each root-cause failure mode were developed in 1991. In 1991–1992, LM made unsolicited proposals for each ECP covering qualification of final engineering and implementation costs. Final Army approval of changes and contract negotiations took place in 1993–1994. Retrofit of fixes into the fleet proceeded throughout the remainder of the 1990s. Qualification testing for these LRUs was tailored to each specific change. For these three ECPs, almost all of the qualification testing was done at LM and LM's suppliers. Airworthiness release was done by the Army, which was minimal in these cases because the changes were made at the component level and did not affect form, fit, or function.[21]

Timeline	FY91	FY95	FY00-01
Investment (FY03 $M)			
R&M		0.442	
Cumulative		0.442	
MTBUR (Hours) [a]	800 [b]		1550 [b]

[a] MTBUR = mean time between unit replacement.

[b] John Lund, Apache PMO, SDI, Inc., e-mail to Bill Esmann, LMI, January 25, 2008.

Achieved Reliability

The gyro ECP was developed as prototype hardware and demonstrated the elimination of a specific failure mode in the laboratory. No dedicated life testing or flight test program was performed. The initial mean time between unit replacement (MTBUR), based on maintenance records and analysis in 1991–1992, was 800 hours. The achieved MTBUR, based on field maintenance data collected during FY00–FY01, was 1,550 hours. The PMO waited until FY01 to collect the data so the modification would have time to be implemented throughout the fleet.

Reliability Investment

Most Army funding was expended during FY95. The gyro was researched by LM in 1990–1991, developed in 1991–1992, proposed to the Army, accepted, and fielded to the Apache A and D model TADS/PNVS systems throughout the remainder of the 1990s under standalone contracts. This work is not part of M-TADS/PNVS. Development work on M-TADS/PNVS started in 2001 and is

[20] John Lund, Apache PMO, SDI, Inc., e-mail to Bill Esmann, LMI, February 19, 2008.

[21] See Note 20.

not connected to these prior ECPs. Reliability investment was a total of $0.442 million in FY03 dollars.[22]

LRU	FY95 $M Invest	RDT&E ADJ	FY03 $ RDT&E
Gyro	0.392	1.127	0.442

Average Production Unit Cost

The investment for the Apache LRUs was stated in FY08 dollars. To make these data consistent with our other data, we deescalated the APUC to FY03 dollars using DoD Green Book escalation factors. The APUC for the gyro LRU is $0.021 million in FY03 dollars.[23]

LRU	FY08 $M LRU price	PROC. ADJ	FY03 $ LRU price
Gyro	0.023	0.903	0.021

Program Name: Apache Laser Transceiver Unit

Military service: Army
Contractor: Lockheed Martin (LM)
Time frame of data: FY91–FY01

Program Overview

This case is one of a group of three ECPs for the TADS/PNVS system of the Apache helicopter. They were identified and researched in 1990–1991, and developed in 1991–1992. All three engineering changes were implemented on components of the TADS/PNVS sensor system on the Apache attack helicopter (AH-64A and 64D models) throughout the remainder of the 1990s under standalone contracts. Development work on the M-TADS/PNVS started in 2001 and was not connected to these prior ECPs. This change (LTU) involves changing the laser cavity reflector material to gold alloy to prevent corrosion and optics burning on internal components of the TADS tactical laser.[24]

[22] John Lund, Apache PMO, SDI, Inc., telephone conversation with Bill Esmann, LMI, February 28, 2008.

23 See Note 22.

[24] See Note 20.

Reliability Improvement

The LTU ECP involves changing the laser cavity reflector material to gold alloy to prevent corrosion and optics burning.[25] LM also funded development of engineering fixes for each root-cause failure mode during 1991. In 1991–1992, LM made unsolicited proposals for each ECP to the Army, covering qualification of final engineering and implementation costs. Final Army approval of changes and contract negotiations took place in 1993–1994. Retrofit of fixes into the fleet proceeded throughout the remainder of the 1990s.[26]

Timeline	FY91	FY95	FY96-01
Investment (FY03 $M)			
R&M		0.388	
Cumulative		0.388	
MTBUR (Hours) [a]	700		1,600

[a] MTBUR = mean time between unit replacement.

Achieved Reliability

The LTU ECP was developed as prototype hardware and demonstrated the elimination of a specific failure mode in the laboratory. No dedicated life testing or flight test program was performed. The initial MTBUR, based on maintenance records and analysis, was 700 hours. The achieved MTBUR, based on field maintenance data collected during FY00–FY01, was 1,600 hours. The PMO waited until FY01 to collect the data so the modification would have time to be implemented throughout the fleet.[27,28]

Reliability Investment

Most Army funding on this ECP was expended during FY93–FY94. The LTU was researched in 1990–1991, developed in 1991–1992, proposed to the Army, accepted, and fielded to the Apache A and D model TADS/PNVS systems throughout the remainder of the 1990s under standalone contracts. This work is not part of M-TADS/PNVS. Development work on the M-TADS/PNVS started in 2001 and is not connected to these prior ECPs. Reliability investment totaled $0.388 million in FY03 dollars. The dollars for the Apache LRUs were submitted in FY08 dollars.

Average Production Unit Cost

The APUC for the LTU is $0.081 million in FY03 dollars.

[25] See Note 20.

[26] John Lund, Apache PMO, SDI, Inc., e-mail to Bill Esmann, LMI, February 2, 2008.

[27] John Lund, Apache PMO, SDI, Inc., e-mail to Bill Esmann, LMI, January 25, 2008.

[28] See Note 22.

PROGRAM NAME: APACHE RATE TNP UPGRADE

Military service: Army
Contractor: Lockheed Martin (LM)
Time frame of data: FY90–FY01

Program Overview

This case is a combination of ECPs identified and researched in 1990–1991 and developed in 1991–1992. All engineering changes were implemented on components of the TADS/PNVS sensor system on the Apache attack helicopter (AH-64A and 64D models) throughout the remainder of the 1990s under standalone contracts. Development work on the Modernized-TADS/PNVS started in 2001 and was not connected to these ECPs.[29]

Problems associated with circuit cards in the Apache Television Sensor (camera) (TVS) were recognized in 1990 based on analysis of repair and maintenance data for the prior 2-year period. This analysis, as well as follow-on research and development, was funded by LM internally. LM conducted research into the physical root cause of each problem in 1990–1991 and developed engineering fixes for each root-cause failure mode in 1991. In 1991–1992, LM made unsolicited proposals for each ECP to the Army covering qualification of final engineering and implementation costs. Final Army approval of changes and contract negotiations took place in 1993–1994. Retrofit of fixes into the fleet proceeded throughout the remainder of the 1990s. Qualification testing for these LRUs is tailored to each specific change. For these ECPs, almost all of the qualification testing was done at LM and its suppliers.[30]

Reliability Improvement

Although similar, none of the circuit cards are interchangeable between the cameras, and none of the cameras are interchangeable between the LRUs. Each LRU required an independent fix application. The program office does not typically allow partial system operation (parallel, redundant, etc., block modeling) for any reliability metrics because the Apache missions can often span the necessary use of every system capability. Consequently, we determined that it would be best to treat the 420 LRUs as one serial system.[31]

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[29] John Lund, Apache PMO, SDI, Inc., e-mail to Bill Esmann, LMI, March 4, 2008.

[30] John Lund, Apache PMO, SDI, Inc., e-mail to Bill Esmann, LMI, February 7, 2008.

[31] See Note 29.

Timeline	FY91	FY95	FY00-01
Investment (FY03 $M)			
R&M			
Gyro		0.250	
Cumulative		0.250	
MTBUR (Hours) [a]	111 [b]		130 [b]

[a] MTBUR = mean time between unit replacement.

[b] John Lund, Apache PMO, SDI, Inc., e-mail to Bill Esmann, LMI, January 25, 2008.

Achieved Reliability

The ECP was developed as prototype hardware and demonstrated the elimination of a specific failure mode in the laboratory. No dedicated life testing or flight test program was performed. Considered to be in series for determining reliability, the initial MTBUR, based on maintenance records and analysis, was 111 hours. The achieved MTBUR, based on field maintenance data collected during FY00–FY01, was 130 hours. The PMO waited until FY01 to collect the data so the modification would have time to be implemented throughout the fleet.

Reliability Investment

Most Army funding was expended during FY95. The improvement to the cameras was researched in 1990–1991, developed in 1991–1992, proposed to the Army, accepted, and fielded to the Apache A and D model TADS/PNVS systems throughout the remainder of the 1990s under standalone contracts. This work is not part of M-TADS/PNVS. Development work on the M-TADS/PNVS started in 2001 and is not connected to these prior ECPs. Reliability investment totaled $0.250 million in FY03 dollars.[32]

Average Production Unit Cost

The investment data were provided in FY08 dollars. To make these data consistent with our other data, we deescalated the APUC to FY03 dollars using DoD Green Book escalation factors. The APUC for the gyro LRU is $0.471 million in FY03 dollars.[33]

[32] See Note 22.

[33] See Note 22.

PROGRAM NAME: C-17 GLOBEMASTER III

Military service: Air Force
Contractor: Boeing
Time frame of data: FY93–FY95

Program Overview

The C-17 is the newest airlift aircraft to enter the Air Force's inventory. The C-17 is a four-engine turbofan aircraft capable of airlifting large payloads over long distances without refueling. Its design is intended to allow delivery of outsize combat cargo and equipment directly into austere airfields. The C-17 will deliver passengers and cargo over intercontinental distances, provide theater and strategic airlift in both air land and airdrop modes, and augment aero medical evacuation and special operations missions. The aircraft is also able to perform theater airlift missions when required.[34] The C-17 made its maiden flight on September 15, 1991, and the first production model was delivered to Charleston Air Force Base, SC, on June 14, 1993. The C-17 achieved initial operational capability (IOC) in early 1995.[35]

Reliability Improvement

The C-17's system specifications included an aircraft mission completion success probability of 93 percent, 18.6 aircraft maintenance man-hours per flying hour, and full and partial mission capable rates of 74.7 and 82.5 percent, respectively, for a mature fleet with 100,000 flying hours.[36] A full-scale engineering and development contract was awarded to Boeing in 1982. The program was delayed by 2 years primarily to redesign the wing and to resolve reliability and maintainability (R&M) issues.[37]

Timeline	FY93	FY95
Investment (FY03 $M)		
R&M	807.7	
Cumulative	807.7	
MTBMc (hours) [a]	0.41	1.09

[a] MTBMc = mean time between maintenance corrective.

Achieved Reliability

The Institute for Defense Analyses (IDA) published data at the 2008 DoD Cost Analysis Symposium (DoDCAS) contrasting projected C-17 mature reliability before and after investment in reliability improvement. The projection of an

[34] Global Security, http://www.globalsecurity.org/military/systems/aircraft/C-17.htm.

[35] Air Force Fact Sheet, http://www.af.mil/factsheets/factsheet.asp?id=86/.

[36] See Note 34.

[37] Institute for Defense Analyses, *Cost of Unsuitability*, Dr. Harold Balaban et al., February 21, 2008.

MTBMc of 0.41 hours is based on a May 1992–January 1993 test of 456 cumulative flight hours. The program was delayed by 2 years primarily to redesign the wing and to resolve R&M issues. The investment of approximately $0.88 billion (FY07 dollars) in 1993–1994 raised its projected reliability to 1.09 hours.[38]

Reliability Investment

We obtained the reliability investment from an IDA study, done for the Director, Defense Operational Test and Evaluation (DOT&E), to determine the effects of operational unsuitability at OT&E. This study was presented at the DoD cost analysis symposium on February 21, 2008.[39] Adjusted to FY03 dollars, the reliability investment is $807.7 million.

Average Production Unit Cost

We obtained the APUC from the Unit Cost Report section of the December 31, 2006, Selected Acquisition Report (SAR) for the C-17. This value, adjusted to FY03 dollars, is $260.5 million.[40]

PROGRAM NAME: F-22 RAPTOR

Military service: Air Force (AF)
Contractor: Lockheed Martin- Boeing
Time frame of data: FY04–FY07

Program Overview

The F-22A Raptor achieved IOC on December 15, 2005. Reaching the IOC milestone culminated a collaborative effort among various Air Force organizations and the service’s industry partners over 25 years. The F-22 completed Milestone I in 1986, Milestone II in 1991, Milestone III in 2005, and IOC in December 2005, when the Air Force began procurement of an 184 aircraft program. By 2006, the Air Force had procured 124 aircraft. The first combat-ready Raptors were assigned to the 27th Fighter Squadron, one of three squadrons assigned to the 1st Fighter Wing. The 27th Fighter Squadron combat deployment capability with the F-22A is a 12-ship deployable package designed to execute air-to-air and air-to-ground missions.[41]

[38] See Note 37, p. 18.
[39] See Note 37, p. 18.
[40] C-17A Selected Acquisition Report, December 31, 2006, p. 21.
[41] Global Security, http://www.globalsecurity.org/military/systems/aircraft/f-22-aircraft.htm.

Reliability Improvement

The 1987 operational requirements document (ORD) established an aggressive goal on mean time between maintenance (MTBM) as a key performance parameter (KPP), which remained unchanged in the 1991 ORD update. The F-22 was found "unsuitable" at initial OT&E (IOT&E) and FOT&E I (June 2005); at FOT&E II (August 2007), it still fell short. The F-22 was judged unsuitable at IOT&E because it did not meet key R&M thresholds, such as the MTBM. The system underwent a continuing reliability and maintainability maturation program and retrofitted the operational fleet to meet the MTBM goal at maturity (100,000 flight hours).[42]

Timeline		FY04	FY05	FY06	FY07
Investment (FY03 $M					
R&M [a]		275.00			
Cumulative					
MTBM (hours)		0.71		0.79	
MTBM=Mean Time Between Maintenance					

[a] R&M = reliability and maintainability.

Achieved Reliability

Considering the F-22's IOT&E in August 2004, IDA projected an MTBM of 0.71 hours, which was significantly short of the expected threshold value of MTBM at maturity of 1.5 hours.[43]

Reliability Investment

Increasing the projected reliability required an investment of $275 million in FY03 dollars.[44]

Average Production Unit Cost

We obtained the APUC for the F-22A from the December 31, 2006, SAR. Since this information was in FY06 dollars, we adjusted it to FY03 dollars to fit our database. The SAR's APUC for the F-22A is $195.2 million in FY06 dollars. After adjustment to FY03 dollars, the APUC is $182.9 million.[45]

[42] See Note 37, p. 11.
[43] See Note 37, p. 18.
[44] See Note 37, p. 18.
[45] See Note 40, p. 22.

PROGRAM NAME: GLOBAL HAWK

Military service: Air Force
Contractor: Northrop Grumman
Time frame of data: FY99–FY06

Program Overview

Global Hawk is the offspring of an effort by the Defense Advanced Research Projects Agency (DARPA) to develop a high-altitude, long-endurance Unmanned Aerial Vehicle (UAV). Global Hawk is a system consisting of aircraft and ground elements. We focused only on the aircraft portion of the Global Hawk system.

Reliability Improvement

The Global Hawk advanced concept technology demonstration (ACTD) began in FY95 under DARPA and transitioned to the Air Force in FY98. In February 2001, DOT&E provided an early operational assessment (EOA) in support of the Milestone II decision; it found the Global Hawk system to be potentially effective and potentially suitable, based on performance from June 1999 to June 2000. Therefore, DOT&E approved the system for transition to the engineering and manufacturing development (EMD) phase and low-rate initial production (LRIP). However, improvements were required in a number of areas. Among them, the EOA noted the need for improvement in reliability to better accommodate stressing OPTEMPO. It also noted a need for maturation of training plans, the logistics infrastructure, and the maintenance concept to provide an operationally suitable system.[46,47]

Timeline	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06
Investment (FY03 $M)								
R&M	14.723	0	5.09	0.197	7.936	59.804	16.118	18.062
Cumulative	14.723	14.723	19.813	20.01	27.946	87.75	103.868	121.93
MTBCF (hours)			67.7	95.7	91	114.2	120	117.1

Achieved Reliability

Reliability was improved from 67.7 hours mean time between critical failure (MTBCF) to 117.1 hours.[48]

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[46] OSD DOT&E, FY 2001 Annual Report, RQ-4A GLOBAL HAWK Unmanned Aerial Vehicle (UAV) Systems, February 2002, pp. V-105–V-106.

[47] Institute for Defense Analyses, *Unmanned Aerial Vehicle Operational Test and Evaluation Lessons Learned*, Paper P-3821, December 2003, pp. C-13–C-14, Table C-7 and Figure C-3.

[48] Institute for Defense Analyses, *Unmanned Aerial Vehicle Operational Test and Evaluation Lessons Learned*, 1999, pp. C-13–C-14, Figure C-3.

Reliability Investment

FY99–FY06 RDT&E budget item justification sheets show that the Air Force emphasized improving overall system reliability as part of improving performance. For example, in FY99, the budget justification called for $5.210 million to improve airframe reliability and maintainability.[49] Further, in FY03, the budget justification states, "continue spiral development and related tasks, including… lithium batteries…to satisfy ORD requirements."[50] The emphasis on reliability improvements is also noted in OSD and program office reports during this time.[51]

Average Production Unit Cost

The APUC, provided by the program manager, is $31.2 million (FY03 dollars).[52]

PROGRAM NAME: MH-60S FLEET COMBAT SUPPORT HELICOPTER

Military service: Navy
Contractor: Sikorsky
Time frame of data: FY01–FY06

Program Overview

Operational in FY02, the MH-60S Fleet Combat Support Helicopter, a remanufacture of the HH-60H, is the replacement for the current CH-46D, UH-3H, and HH-1N, all of which have exceeded their original service lives. The primary mission of the baseline MH-60S configuration is to provide the Navy's Combat Logistics Force with responsive vertical replenishment, vertical onboard delivery, ship-to-shore airhead support, and Amphibious Task Force search and rescue. Secondary missions include special warfare support (over water), medical evacuation, and noncombatant evacuation. A second MH-60S configuration, the Armed Helicopter, will support three missions: combat search and rescue, anti-surface warfare, and aircraft carrier plane guard. A third MH-60S configuration will support the organic airborne mine countermeasure mission.[53]

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[49] RDT&E Budget Item Justification Sheet, Exhibit R-2A (PE 0305205F), Endurance Unmanned Aerial Vehicles, Project 4799 Global Hawk, February 1999, p. 8.

[50] RDT&E Budget Item Justification Sheet, Exhibit R-2A (PE 0305205F), Endurance Unmanned Aerial Vehicles, Project 4799 Global Hawk, February 2003, p. 11.

[51] OSD DOT&E, DOT&E Report on IOT&E, September 2001, p. V-105.

[52] Maj Martin J. O'Grady, 303 AESG/PM, e-mail to Andy Long, LMI, May 9, 2007.

[53] CAPT Paul Grosklags, USN, Multi-Mission Helicopter Program Office (PMA-299), OSD IDA Conference, November 8, 2006.

Reliability Improvement

The operational evaluation of the MH-60S Fleet Combat Support Helicopter was conducted from October 24, 2001, through March 7, 2002. The aircraft was reliable during the OT&E. The ORD threshold requirement—mean time between operational mission failure (MTBOMF) of 20.3 hours—was exceeded by 3.7 hours (for an MTBOMF of 23.96 hours).[54] The ORD requirement for maintainability was a mean corrective maintenance time (MCMT) of less than 3.6 hours. During OT&E, the achieved MCMT was 2.72 hours. Since FY02, the reliability data parameter measured in the field has been MTBF rather than the ORD metric of MTBOMF. Therefore, LMI used MTBF to assess reliability improvement.

Timeline			FY01	FY02	FY03	FY04	FY05	FY06
Investment (FY03 $M)[a]								
R&M						0.25	5.88	0.44
Cumulative						0.25	6.13	6.56
MTBF (hours) [b]								
HH-60								2.40
MH-60S								3.60

[a] CAPT Paul Grosklags USN, OSD IDA Conference, Chartered H-60 PETs, November 8, 2006.

[b] Gina Kleinkauf, PMA-299 Senior Analyst, HH-60H NALDA LMDSS Aircraft Verified Failure and BCM Report, e-mail to Andy Long, LMI, June 2007.

Achieved Reliability

In contrast to other projects we studied, the comparison in this case is between the reliability of the HH-60 and its successor, the MH-60S. Similarly, the investment costs are for the reliability improvements incorporated into the MH-60S. We obtained before and after reliability and production unit cost data on a sample of components from PMA-299, the HH-60 Program Office. At the component level, the MTBF went from 2.4 hours in FY06 for the HH-60H to 3.6 hours in FY06 for the MH-60S—a 50 percent improvement.

Reliability Investment

Because the MH-60S is a remanufacture of the HH-60 variant, we were unable to find reliability investment dollars (specifically targeted toward the support helicopter) in RDT&E budget justification exhibits prior to IOC. However, PMA-299 provided us with investment data for a sample of components that are functionally common to both variants. Reliability investment specific to these components was $6.6 million in FY03 dollars.

–Average Production Unit Cost

The APUC documented in the December SARs for 1996–2004 was $22.8 million (FY03 dollars). Thus the annual investment in reliability was about 12 percent of

[54] DOT&E, *Combined Operational Test and Development and Live Fire Test and Evaluation on MH-60S Fleet Combat Support Helicopter*, August 2002, p. 19.

the APUC for a single MH-60S. Assuming we captured only 50 percent of the actual reliability investment, the investment as a percentage of APUC would be about 23 percent.

PROGRAM NAME: V-22

Military service: Marine Corps
Contractor: Boeing/Bell Helicopter
Time frame of data: FY01–FY05

Program Overview

The V-22 Osprey is a tilt-rotor vertical/short takeoff and landing (VSTOL), multi-mission aircraft developed to fill multi-service combat operational requirements. The MV-22 replaces the current Marine Corps assault helicopters in the medium-lift category (CH-46E and CH-53D). The Air Force variant, the CV-22, replaces the MH-53J and MH-60G and augments the MC-130 fleet in the Special Operations mission. The Air Force requires the CV-22 to provide a long-range VTOL insertion and extraction capability.

Reliability Improvement

An operational evaluation (OPEVAL) during 1999–2000 demonstrated poor reliability and maintainability; two fatal crashes occurred in 2000. During 2001–2005, the system underwent redesign and modification. From March to June 2005, an OT&E found the Osprey operationally suitable and operationally capable. On September 28, 2005 the Defense Acquisition Board endorsed the V-22 Osprey and recommended moving toward full production of the aircraft.[55,56]

Timeline	FY01	FY05
Investment (FY03 $M)		
R&M	807.70	
Cumulative		
MFHBF (hours) [a]	0.91	1.66

[a] MFHBF = mean flight hours between failure.

Achieved Reliability

The IDA report on the cost of unsuitability discusses the V-22 in terms of projected reliability before investment and projected reliability after investment. IDA's model projected a mature MFHBF of 0.91 hours before any investment to improve reliability; the projection is based on the results of OPEVAL I held in 1999–2000. After redesign and modification during 2001–2005 and an investment

[55] Global Security, http://www.globalsecurity.org/military/systems/aircraft/v-22-history.htm.
[56] See Note 37, p. 11.

of $0.88 billion, the aircraft successfully completed OPEVAL II in 2005. As a result, the projected mature reliability of the V-22 was now 1.66 hours.

Reliability Investment

We obtained the reliability investment from the IDA study on cost impacts of operational unsuitability at OT&E. This study was done for the DOT&E. The study was presented at the DoDCAS on February 21, 2008.[57] Adjusted to FY03 dollars, the reliability investment is $807.7 million.

Average Production Unit Cost

We obtained the APUC from the Unit Cost Report section of the December 31, 2006 SAR for the V-22. This value, adjusted to FY03 dollars, is $79.9 million.[58]

PROGRAM NAME: PREDATOR UNMANNED AERIAL VEHICLE

Military service: Air Force
Contractor: General Atomics Aeronautical Systems
Time frame of data: FY98–FY06

Program Overview

The Predator design evolved from the DARPA/Leading Systems Amber program (FY84–FY90). The Predator is a system, not just an aircraft. A fully operational system consists of four aircraft (with sensors), a ground control station, and primary satellite link. We analyzed only the aircraft portion of the Predator system.

The Predator aircraft is a single-engine, propeller-driven, remotely piloted aircraft designed to operate at medium altitude for long-endurance sorties. It receives control commands from its control station and provides sensor and telemetry data in return. In January 1994, the Army awarded General Atomics Aeronautical Systems a contract to develop the Predator system.

The initial ACTD phase lasted from January 1994 to June 1996. During the initial part of the ACTD phase, the Army led the evaluation program, but in April 1996, the Air Force replaced the Army as the operating service for the initial ACTD aircraft (RQ-1) (the “R” designates reconnaissance role).

[57] See Note 37, p. 11 and p. 18.
[58] V-22 Selected Acquisition Report, December 31, 2006, p. 31.

Reliability Improvement

Because the Predator started as an ACTD, the program had no formal reliability requirements. Development of the ORD, usually produced early in a program to guide system design, did not begin until after the ACTD ended. The threshold ORD requirement—mean time between system failure (MTBSF) of 40 hours—was achieved soon after ACTD.[59] Thus, the reliability requirement is a reflection of what had been achieved rather than what should be achieved through design; in other words, the requirement did not drive design. Although the system performed well when compared to requirements outlined in the ORD, reliability issues surfaced during Operation Enduring Freedom (OEF). Performance and vehicle losses then drove the need to improve reliability. After initial fielding, the Air Force upgraded the ACTD Predator with a better performing and more reliable engine, communications, flight controls, and sensor payloads.[60]

Timeline	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06
Investment (FY03 $M)									
R&M	11.43	2.29	2.67	2.22	0.96	0.95	7.86	5.63	5.12
Cumulative	11.43	13.72	16.39	18.61	19.57	20.52	28.38	34.00	39.13
MTBF (hours)	40	55	58	61	66	71	72	74	77

Achieved Reliability

The ORD reliability goal was 40 hours.[61] The overall failure rate was reduced by 48.1 percent, resulting in an overall improvement in MTBF from 40 hours in FY98[62] to 77 hours in FY06, or 92.5 percent.[63]

Reliability Investment

FY98–FY06 RDT&E budget item justification sheets show clear evidence that Air Force management emphasized improving overall system reliability as part of improving performance. For example, in FY99, 1 year before IOT&E, the budget justification called for $588,000 to “improve system R&M to meet ORD requirements.” The cumulative reliability investment for FY98–FY06 is $39.1 million, or approximately $4.3 million per year.

Average Production Unit Cost

The APUC, taken from the SAR, is $4.2 million (FY03 dollars).[64] Thus the annual investment in reliability was just about the same magnitude as the Predator APUC.

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[59] See Note 51, pp. 27–28.

[60] OSD, UAV Reliability Study, February 2003, p. 25, Figure 3-4.

[61] See Note 51, pp. 27–28.

[62] See Note 51, pp. 27–28.

[63] See Note 60, p. 25.

PROGRAM NAME: C-17 (OBIGGS 1.1)

Military service: Air Force (AF)
Contractor: Boeing
Time frame of data: FY03–FY07

Program Overview

The C-17 aircraft delivers cargo and troops directly to the battlefield. Therefore, the aircraft may be subject to ground fire as it lands. This led to a requirement for an inerting system to protect C-17 fuel tanks from exploding when hit by ground fire. Boeing delivered the first 141 C-17s with an On-Board Inert Gas Generating System (OBIGGS). The OBIGGS protects the C-17 from fuel tank explosions by filling the empty space in the fuel tanks with inert nitrogen gas. The initial OBIGGS, which Boeing called OBIGGS 1, successfully protected the fuel tanks, but required frequent maintenance and negatively affected mission capable rates.[65,66]

Reliability Improvement

At one point, the OBIGGS 1 was secondary only to the engine as a cause of C-17 maintenance downtime. The DOT&E FY99 Annual Report mentions OBIGGS 1 as one of the major causes of low C-17 mission capable rates.[67] Boeing also observed that improving OBIGGS I reliability would have more impact on the airplane's reliability than almost any other system. The Boeing team first worked to improve the reliability of the OBIGGS I by identifying weak components and upgrading them.

The effort to improve OBIGGS I was moderately successful, but it became clear that the OBIGGS 1 was too inherently complex to upgrade to the level desired. In addition, even if the reliability problem were resolved, the time required to initialize the system would not be reduced, due to its inherent design. Further improvement would require complete redesign. The new project resulted in the development of OBIGGS II (discussed later in this appendix).[68]

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[64] Under Secretary of Defense for Acquisition and Technology, Selected Acquisition Reports, December Reports, 1996–2004.

[65] OBIGGS II Project Improvement Team, presentation to the ASQ World Conference for Quality and Improvement, April 30, 2007.

[66] See http://www.boeing.com/news/frontiers/archive/2005/september/i_ids1.html.

[67] See Note 65.

[68] See Note 65.

Timeline	FY03	FY04	FY05	FY06	FY07
Investment (FY03 $M)					
R&M				5.62[a]	
Cumulative				5.62	
Reliability (MTBMc, hours)	65 [a]				126 [a]

[a] OBIGGS II Project Improvement Team, presentation to the ASQ World Conference for Quality and Improvement, April 30, 2007.

Achieved Reliability

The data compare the MTBMc of OBIGGS 1 for 2003, OBIGGS 1.1 for 1 year ending September 2007, and OBIGGS II for 1 year ending September 2007.[69] The initial reliability for OBIGGS 1 was estimated based on Air Force maintenance database records using internal Boeing tools (FRACAS and GOLD) that track the reliability of each subsystem and component on the airplane. These tools confirmed the low reliability of the OBIGGS 1 components. The OBIGGS 1.1 project improved OBIGGS reliability from 65 hours MTBMc to 126 hours; OBIGGS 1.1 achieved a 126 MTBMc for the year ending September 2007.[70] The Air Force/Boeing team determined that by using improved air separation membrane technology, they could further simplify and improve the OBIGGS.

Reliability Investment

The definitized cost to develop OBIGGS 1.1 was $5 million, with an award fee pool of $621,118. Information on the amount of award fee earned was not available but was estimated at $0.5 million for a total price of $5.5 million; these were FY03 3010 BP10 funds.[71] This investment resulted in OBIGGS 1.1, which was an interim replacement for OBIGGS 1. OBIGGS 1.1 was not a new system but used improved parts and technology insertion to upgrade the system reliability.

Average Production Unit Cost

The table below shows average production unit cost data for OBIGGS 1. The values were determined through negotiation between Boeing and the Air Force and apply to OBIGGS 1. The purpose of this action was to determine the credit to give Boeing for its OBIGGS 1 effort when the new OBIGGS II was complete. We converted all values to FY03 dollars and used the average of those values as our APUC.

[69] See Note 65.

[70] John Watson Jr., Boeing Reliability Analyst, e-mail to John Stewart, November 19, 2007.

[71] Contract F33657-01-D-2000, Delivery Order 00 (AFD-070817-079), specifies the cost of OBIGGS I systems; see paragraph H037, pp. 38–41.

OBIGGS I APUC [c]		
FY	TY $ M	FY03$M
FY05	1.2	1.11
FY06	1.2	1.12
FY07	1.225	1.12
FY08	1.225	1.10
Average		1.11

PROGRAM NAME: C-17 (OBIGGS II)

Military service: Air Force (AF)
Contractor: Boeing (McDonnell Douglas)
Time frame of data: FY03–FY07

Program Overview

The C-17 aircraft delivers cargo and troops directly to the battlefield. Therefore, the aircraft may be subject to ground fire as it lands. This led to a requirement for a reliable inerting system to protect C-17 fuel tanks from exploding when hit by ground fire. Boeing delivered the first 141 C-17s with an OBIGGS. The OBIGGS protects the C-17 from fuel tank explosions by filling the empty space in the fuel tanks with inert nitrogen gas. The initial OBIGGS, called OBIGGS 1, successfully protected the fuel tanks, but required frequent maintenance and negatively affected mission capable rates because it worked so slowly. A reliability improvement effort led to an improved configuration of the OBIGGS 1, OBIGGS 1.1. OBIGGS 1.1 was intended to be an interim system until a more reliable OBIGGS with better performance could be developed.[72]

Reliability Improvement

The Air Force/Boeing team discovered that although it fixed the original root causes of the component failures in OBIGGS 1, new failure modes appeared, preventing the breakthrough reliability improvement that was expected. As a result, the Air Force initiated the OBIGGS II improvement project to determine whether a different and simpler method of inerting the fuel tanks was feasible.[73]

The primary problem with reliability was that OBIGGS 1 was too complex to make major reliability improvements. At the same time, the initialization time to inert the fuel tanks was far in excess of requirements. Considering the initial work on OBIGGS I, Boeing and the Air Force determined that OBIGGS reliability and performance could be improved by developing a new continuous flow system

[72] See Note 65.
[73] See Note 65.

(OBIGGS II) with improved air separation membranes (ASMs). That approach resulted in a significant improvement in reliability and initialization time.[74]

The new system is a continuous flow design, as opposed to the OBIGGS 1 accumulation/storage version. Molecular sieve ASMs in the OBIGGS 1 system were not efficient enough to generate nitrogen enriched air (NEA) as required. Thus, NEA was accumulated and stored. High pressure was necessary to minimize storage volume, so a compressor was required. Permeable membrane ASMs in the new system are efficient enough to generate NEA as required. Therefore, compression of nitrogen and storage in pressurized bottles is not required; consequently, these components were eliminated. With the OBIGGS II, mission planning adjustments to allow NEA accumulation are no longer necessary; the new system will automatically initialize by running for 20 to 40 minutes. In addition, the OBIGGS II weighs approximately 475 pounds less than the OBIGGS 1.1.[75]

Timeline	FY03	FY04	FY05	FY06
Investment (FY03 $M)				
R&M	82			
Cumulative	82	82	82	82
MTBMc (hours)	65			299

Achieved Reliability

We evaluated the improvement of reliability from the OBIGGS I (65 MTBMc) to the OBIGGS II. Based on Air Force maintenance databases, OBIGGS II achieved an MTBMc of 299 hours. This achieved MTBMc includes ASM failures, which can cause failure of the OBIGGS. Without including the ASM failures, OBIGGS II achieved an MTBMc of 770 flight hours.[76]

Reliability Investment

Contract document AFD-070817-079 provides the investment cost to improve MTBR from the OBIGGS 1 reliability of 65 flight hours to the OBIGGS II reliability of 299 flight hours (including ASM failures). This value was approximately $82 million.[77] The C-17 program office point of contact confirmed that $82 million was the cost to develop OBIGGS II.[78,79]

[74] See Note 65.

[75] See Note 65.

[76] See Note 70.

[77] See Note 71.

[78] John W. Stewart, AESG/ENFE, e-mail to Bill Esmann, LMI, November 20, 2007.

[79] See Note 71.

Average Production Unit Cost

We used the APUC for OBIGGS I in our model because OBIGGS 1.1 did not go into production per se (it is the aggregate of a number of LRU upgrades). The APUC for OBIGGS I was calculated from the backup data for the OBIGGS 1.1 contract modification.[80] The APUC is $1.11 million in FY03 dollars.

PROGRAM NAME: CH-47F

Military service: Army
Contractor: Boeing
Time frame of data: FY02–FY06

Program Overview

The CH-47F is a remanufactured version of the CH-47D Chinook cargo helicopter with the new T55-GA-714A engines. The program was initiated to extend the service life of the CH-47 airframe, while reducing operations and support (O&S) costs. The CH-47D cargo helicopter fleet was unable to support the requirements of a primarily CONUS-based contingency force. The operational capability that is critical to support the anticipated range of contingencies could not be provided by the CH-47D without improvements. The first CH-47D aircraft reached their service life goal of 20 years in FY02. Continually increasing maintenance rates (measured as man-hours per flight hour), resulting from years of high use, were adversely impacting units' ability to maintain the fleet to Army standards. Increases in O&S costs, cargo weight, range requirements, and OPTEMPO, as well as emphasis on rapid self-deployability and threat anti-aircraft vulnerabilities, reduced the effectiveness of the CH-47D fleet.

Reliability Improvement

IOT&E Phase 1 was conducted in May 2004. Results of the evaluation indicated that the mean time between mission abort (MTBMA) was 19.7 hours, significantly lower than the ORD threshold requirement of 44 hours.[81] Later in the same year, Boeing conducted a 1,000-hour flight test program, which achieved an MTBMA of 31.4 hours.[82] In FY06, the ORD requirement for MTBMA was decreased from 44 hours to 30 hours.[83] For OT, the achieved MTBMA was 3.5 hours.[84] LMI used the Boeing MTBMA value, because Boeing's analysis included pre-IOT&E and post-IOT&E data as one large block of 1,100 flying hours

[80] See Note 71.

[81] DOT&E, FY 2004 Annual Report, CH-47F Improved Cargo Helicopter (ICH), 2004, pp. 61–63.

[82] Boeing, CH-47F 1,000 Hour Flight Test Program Report, June 25, 2004, Figure 2.

[83] Operational Requirements Document for the CH-47F Cargo Helicopter, June 2006.

[84] Tom Snow, Avion, R&M Scoring Conference Minutes, Section 2 (Summary of Results), February 2007.

as compared to 100 flying hours for IOT&E. In January 2007, the Chinook Scoring Conference reported an MTBMA of 46.7 hours.[85]

Timeline	FY02	FY03	FY04	FY05	FY06
Investment (FY03 $M)					
R&M	13,859	0	4,666	11,501	9,568
Cumulative	13,859	13,859	18,525	30,026	39,594
MTBMA (hours)		30.1	31.4	43.5	46.7
MTBMA=Mean Time Between Maintenance Action					

Achieved Reliability

The $13.9 million FY02 investment was the total engineering investment for the upgrade of the CH-47D to the CH-47F.[86] As result of the Army's investment in improving the CH-47F, the aircraft's overall failure rate was reduced by 35.8 percent, resulting in a 55.5 percent improvement in MTBMA, from 30.1 hours in FY03 to 46.7 hours in FY06.

Reliability Investment

In DoD budget materials, we found the CH-47F reliability investment to be $39.6 million in FY03 dollars.[87]

Average Production Unit Cost

The CH-47F APUC, taken from the SAR, is $23.1 million (FY03 dollars).[88]

PROGRAM NAME: A-10 GLOBAL POSITIONING SYSTEM

Military service: Air Force
Contractor: Unknown
Time frame of data: FY94–FY98

Program Overview

The A-10 LN-39 inertial navigation unit (INU) needed to be upgraded to provide a GPS capability. The Air Force had initially decided to add a GPS receiver to the

[85] See Note 84.

[86] See Note 84.

[87] Army RDT&E Budget Item Justification (R-2A Exhibit), 0203744A—Aircraft Modification/Product Improvement Program, 0203744A (430) Item 161, p. 10, Continuing Engineering Manufacture Development (EMD), February 2007.

[88] See Note 64.

LN-39 INU, but decided to replace the LN-39 INU with a higher reliability ring laser gyro with embedded GPS.[89]

Reliability Improvement

Replacing the LN-39 INU with a higher reliability ring laser gyro with embedded GPS improved MTBF from approximately 415 hours to approximately 1,975 hours.[90]

Timeline	FY94	FY95	FY96	FY97	FY98
Investment (FY1995 $K)					
R&M	800	3,100	1,200	1,100	300
Cumulative	800	3,900	5,100	6,200	6,500
MTBF (hours)	415				1,975

Achieved Reliability

Reliability improved from a MTBF of 415 hours to 1,975 hours.[91]

Reliability Investment

The investment was $6.5 million in FY95 dollars.[92]

Average Production Unit Cost

The APUC was $31.643 million in FY95 dollars.[93]

PROGRAM NAME: AH-64 HYDRAULIC PUMP

Military service: Army
Contractor: Boeing
Time frame of data: FY94–FY96

Program Overview

The Apache hydraulic system was pressurized during non-operation to prevent cavitation of the hydraulic pump during start-up. After extended operation, pressure would be lost, with the result that the pump and manifold would incur exces-

[89] LMI, *Using Technology to Reduce Cost of Ownership*, Volume 2, Appendix G, Report LG404RD4, Donald W. Hutcheson et al., April 1996.

[90] See Note 89.

[91] See Note 89.

[92] See Note 89.

[93] See Note 89.

sive wear at start-up. In addition, pressurization during non-operation resulted in static leakage.[94]

Reliability Improvement

The objective of the reliability redesign was to modify the hydraulic system to pressurize during start-up and release pressure during non-operation. The redesign was accomplished during Longbow remanufacture. Reliability, measured in mean time between demand (MTBD) on supply per aircraft, improved from 1.52 years to 2.31 years.[95]

Timeline	FY94	FY96
Investment (FY1995 $M)		
R&M	0.225	
Cumulative	0.225	0.225
MTBD (years) [a]	1.52	2.31

Achieved Reliability

Reliability, measured in MTBD on supply per aircraft, improved from 1.52 years to 2.31 years.[96]

Reliability Investment

The reliability investment was $225,000 in FY95 dollars.[97]

Average Production Unit Cost

The APUC is $0.202 million in FY95 dollars.

PROGRAM NAME: FORCE XXI BATTLE COMMAND BRIGADE AND BELOW

Military service: Army
Contractor: Northrop Grumman Mission Systems
Time frame of data: FY99–FY04

Program Overview

The FBCB2 system is the principal network-enabled command and control (C2) system providing a seamless battle command capability to Army components at

[94] LMI, *Using Technology to Reduce Cost of Ownership*, Volume 2, Appendix I, Report LG404RD4, Donald W. Hutcheson et al., April 1996.

[95] See Note 94.

[96] See Note 94.

[97] See Note 94.

the brigade level and below. The FBCB2, along with associated communication and GPS equipment, allows each platform user in the network to send and receive information across the depth and breadth of the battlefield. This shared common battlefield picture displays near-real-time information that contributes to situational awareness, provides graphics and overlays, and allows the exchange of C2 messages. The primary development contractor is Northrop Grumman Mission Systems. Acquisition services are provided by the FBCB2 program office.

The FBCB2 system began its life in FY94 as a prototype. From FY00 to FY02, the system matured through a series of reliability demonstration tests, field demonstrations, and limited user tests. Fielding of the FBCB2 system began in FY02, with 1,722 systems going to the 4th Infantry Division. IOT&E was a combination of events, including LUT-2A in FY01, OEF in FY04, and development test/operational test (DT/OT) in FY04.[98] In FY04, the Army decided to go to full-rate production amid a disagreement with DOT&E over whether or not to include government-furnished equipment (GFE) in the DT/OT.

Reliability Improvement

The FBCB2 ORD specified reliability threshold requirements for three blocks of mean time between essential function failure (MTBEFF): for Block 1, an MTBEFF of 500 hours; for Block 2, an MTBEFF of 710 hours; and for Block 3, an MTBEFF of 910 hours. For our reliability growth assessments, LMI used only the Block 1 requirement. During IOT&E, the U.S. Army Training and Doctrine Command (TRADOC) and DOT&E interpreted the requirement differently. The difference concerned whether or not GFE failures should be included in the assessed system MTBEFF. TRADOC's position, based on its Failure Definition Scoring Criteria (FDSC), was that only the FBCB2 system hardware and software should be evaluated, because the program manager had no control over the reliability of communications links.[99] DOT&E took the user's perspective, advocating the inclusion of GFE because the user does not care why the system failed but only that it failed.[100] Although reasonable, the DOT&E interpretation meant that the FBCB2 system would never be able to meet the Block 1 threshold requirement in the ORD.

Given the DOT&E assessed reliability for GFE (MTBEFF of 149 hours), the FBCB2 system would fail to meet the requirement even if the FBCB2 hardware and software were 100 percent reliable.

[98] FY 2004 DOT&E Report, Force XXI Battle Command, Brigade and Below/Blue Force Tracker (FBCB2/BFT) Block I, Summary, p. 70.

[99] TRADOC, Combat Development Engineering, FDSC for FBCB2 BFT System, December 2003, p. 13.

[100] IDA, Operational Evaluation Division, Interoffice Memorandum, "FBCB2 BLRIP Suitability Submission," June 15, 2004, p. 6, Figure 1.

Timeline	FY99	FY00	FY01	FY02	FY03	FY04
Investment (FY03 $M)						
R&M	3,048	0	29,600	17,607	18,295	18,838
Cumulative	3,048	3,048	32,648	50,255	68,550	87,388
MTEFF (hours)			47	121	333	364

Achieved Reliability

Since DT/OT in FY04, no additional tests of the FBCB2 system have been done. The overall failure rate for the FBCB2 system was reduced by 87.1 percent, resulting in a 674.5 percent improvement in MTBEFF, from 47 hours in FY01 to 364 hours in FY04.[101]

Reliability Investment

FY99–FY04 RDT&E budget item justification sheets provide evidence that Army management emphasized improving overall system reliability as part of improving performance. For example, in FY99, the budget justification called for about $3 million (FY03 dollars) for hardware development.[102] Further, in FY03, the budget justification showed a line entry for nearly $5 million to "conduct Development Test/Operational Test for Block I Capability of FBCB2-Blue Force Tracker (BFT) at the U.S. Army Electronic Proving Ground and at Fort Irwin, CA."[103]

Average Production Unit Cost

The APUC, taken from the SAR, is $38.7 million in FY03 dollars.[104] From FY99 to FY04, 10,225 FBCB2 systems were fielded.[105] Thus, the annual investment in reliability per unit fielded was approximately $8,600, or about 22 percent of the APUC for a single FBCB2 system.

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[101] See Note 100.

[102] Army RDT&E Budget Item Justification, PE Number 0203759A, Project D120, p. 4, Exhibit R-3, Cost Analysis, Force XXI Battle Command, Brigade and Below (FBCB2) 228 Budget Item Justification, February 1999.

[103] Army RDT&E Budget Item Justification, PE Number 0203759A, Item 164, p. 5, Exhibit R-3, Cost Analysis, Force XXI Battle Command, Brigade and Below (FBCB2) 228 Budget Item Justification, February 2003.

[104] See Note 64.

[105] COL Brett Weaver, TSM Force XXI (FBCB2), Force XXI Battle Command Brigade and Below (FBCB2), Computer Set, Digital, January 25, 2005.

Appendix C
Mathematics of the Intermediate Model: Design Period

In this appendix, we describe the development of the intermediate model for design-period improvement as a function of cost. We also show an initial calibration of the model, with data from two platforms. We based our understanding of design-period operations on the overall framework for reliability engineering laid out in Sanjay Tiku's doctoral dissertation, "Reliability Capability Evaluation for Electronics Manufacturers."

In the design period, tasks like engineering labor applied to the PoF analyses, HALT exercises, and durability studies are homologous to the testing part of the TAAF period, in which identification of a B-mode failure leads to analysis of its causes and "fixing." However, in the design period, identification of a potential failure mode by analysis leads to further analysis to determine how the mode might be eliminated or reduced in rate and to changes in component design or in operations concept.

Accordingly, we model the relation between reliability improvement and cost in the design period with the same equations that we developed to model that relation in the TAAF period. Of course the parameters of the design-period model will differ from those of the TAAF-period model, reflecting the different underlying processes of the two periods. Thus our model of reliability improvement in the design period and its associated costs is given by

$$\rho_D(\tau) = \lambda_A + (1-\mu_D)\lambda_{B,K}^D + \frac{\mu_D \lambda_{B,K}^D}{(1+\tau)^{\alpha_D+2}} \qquad \textit{(Eq. C-1)}$$

and

$$\gamma_D(\tau) = \frac{g_D}{\beta_D} t + \frac{\lambda_{B,K}^D \mu_b^D}{\beta_D} \tau \; {}_2F_1(\alpha_D + 2, 1; 2; -\tau)\,. \qquad \textit{(Eq. C-2)}$$

In Equation C-1 and Equation C-2, we have written failure rate ρ_D and associated cost γ_D as functions of $\tau = \beta_D t$ to emphasize that those two equations are parametric equations for failure rate as a function of cost, with parameter τ.

Our intention is to represent reliability improvement as a function of cost. Equation C-1 and Equation C-2 do that, simply regarding τ as a parameter. The time t could be viewed as the total full-time-equivalent time invested in the design period.

As in the TAAF period, it may be useful in the design period to consider the large-K limit of the model. That is given by

$$\rho_D(\tau) = \lambda_A + (1-\mu_D)\lambda_B^D + \frac{\mu_D \lambda_B^D}{1+\tau} \qquad \textit{(Eq. C-3)}$$

and

$$\gamma_D(\tau) = \frac{g_D}{\beta_D}\tau + \frac{\lambda_B^D \mu_B^D}{\beta_D}\ln(1+\tau). \qquad \textit{(Eq. C-4)}$$

The parameters of the design-period model have the same meanings in relation to the design period and its operations as do the homologous parameters of the TAAF period in relation to the TAAF period and its operations. The parameters α_D and β_D determine the central tendency and dispersion of the set of B-modes in the system at the start of design. These parameters consequently reflect features of the system, which the design period will modify.

The parameter λ_A is the failure rate of the system's A-modes. The parameter $\lambda_{B,K}^D$ or its limiting value λ_B^D gives the initial B-mode failure rate. The parameter μ_D is the fraction of a B-mode failure rate eliminated by the design process. Although the homologous TAAF parameter μ_D generally takes values around 70 percent, we believe that μ_D may be significantly larger, approaching 1 in some cases, because of the wider and more fundamental options available for attacking B-modes in the design period.

The parameter g_D reflects the "burn rate" of engineering labor in the design period, and the parameter μ_b^D gives the cost of ameliorating B-modes identified in the design period.

CHARACTERISTICS OF THE DESIGN-PERIOD MODEL

To discuss the general nature of the design-period model, it will be convenient to have it in a non-dimensional form. Let q denote the fraction of the initial failure rate due to λ_A, that is, $q \equiv \lambda_A M_0$. It follows that

$$\lambda_B = (1-q)/M_0. \qquad \textit{(Eq. C-5)}$$

Recognizing that $\rho_D = 1/M_i$ at the end of the design period, multiplying Equation C-3 by M_0 then gives an equation for the ratio M_0/M_i:

$$\frac{M_0}{M_i}(\tau) = q + \nu_D(1-q) + \frac{\mu_D(1-q)}{1+\tau}. \qquad \textit{(Eq. C-6)}$$

Equation C-6 involves just two parameters, q and μ_D, since $\nu_D = 1-\mu_D$.

Now let us develop a non-dimensional form of Equation C-4. Using λ_B from Equation C-5, we see that Equation C-4 can be written in the form

$$\gamma_D(\tau) = \frac{M_0 g_D}{(1-q)} \frac{\lambda_B^D}{\beta_D} \tau + \frac{\lambda_B^D \mu_B^D}{\beta_D} \ln(1+\tau)\,. \qquad \textit{(Eq. C-7)}$$

The quantity $M_0 g_D$ has a straightforward meaning: it is the cost of operating the design period for time M_0. This suggests non-dimensionalizing Equation C-7 by dividing each side by $M_0 g_D$. That will leave the ratio λ_B^D / β_D in the equation. Let us explore the meaning of that ratio.

Straightforward calculations with the Gamma distribution function show that

$$cv \equiv \frac{s.d.(\sum \lambda_i)}{<\sum \lambda_i>} = \frac{\beta_D \sqrt{K(\alpha_D + 1)}}{\beta_D K(\alpha_D + 1)} = \frac{1}{\sqrt{K(\alpha_D + 1)}} = \sqrt{\frac{\beta_D}{\lambda_{B,K}}} \to \sqrt{\frac{\beta}{\lambda_B}} \qquad \textit{(Eq. C-8)}$$

expresses the coefficient of variation cv of the sum whose large-K limit gives the initial B-mode failure rate λ_B^D in terms of the ratio λ_B^D / β_D. Specifically,

$$\frac{\lambda_B^D}{\beta_D} = \frac{1}{cv^2}\,. \qquad \textit{(Eq. C-9)}$$

The coefficient of variation cv is a property of the process that preceded the design period and led to initial MTBF M_0. More discipline in that process would lead to smaller values of cv, and conversely, smaller values of cv would lead to more discipline in the process.

We take cv as a parameter to be determined and write Equation C-4 in non-dimensional form as

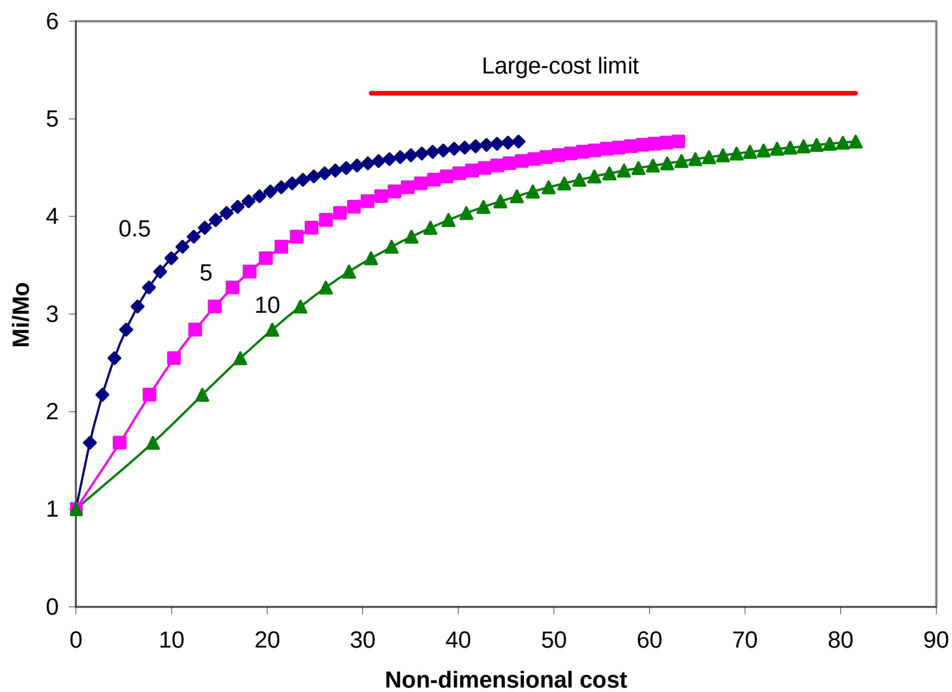
$$cv^2 \frac{\gamma(\tau)}{M_0 g_D} \equiv \hat{\gamma}_D(\tau) = \frac{\tau}{1-q} + \frac{\mu_B^D}{M_0 g_D} \ln(1+\tau)\,. \qquad \textit{(Eq. C-10)}$$

Our model for reliability improvement in the design period, as a function of cost, is represented by Equation C-6 and Equation C-10. In non-dimensional form, the model has three parameters: q, μ_D, and $\frac{\mu_B^D}{M_0 g_D}$. The last of those is the ratio of the cost of ameliorating a B-mode (identified in the design period) to the cost of operating the design period for time M_0.

The multiplicative factor cv^2 in the definition of $\hat{\gamma}(\tau)$ in Eq. C-10 implies that, with all other factors remaining the same, reliability improvement efforts on a system in which initial reliability M_0 resulted from a well-disciplined development effort will cost more for a given improvement than will efforts on a system in which M_0 resulted from a less-disciplined development. This seems to be a reasonable reflection of the fact that improving on a good job will generally be harder than improving on a poor one.

Figure C-1 shows an example of the variation of M_i/M_0 with cost, for $\frac{\mu_B^D}{M_0 g_D}$ equal to 0.5, 5, and 10. The other parameters are q = 0.1 and $\mu_D = 0.9$.

Figure C-1. Design-Period Reliability Improvement as a Function of Cost



Initial Calibration of the Design-Period Model

We obtained data on reliability improvement in the design period, and their associated costs, for efforts on two fundamentally different platforms: U.S. Marine Corps Expeditionary Fighting Vehicle (EFV), and tri-service air-to-air missile AIM-9X.

The best data for calibration would cover reliability improvements and associated costs for complete programs. Discussions with engineers in the EFV and AIM-9X programs led us to conclude that it would be reasonable to make an initial calibration of our design-period model, using data on the relation between reliability improvement and cost for certain components of those two platforms. In this way, we obtained a set of 14 data points, 13 for EFV and 1 for AIM-9X.

We were given dollar costs for materials used in the proactive work of the design period, but only engineering hours for the engineering labor. We priced engineering hours at $150 per hour, which we found to be at the higher end of the GSA rates for systems engineers.

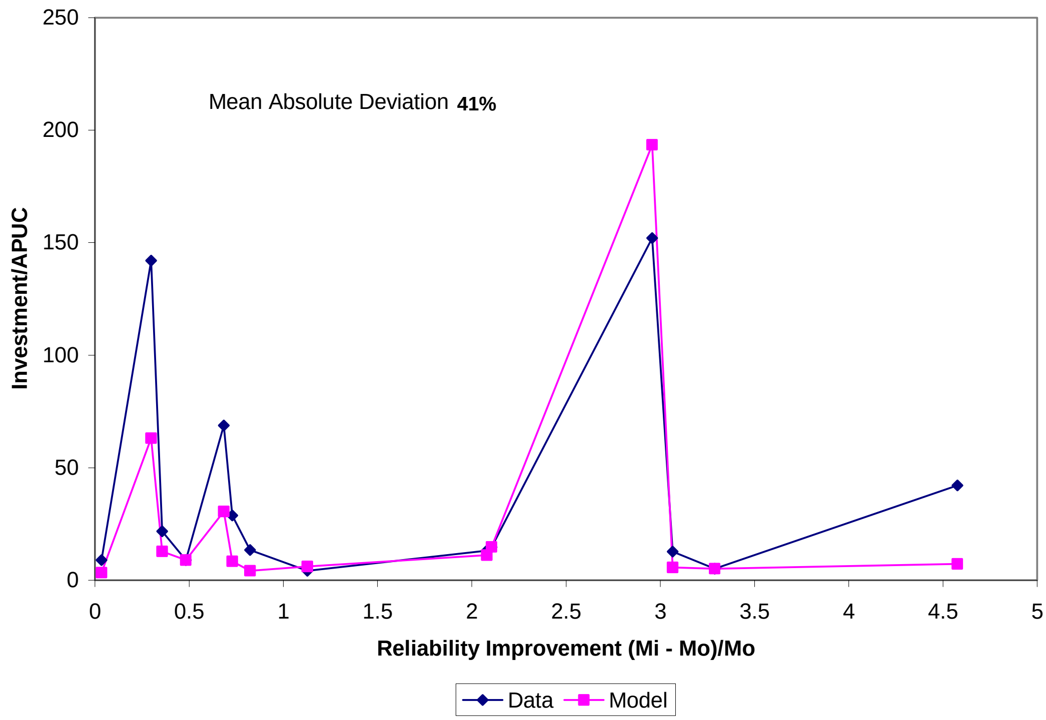
We modeled our model's parameters by setting $q = 0$ and $\mu_D = 1$, on the grounds that A-modes were not significant in the design-period cases considered and that all the failures associated with a B-mode identified in the design period would be eliminated by redesign.

We allowed g_D to be an adjustable parameter. We modeled μ_D as proportional to a power of each component's APUC, and took the constant of proportionality and the power as two adjustable parameters.

We modeled cv^2 as taking one of four discrete values. We expect that the "goodness" of initial systems will generally be adequately described by such small sets of values.

Thus we had seven adjustable parameters. We adjusted them to minimize the mean absolute deviation of the model's costs from the observed costs. Figure C-2 shows the result: cost as a function of relative improvement.

Figure C-2. Initial Calibration of Design-Period Model



We are cautiously encouraged by the result. The model captures the trend of cost as a function of improvement reasonably well, and it treats data from two distinct platforms consistently. (The AIM-9X datum, the second point from the right in Figure C-2, is not an outlier, but happens to be one of the best-fit points.)

We look forward to obtaining data from other reliability programs so that we can improve the calibration of our model and increase our understanding of the relation between reliability improvement and cost in the design period.

VALIDATION PERIOD

It is not sufficient for the design and TAAF periods of a reliability improvement program to have generated MTBF $M_f \geq M_g$, where M_g is the goal of the program. Rather, the program must give an assigned confidence that the system's MTBF, M, is not less than M_g. This means that some reliability testing must take place, even if the system's estimated reliability at the end of the design period, M_i, is not less than M_g.

We have considered modeling the cost of a validation period. However, such a model was not part of our present task. We look forward to developing and calibrating a model of the validation period in subsequent work.

Appendix D
Mathematics of the Intermediate Model: TAAF Period

In this appendix, we describe how we incorporated a cost model into AMSAA's AMPM reliability maturity model and show that the resulting TAAF-period model fits certain data reasonably well.

CHARACTERISTICS OF THE AMPM MODEL

The AMPM assumes that the failure rates of the system's B-modes at the start of TAAF is given by the vector $\underline{\lambda} = (\lambda_1, \lambda_2, ..., \lambda_K)$, the components of which are assumed to be realizations of K independent random variables identically distributed with the Gamma distribution having parameters α, β. That is,

$$\lambda \sim \frac{\lambda^{\alpha} e^{-\lambda/\beta}}{\alpha! \beta^{1+\alpha}} \qquad \textit{(Eq. D-1)}$$

for all λ_i.

Making expected values first with respect to time of first occurrence of B-mode i, then with respect to the ensemble of $\underline{\lambda}$, the AMPM authors arrive at a failure intensity $\rho(t)$ given by

$$\rho(t) = \lambda_A + (1 - \mu_d)\lambda_{B,K} + \frac{\mu_d \lambda_{B,K}}{(1+\tau)^{\alpha+2}} \qquad \textit{(Eq. D-2)}$$

where the nondimensioned time variable $\tau \equiv \beta t$ and where $\lambda_{B,K}$ is the B-mode failure rate at the start of TAAF. The parameter λ_A is the (unchanging) A-mode failure rate, and the parameter μ_d is the mean value of the improvement made in "fixing" a B-mode identified during TAAF. That is, the failure rate of a B-mode "fixed" during the TAAF process is reduced to $(1 - \mu_d)$ of its initial value.[1]

[1] For the complete mathematical derivation of this model, see LMI, *Intermediate Reliability Investment Model, Version 0.5*, Task HPT80.01, D. Lee, J. Forbes, E.A. Long, and D.D. Robertson, January 2008.

THE COMPLETE RELIABILITY IMPROVEMENT-COST MODEL FOR THE TAAF PERIOD

We introduced cost to the TAAF process with the assumptions that operating the TAAF incurs cost proportional to TAAF time t, plus a random increment at each fix operation. Carrying out the same expected value operations as the ones that gave Equation D-2, we find that the cost $\gamma(t)$ of the TAAF period is

$$\gamma(t) = gt + \frac{\lambda_{B,K}\mu_b}{\beta}\tau\, {}_2F_1(\alpha + 2, 1; 2; -\tau) \qquad \textit{(Eq. D-3)}$$

where g \$/time is the burn rate of the TAAF and μ_b is the mean value of the costs of fixing an identified B-mode. The well-studied function ${}_2F_1(a, b; c)$ in Equation D-3 is known as a hypergeometric function and is defined by

$${}_2F_1(a, b; c; z) \equiv \sum_0^\infty \frac{(a)_k (b)_k}{(c)_k} \frac{(z)^k}{k!}\,. \qquad \textit{(Eq. D-4)}$$

The Pochhammer symbol $(z)_n$ used in Equation D-4 is defined by

$$(a)_n \equiv a(a+1)(a+2)\ldots(a+n-1)\,. \qquad \textit{(Eq. D-5)}$$

Our complete reliability improvement/cost model for the TAAF period comprises Equation D-2, which gives the improvement in B-mode failure rate with increasing TAAF time t, and Equation D-3, which gives the associated cost. The two equations determine failure intensity ρ as a function of cost parametrically, with parameter t.

Our TAAF-period model has seven parameters: five parameters λ_A, $\lambda_{B,K}$, α, β, and μ_d of the original AMPM, plus two parameters g and μ_b of our cost model.

According to AMSAA, the limiting form of the AMPM for large values of K (large numbers of B-modes) is often useful.[2] In that limit, our reliability improvement/cost model for the TAAF period is

$$\rho(t) = \lambda_A + (1-\mu_d)\lambda_B + \frac{\mu_d \lambda_B}{1+\tau} \qquad \textit{(Eq. D-6)}$$

and

[2] U.S. Army Materiel Systems Analysis Activity, *AMSAA Reliability Growth Guide*, AMSAA TR-652, W.J. Broemm, P.M. Ellner, and W.J. Woodworth, September 2000.

$$\gamma(t) = gt + \frac{\lambda_B \mu_b}{\beta} \ln(1+\tau). \qquad \textit{(Eq. D-7)}$$

The expression for $\tau\, {}_2F_1(1,1;2;-\tau)$ used in Equation D-7 follows from a standard identity.[3]

In the large-K limit, our model has six parameters: four parameters λ_A, λ_B, β, and μ_d of the limiting form of the AMPM, and two parameters g and μ_b of the cost model.

INITIAL CALIBRATION OF THE TAAF-PERIOD MODEL

AMSAA personnel obligingly gave us data on the cost of TAAF periods for 26 cases involving eight platforms. These data came from three suppliers who are currently engaged in the design and development of ground combat systems. Nondisclosure agreements preclude us from naming the suppliers or the systems in this report. The data represent the suppliers' estimates of the investment required to improve (grow) platform reliability from M_i (initial MTBF) to M_f (final MTBF). M_i is the level of platform reliability as the system enters the TAAF period. M_f is the target, or required, level of reliability that will be achieved through growth during the TAAF period. The systems have multiple reliability-growth stages, and the intermediate targets and the cumulative reliability investments are shown in Table D-1. APUC is representative of the complexity of the platform under development.

Table D-1. TAAF Model Calibration Data

Ground combat system	APUC ($)	M_i	M_f	M_f/M_i	Total cost ($)
Platform A	3,200,000	126	175	1.389.	491,931
			230	1.825	818,876
			287	2.278	1,438,961
Platform B	6,900,000	101	200	1.980	1,919187
			310	3.069	6,050,091
Platform C	7,500,000	107	185	1.729	1,214,856
			320	2.991	5,126,192
			329	3.075	5,391,669
Platform D	8,100,000	109	170	1.560	911,040
			230	2.110	2,153,125
			287	2.633	3,988,316

[3] See, for example, F. Oberhettinger, "Hypergeometric Functions," in *Handbook of Mathematical Functions*, M. Abramowitz and I. Stegun, editors, p. 556, Equation 15.1.3.

Table D-1. TAAF Model Calibration Data

Ground combat system	APUC ($)	M_i	M_f	M_f/M_i	Total cost ($)
Platform E	8,900,000	74	110	1.486	646,069
			150	2.027	1,427,564
			185	2.500	2,428,268
Platform F	428,000	179	210	1.173	388,493
			340	1.8989	1,215,510
			465	2.598	2,829,686
			550	3.073	3,970,387
Platform G	5,600,000	95	100	1.053	242,330
			150	1.579	800,990
			200	2.105	1,742,085
			253	2.633	3,255,225
Platform H	9,500,000	105	110	1.048	286,128
			170	1.619	1,032,182
			230	2.190	2,430,510
			287	2.733	4,514,546

To calibrate the model we used the large-K limiting form, given in Equations D-6 and D-7. Neglecting λ_A, the value of MTBF at the start of TAAF, M_i, is equal to $1/\lambda_B$, and the value of MTBF at the end of TAAF, M_f, is equal to the value of $1/\rho$ at the end of TAAF. Thus, the ratio M_i/M_f is equal to the ratio $\rho(\tau_f)/\lambda_B$, where τ_f is the nondimensional time at the end of TAAF. Dividing both sides of Equation D-6 by λ_B and solving for τ evaluates t_f in terms of the MTBF ratio and the parameter μ_d. The result is

$$\tau_f = \left(M_f / M_i - 1\right) / \left(1 - \nu_d M_f / M_i\right) \qquad \textit{(Eq. D-8)}$$

where we have written ν_d for $(1–\mu_d)$.

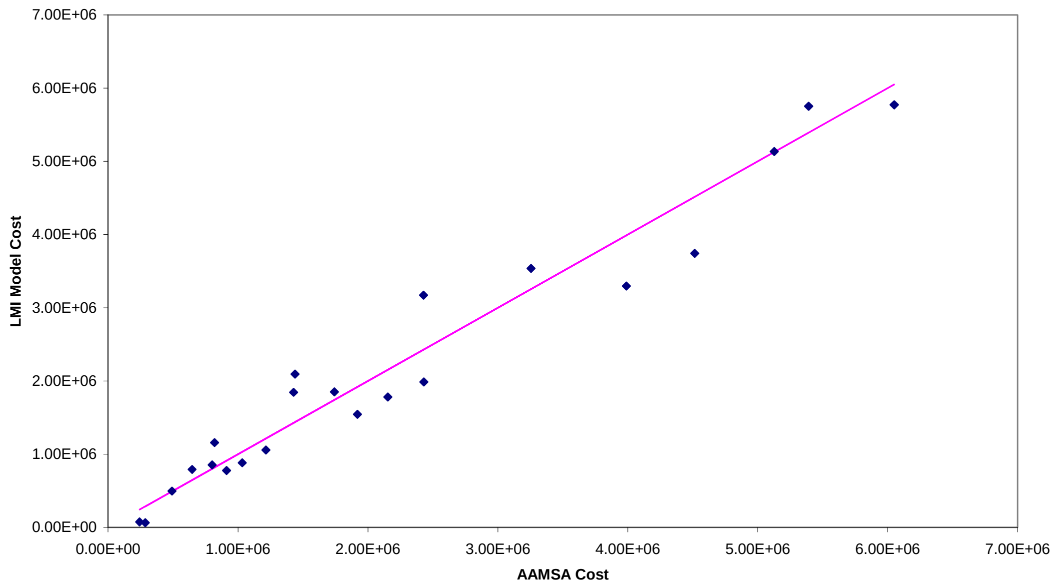
With the value of τ at the end of TAAF, we entered Equation D-7 to find the cost that our model implies to be associated with the observed reliability improvement. This cost is

$$\gamma(\tau_f) = \frac{g}{\beta}\tau_f + \frac{1}{M_i}\frac{\mu_b}{\beta}\ln(1+\tau_f)\,. \qquad \textit{(Eq. D-9)}$$

Thus, our model requires, apart from the AMPM parameter μ_d, values of two adjustable parameters g/β and μ_b/β.

We used the AMSAA-suggested value of 0.75 for μ_d and adjusted g/β and μ_b/β to minimize the mean absolute deviation of the model from the AMSAA data. The results are tabulated in the last column of Table D-1 and displayed in Figure D-1.

Figure D-1. Comparison of Model with AMSAA Data



The mean absolute deviation of the model from the data is 19 percent. That is, the model predicts the AMSAA cost information with an average error of 19 percent. We find that fact, and the general appearance of the results shown in the figure, encouraging. The reliability improvement/cost model for the TAAF period is able to reproduce AMSAA data reasonably well.

Appendix E
A Dynamic System Model for A_o Analysis

A classic simple definition of operational availability Ao is

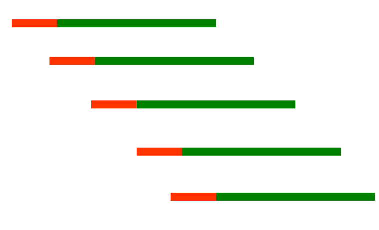
$$\mathrm{Ao} = \frac{\mathrm{MTBM}}{\mathrm{MTBM} + \mathrm{MDT}}, \qquad \textit{(Eq. E-1)}$$

where MTBM is mean time between maintenance and MDT is mean downtime for maintenance. This definition may be used to get rough indications of the force levels required for specific military effectiveness. This appendix shows how probabilistic considerations of time between maintenance and downtime affect the force levels required for given confidence in a specified military effectiveness. With an example, we see that the constant-time assumption leads to significantly less availability than desired, for a given MTBM/MDT ratio.

Planning with Constant Time between Maintenance and Downtime

We consider the case in which military effectiveness requires a given number M of units to be operational. Because each unit is assumed to operate for a constant TBM, and then requires maintenance with a constant DT, planning is straightforward. For example, suppose M = 5 and DT/TBM = 0.2. Then six units suffice, as indicated by Figure E-1.

Figure E-1. Plan with Constant TBM and DT



The maintenance schedules of five of the units are shown by the red bars in the figure and allow for extra maintenance if necessary. The sixth unit operates in the times indicated by the red bars, and the sixth unit is maintained at the time indicated by the yellow bar.

PLANNING WITH RANDOM TIME BETWEEN MAINTENANCE AND DOWNTIME

Actual times between maintenance are not constant, of course, nor are downtimes. Let us see how this randomness affects mission planning, when N units are required to be operational with 95 percent confidence.

For the sake of illustration, we assume that time between maintenance has an exponential distribution with parameter λ (MTBM = $1/\lambda$), and that downtime has an exponential distribution with parameter μ (MDT = $1/\mu$). The exponentiality of downtime is not realistic, but it does simplify the discussion. Our analysis generalizes readily to downtimes with Erlang distributions, or with generalized Erlang distributions.[1] This class seems sufficiently general to represent realistic downtime statistics.

We introduce a stochastic process, with system state j equal to the number of operational units. When M units are fielded, the system is in one of M + 1 states, j ranging from 0 to M. Let $P_j(t)$ denote the probability that the system is in state j—that is, that j units are operational—at time t.

When the system is in state M, that is, all units are operational, a need for maintenance causes the system to transition to state M − 1. A transition from state M − 1 caused by completion of downtime brings the system into state M.

The probability that the system experiences a need for maintenance in a small time interval δt while in state M, in which M units are operational, is equal to $M\lambda\delta t$. The probability that maintenance is completed in an interval δt while the system is in state M − 1, when one unit is undergoing maintenance, is $\mu\delta t$. Thus

$$P_M(t+\delta t) = P_M(t) - M\lambda\delta t P_M + (M-1)\mu\delta t P_{M-1}. \qquad \textit{(Eq. E-2)}$$

Subtracting $P_M(t)$ from both sides of Equation E-2, dividing by δt, and taking the limit as $\delta t \to 0$ gives

$$\dot{P}_M(t) = -M\lambda P_M + (M-1)\mu P_{M-1}, \qquad \textit{(Eq. E-3)}$$

where the dot over a symbol denotes differentiation with respect to time.

[1] A generalized Erlang distribution is the distribution of the sum of K exponentially distributed random variables, whose parameters may be distinct. The Erlang distribution results when all the parameters are the same.

When the system is in state j, $1 \le j < M$, either a need for maintenance, or completion of maintenance, moves the system out of state j. A need for maintenance in state j + 1, or completion of maintenance in state j − 1, brings the system into state j. It follows that

$$\dot{P}_j(t) = -[j\lambda + (M-j)\mu]P_j + (j+1)\lambda P_{j+1} + (M-j+1)\mu P_{j-1}\,. \qquad \textit{(Eq. E-4)}$$

If the system is in state 0, that is, all units are in maintenance, completion of maintenance brings the system out of that state; the need for maintenance in state 1 brings the system to state 0. It follows that

$$\dot{P}_0(t) = -M\mu P_0 + \lambda P_1\,. \qquad \textit{(Eq. E-5)}$$

Equations E-3, E-4, and E-5 are the evolution equations (forward Chapman-Kolmogorov equations) for our system. These equations are a set of M + 1 linear ordinary differential equations with constant coefficients, and it is a straightforward task to exhibit their solution starting with any prescribed initial condition. For example, if the system began with all units operational, then the initial condition would be $P_M = 1$, with all other $P_j = 0$.

Of greatest interest, however, is the steady-state behavior of the system. The steady-state probabilities follow from the solution of the set of M + 1 homogeneous linear algebraic equations obtained by setting the left sides of Equations E-3, E-4, and E-5 equal to zero. Conservation of probability requires the sum of the right sides of Equations E-3, E-4, and E-5 to be identically zero. Thus the homogeneous linear algebraic equations are linearly dependent, so the homogeneous system has nontrivial solutions (solutions for which not all P_j are 0). Obviously, if a given set of P_j solves the homogeneous equations, so does the set cP_j, where c is an arbitrary constant. That is, the homogeneous system determines the P_j only within an arbitrary multiplicative constant. The fact that the system must be in some state requires that $\sum_0^M P_j(t) \equiv 1$ for all t, and this determines the value of that constant.

We may use these facts to evaluate the steady-state probabilities by solving a system of M + 1 linear algebraic equations. The structure of that system makes it particularly simple to construct its solution. The solution depends only on the ratio μ/λ, that is, on the ratio MTBM/MTD, and not on the parameters individually. The solution takes a simple form, which we now develop. For simplicity of notation, we will continue to use the notation P_j to denote the steady-state values of $P_j(t)$.

Setting the right sides of Equation E-4 equal to zero and dividing the result by λ give

$$0 = -[j + (M - j)\rho]P_j + (j+1)P_{j+1} + (M - j + 1)\rho P_{j-1}, \qquad \textit{(Eq. E-6)}$$

where ρ denotes the ratio μ/λ. Equation E-6 implies a two-term recursion relation for the P_j:

$$P_{j+1} = \frac{1}{j+1}\left\{-[j\lambda + (M - j)\rho]P_j + (M - j + 1)\rho P_{j-1}\right\}, 1 \le j \le M - 1. \qquad \textit{(Eq. E-7)}$$

Equation E-5 implies that in steady state, when P_0 is unchanging,

$$P_1 = M\rho P_0. \qquad \textit{(Eq. E-8)}$$

Equation E-8 and the recursion (Equation E-7) allow one to express all the P_j in terms of P_0. The condition that the P_j sum to 1 then determines the value of P_0. In that way, all the P_j are evaluated.

These considerations suffice to determine the P_j. We can, however, go further and obtain a simple, closed-form expression for the P_j. The result will be useful for large values of M.

Equation E-8 and the recursion (Equation E-7) show that

$$P_2 = \frac{1}{2}\left\{[1 + (M-1)\rho]M\rho P_0 - M\rho P_0\right\} = \frac{M(M-1)}{2}\rho^2 P_0. \qquad \textit{(Eq. E-9)}$$

Using the last expression for P_2 in Equation E-9 and Equation E-8 for P_1 in the recursion (Equation E-7) shows that

$$P_3 = \frac{M(M-1)(M-2)}{2 \cdot 3}\rho^3 P_0. \qquad \textit{(Eq. E-10)}$$

These results suggest that

$$P_j = \binom{M}{j}\rho^j P_0. \qquad \textit{(Eq. E-11)}$$

A simple proof by induction, the details of which we omit, shows that Equation E-11 is in fact true for all $1 \le j \le M$.

In view of Equation E-11,

$$\sum_0^M P_j = \sum_0^M \binom{M}{j} \rho^j P_0 = (1+\rho)^M P_0 \ . \qquad \textit{(Eq. E-12)}$$

Using Equation E-12 and the fact that the P_j sum to 1 evaluates P_0 as $(1 + \rho)^{-M}$, and this allows us to write the P_j explicitly in closed form as

$$P_j = \frac{1}{(1+\rho)^M} \binom{M}{j} \rho^j, \ 0 \le j \le M \ . \qquad \textit{(Eq. E-13)}$$

Equation E-13 shows that in steady state, the P_j have the binomial distribution. We can see that the probability parameter p of that distribution is equal to $\rho/(1 + \rho)$, since with that value for p,

$$p^j (1-p)^{M-j} = \frac{\rho^j}{(1+\rho)^M} \ . \qquad \textit{(Eq. E-14)}$$

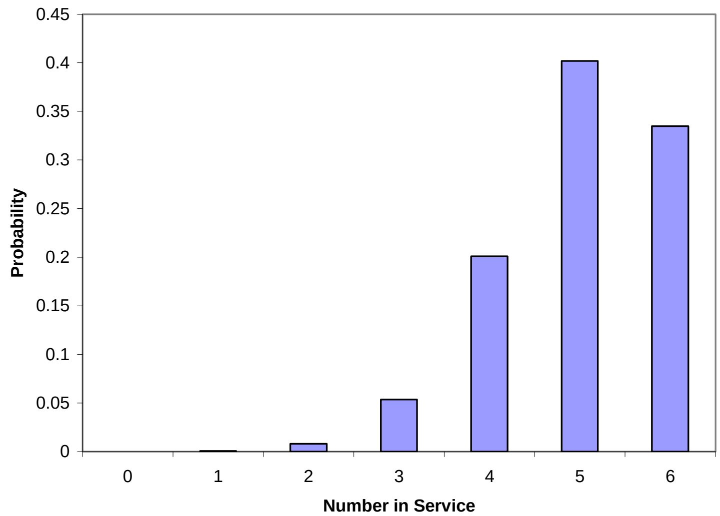
Equations E-13 and E-14 allow us to use the normal approximation of the binomial distribution to discuss the probability of more than N operational units, for cases of large M. The approximating normal distribution has mean Mp and variance Mp(1–p). Thus

$$P(\text{at least N operational units}) \approx 1 - CN(N, M\rho/(1+\rho), \sqrt{M\rho}/(1+\rho)), M >> 1 \qquad \textit{(Eq. E-15)}$$

In Equation E-15, $CN(x, \mu, \sigma)$ denotes the cumulative normal distribution with mean μ and standard deviation σ, evaluated at x.

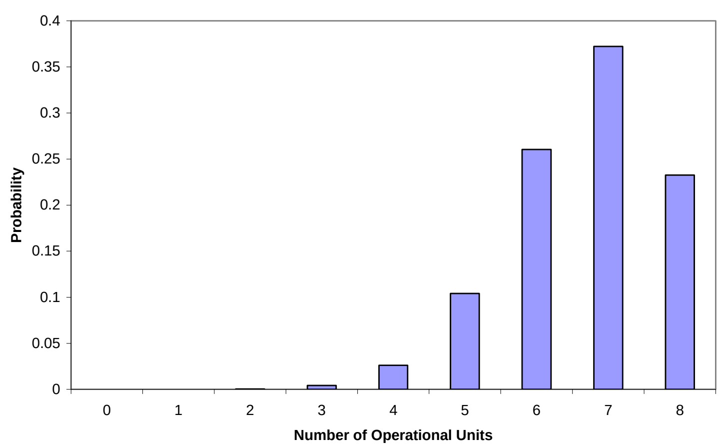
Finally, let us see how well the assumption of constant times between maintenance and maintenance times works, when compared with a more careful analysis considering the random nature of maintenance need and repair time. For the case N = 5, the constant-time plan found it adequate to field six units, when MTBM/MTD = 5. Figure E-2 shows the state probabilities for six fielded units for that case. The probability of at least five operational units is 0.74, well below the 95 percent requirement.

Figure E-2. Probability Distribution, M = 6



Fielding seven units gives 90 percent probability of five or more operational units in steady state. Raising the number of units fielded to eight gives the distribution of Figure E-3, and 97 percent probability of at least five operational units. Thus when MTBM/MTD = 5, eight units must be fielded for 95 percent confidence in five operational units.

Figure E-3. Steady-State Probability Distribution, M = 8



We may ask for the value of the μ/λ ratio that would make the constant-time plan viable. That value is 14.9.

Thus, in this example, planning, with the assumption of constant time between maintenance and maintenance time, underestimated the number of units required by 25 percent. Acting on the constant-time plan would have resulted in a substantial shortfall in required operational units. To make the constant-time plan viable would require a ratio of MTBM to MTD nearly five times as great as the one used in the plan.

Appendix F
Cost Analysis Strategy Assessment Model

To estimate life-cycle costs (LCCs) and to establish a relationship between achieved reliability improvement and reduction in support cost, LMI used the CASA model. This appendix summarizes the characteristics of a government-approved model and then describes the CASA model relative to them.

BACKGROUND

The CASA model was developed by the Defense Systems Management College in cooperation with Honeywell Avionics Division's logistics technical staff in response to a broad range of requirements gathered by the military services' acquisition program offices. Over the past several years, the model has been validated and used successfully by all of the DoD services, industry contractors, and other government agencies. The CASA program has the following users:

- Air Force (government and industry)—141
- Army (government and industry)—459
- Navy (government and industry)—170
- Marines (government and industry)—19
- Other DoD components (Coast Guard, OSD, etc.)—150
- Other entities (NASA; Federal Aviation Administration; Energy, Transportation, and Commerce departments; U.S. Senate; colleges; and state and local agencies)—81.

The model is not service or equipment specific and can handle a wide variety of "relevant costs." The model is comprehensive but highly tailorable. As user requirements have evolved, the model has evolved to the current 9.0 version.[1] LMI used version 8.0 for this study.

[1] Interview with Phillip Paschel, Program Manager, CASA, May 22, 2007.

CHARACTERISTICS OF A GOVERNMENT-APPROVED LCC MODEL

Research shows that a wide variety of both general-purpose and special-purpose LCC models have been developed. The government has regularly required that studies use the “government-approved” models when estimating the cost of ownership of alternative solutions. This requirement ensures that all of the contractors and government LCC estimates are comparable, repeatable, and understandable. Many of these models are cataloged in the DoD Acquisition Logistics Guide distributed by the Logistics Support Activity (LOGSA), an agency of the Army Material Command that serves all of DoD in the area of logistics supportability assessment and related tools.

Interviews with and surveys of many industry representatives have resulted in a finding that many government models were considered unnecessarily complex and “input data hungry.” Both industry and government program managers need a flexible model that can operate effectively with tailored levels of input detail, from simple to complex, depending on the decision being considered. The next section will show that the CASA model fits all of these requirements.[2]

DESCRIPTION OF THE CASA MODEL

The CASA model is basically a management decision aid based on LCC. In actuality, CASA is a set of analysis tools formulated into one functioning unit. It collects, manipulates, and presents as much of the total cost of ownership as the user desires. It contains a number of programs and submodels that allow the user to perform several tasks, such as the following:

- Generate program data files
- Perform life-cycle costing
- Perform sensitivity analysis
- Perform LCC risk analysis
- Perform LCC comparisons and summations on up to 2,000 repairable candidates.

The model also includes a wide variety of preprogrammed output report formats designed to support the analysis process. The CASA model covers the entire life of the system, from its initial research costs to those associated with yearly

[2] Defense Systems Management College, *Acquisition Logistics Guide*, Part 3, Logistics Resources and Tools, Chapter 16: Cost Analysis Strategy Assessment Model (CASA), Third Edition, December 1997.

maintenance, as well as spares, training costs, and other expenses incurred once the system is delivered. Currently, RDT&E and production costs are “throughput” costs, meaning they are not derived by the model. They are input and reported in some report outputs depending on their relevance to the analysis. The model calculates and projects the operations and support costs over the 20 to 30 years of operating the system. RDT&E and production cost estimating modules are being considered in response to numerous users’ requests.

The CASA model employs some 82 algorithms with 190 variables. A few inputs are mandatory, but most of the inputs are optional and are subject to tailoring to the analysts’ needs. Inputs include the following:[3]

- General information (study life, operating hours, etc.)
- Maintenance-level information (1 to 10 levels)
- System production and cost data
- System deployment data
- System hardware data (MTBF, MTTR, unit cost, etc.)
- Support equipment data
- Transportation data
- Training data
- Failure data
- Warranty data
- Inflation and discounting factors.

The CASA model, therefore, is a relatively “compact” model designed to facilitate well-informed decisions while holding model input data gathering to a moderate level. CASA works by taking the data entered, calculating the projected costs, and determining the probabilities of meeting, exceeding, or falling short of any LCC target value. Offering a variety of strategy options, CASA allows the user to alter original parameters to observe the effects of such changes on strategy options. At any number of program junctions, inputs may be saved and calculations may be made to that point for later evaluation. Furthermore, CASA will accept only correct inputs. It checks every entry as it is input; incorrect data will cause the cursor to refrain from movement or will alert the user.

[3] U.S. Army Materiel Command, Logistics Support Activity, Logistics Information Warehouse (LIW) Version 1.00, https://liw.logsa.army.mil/index.cfm?fuseaction=login.main (1 of 2), accessed May 22, 2007.

The CASA model can be used for a wide range of analytical tasks:[4]

- LCC estimates (system and subsystem)
- Item tradeoff analysis
- Support concept analysis
- Production rate and quantity analysis
- Warranty analysis
- Spares provisioning
- Reliability growth analysis
- Operational availability analysis
- Software project cost estimation.

OBTAINING CASA

Version 9.0 is the latest version of the CASA model. This version has new and improved system wizards and reporting capabilities and new data implementation. Major enhancements enable the user to do the following, among other things:

- Map program cost requirements within the acquisition life cycle
- Use reports as resource documentation for business case analysis, decision support, and Integrated Product Team meetings
- Connect data sources directly to the CASA model
- Eliminate data entry
- Create a reusable cost modeling capability.

The CASA model runs on any Windows-based operating system (Windows 95 or later) and is downloadable directly from the LOGSA Logistics Information Warehouse: https://www.logsa.army.mil/alc/casa/.[5]

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[4] Phillip Paschel, U.S. Army Materiel Command, Cost Analysis Strategy Assessment (CASA), April 9, 2007.

[5] Interview with Phillip Paschel, Program Manager, CASA, May 22, 2007.

Appendix G
Reliability Engineering Task Framework for Reliability Design

To develop a model of the relationship between the cost to improve reliability during the design period and achieved improvement, we needed a framework defining the tasks occurring during the design period. For a framework, we used Sanjay Tiku's model, which provides a global perspective of reliability engineering.[1]

As illustrated in Figure G-1, the Tiku model comprises eight key practice areas, each of which has five maturity levels.

Figure G-1. Tiku Reliability Engineering Capability Model

Practice Areas	Maturity Levels
1. Reliability requirements and planning	I. Reactive
2. Training and development	II. Repeatable
3. Reliability analysis	III. Defined
4. Reliability testing	IV. Managed
5. Supply chain management	V. Proactive
6. Failure data tracking and analysis	
7. Verification and validation	
8. Reliability improvements	

We anticipated that a global framework would be more general than we needed, and this proved to be the case. For developing a design period model, only the third practice area of Tiku's model, reliability analysis, was of significance. The other seven of the eight practice areas were not of significance for the following reasons:

- The 1st, 2nd, 7th, and 8th practice areas are, in general, organizational background tasks rather than product specific.
- The 4th practice area is most closely related to TAAF, which is addressed in a separate model.

[1] Sanjay Tiku, *Reliability Capability Evaluation for Electronics Manufacturers* (dissertation, University of Maryland, College Park, MD, 2005).

- The 5th practice area is an integral part of most major DoD acquisition programs.
- The 6th practice area occurs during the TAAF period.

Having made reliability analysis our focal point, we turned our attention to the Tiku maturity levels within practice area 3.

As illustrated in Table G-1, comparison of the repeatable, defined, and managed tasks within the analysis practice area reveals considerable harmony with MIL-STD-785B, "Reliability Program for Systems and Equipment, Development and Production" (last updated in 1980 and canceled in 1986). Although canceled, MIL-STD-785B is still a reasonable statement of traditional reliability engineering, and the tasks remain relevant today. We believe that most contractors doing reliability improvement work for DoD fulfill the intent of MIL-STD-785B.

Table G-1. Comparison of Tiku Reliability Analysis Practice Area to MIL-STD-785 B Design Tasks

Program maturity level	Practice area: reliability analysis (Tiku model)	Translation to reliability methods, tools, and activities	MIL-STD-785B tasks
Reactive	Analysis of product design is minimal, mainly based on manufacturing issues.		
Repeatable	Point reliability predictions are made for products using modeling or reliability prediction handbooks.	Reliability allocation and prediction based on similar items/parts count analysis	203
	Life-cycle costs or a product are optimized based on reliability versus cost tradeoffs.	LCC and trade studies	101
Defined	Materials used in product design are characterized.	Availability and use of material performance specifications	102
	Adherence to design rules is verified.	Design and peer reviews	103
	The warranty cost estimates and spares provisioning are made based on reliability predictions.	Assumed for DoD programs	
Managed	Potential failure modes and single points of failure are identified for products.	FMECA, fault-tree analysis	204, 208
	The criticality of components in a product design is quantified.	FMECA, finite element analysis, risk analysis	204,208
	Reliability predictions are provided as distributions, not as point estimates.	Reliability predictions provided as distributions	203
Proactive	Potential failure mechanisms are identified for products.	Physics of failure, durability analysis, thermal analysis, environmental characterization, dormancy analysis	
	Critical failure modes and mechanisms are identified for all products.	Comprehensive FMECA, fault-tree analysis	
	Reliability analysis is used to design specific reliability tests for a product.	Test strategy reflecting design of experiments based on reliability analysis	

Note: FMECA = failure mode, effects, and criticality analysis.

Key activities not in MIL-STD-785B are in the proactive maturity level. It is here that one will find modern, PoF-based methods and HALT exercises. Creditable arguments can be made that the classic MIL-STD-785B tasks do a dependable job of planning reliability; providing essential data that are used in many processes, including safety and logistics engineering; and developing reliability predictions. But they do not provide a basis for reliability improvement during design. Historically, if addressed, that has been left to the TAAF phase. More recently, PoF-based methods such as thermal analysis and vibration analysis—accompanied by focused design-time testing such as HALT—have enabled reliability improvement during the design phase. (The upcoming GEIA Reliability Standard 0009 provides detail on proactive design techniques.)[2]

As such, we concluded that reliability improvement in the engineering design phase depends on proactive activities. Consequently, estimating the costs and effectiveness of reliability improvement during the design phase is the same thing as characterizing the existence, cost, and effectiveness of proactive tasks. The costs and effectiveness of the design phase in the intermediate model are based on this premise.

The design phase model begins with the same characterization of failures into A- and B-modes as used in the TAAF phase model. We believe that identifying and mitigating B-modes in the design phase result from processes whose behavior and cost work very much like those of the TAAF phase.

In the design phase, engineering labor applied to PoF analyses, HALT exercises, and durability studies is analogous to the testing part of the TAAF phase. As in the TAAF phase, observing a B-mode failure leads to analysis of its root causes and mitigation. In the design phase, identifying a potential failure mode by analysis leads to further analysis to determine how the mode might be eliminated or reduced in rate, and then to implementation of changes in component design or in operations concept.

Because A-modes are not removed, the failure rate attributable to them will not be affected. Thus, estimating the effectiveness and cost of reliability improvement in the design phase becomes a matter of estimating the number of B-mode failures, their corresponding failure rates, and the cost of the nonrecurring engineering and design effort to remove them.

[2] GEIA Reliability Standard 0009 is due to be published in September 2008.

Appendix H
Bibliography

Air Force, C-17 Contract F33657-01-D-2000, Delivery Order 00 (AFD-070817-079), paragraph H037 (specifies cost of OBIGGS 1 systems).

Air Force, Fact Sheet, http://www.af.mil/factsheets/factsheet.asp?id=86/.

Air Force, Modification of Aircraft, Exhibit P3A (PE 0207130F) APG-63V(1) Upgrade, February 15, 2000.

Army, Operational Requirements Document for the CH-47F Cargo Helicopter, June 2006.

Battlefield On-Line.com, http://www.bf2online.com/modules/wfsection/article.php?articleid=16, March 4, 2008.

Boeing, *CH-47F 1000 Hour Flight Test Program Report*, June 25, 2004, Figure 2.

Department of Defense, *Annual Report to Congress on Defense Acquisition Challenge Program for FY 2006*, June 2007.

Director, Operational Test and Evaluation, *Combined Operational Test and Development and Live Fire Test and Evaluation on MH-60S Fleet Combat Support Helicopter*, August 2002.

Director, Operational Test and Evaluation, *Force XXI Battle Command, Brigade and Below/Blue Force Tracker (FBCB2/BFT) Block I*, Summary, 2004.

Director, Operational Test and Evaluation, *FY 2001 Annual Report, RQ-4A Global Hawk Unmanned Aerial Vehicle (UAV) Systems*, February 2002.

Director, Operational Test and Evaluation, *FY 2004 Annual Report, CH-47F Improved Cargo Helicopter*, 2004.

Director, Operational Test and Evaluation, Report on IOT&E, September 2001.

Ecker, Major Kris, F-15 PEM, SAF/AQPB (Pentagon), e-mails to Bill Esmann, LMI, March 3 and 7, 2008.

Global Security, http://www.globalsecurity.org/military/systems/aircraft/f-15-design.htm.

Global Security, http://www.globalsecurity.org/military/systems/aircraft/f-22-aircraft.htm, March 9, 2008.

Grosklags, CAPT Paul, USN, Multi-Mission Helicopter Program Office (PMA-299), OSD IDA Conference, November 8, 2006.

Institute for Defense Analyses, *Unmanned Aerial Vehicle Operational Test and Evaluation Lessons Learned*, Paper P-3821, December 2003.

Institute for Defense Analyses, Operational Evaluation Division, Interoffice Memo, FBCB2 BLRIP Suitability Submission, June 15, 2004.

Jay, David (577 AESG/YN), e-mails to Bill Esmann, LMI, November 2007–March 2008.

Kleinkauf, Gina, PMA-299 Senior Analyst, HH-60H NALDA LMDSS Aircraft Verified Failure and BCM Report, e-mails to Andy Long, LMI, 2007.

LMI, *Empirical Relationships between Reliability Investments and Life-Cycle Support Costs,* Report SA701T1, Andrew Long et al., June 2007.

LMI, *Using Technology to Reduce Cost of Ownership*, Volume 2, Appendixes G and I, Report LG404RD4, Donald W. Hutcheson et al., April 1996.

Lo, Tzee-Nan, et al., Institute for Defense Analyses, “Cost of Unsuitability” (presentation, DoD Cost Analysis Symposium, February 21, 2008), http://www.dodcas.org/DoDCAS2008presentations/T1/T1S5b_Lo.pdf.

Lund, John, Apache PMO–SDI, Inc., e-mails to Bill Esmann, LMI, January–February 2008.

O’Grady, Major Martin J., 303 AESG/PM, e-mail to Andy Long, LMI, May 9, 2007.

Office of the Secretary of Defense, *UAV Reliability Study*, February 2003.

RDT&E Budget Item Justification, Exhibit R-2A, PE 0203744A, Aircraft Modification/Product Improvement Program, Improved Cargo Helicopter, Continuing Engineering Manufacture Development, 2003–2007.

RDT&E Budget Item Justification, Exhibit R-2A, PE 0305205F, Endurance Unmanned Aerial Vehicles, Project 4799, Global Hawk, February 1999.

RDT&E Budget Item Justification, Exhibit R-2A, PE 0305205F, Endurance Unmanned Aerial Vehicles, Project 4799, Global Hawk, February 2003.

RDT&E Budget Item Justification, Exhibit R-3, PE 0203759A, Cost Analysis, Force XXI Battle Command, Brigade and Below (FBCB2), February 1999.

RDT&E Budget Item Justification, Exhibit R-3, PE 0203759A, Cost Analysis, Force XXI Battle Command, Brigade and Below (FBCB2), February 2003.

RDT&E Project Justification, Exhibit R-2A, PE 0604051D8Z, February 2007.

RDT&E Supporting Data for Fiscal Year 1999 Amended Budget Estimates, Descriptive Summaries, Volumes I, II, and III, February 1998.

Snow, Donald, et al., Boeing OBIGGS II Project Improvement Team (presentation, ASQ World Conference for Quality and Improvement, April 30, 2007).

Snow, Tom, Avion Corporation, CH-47F R&M Scoring Conference Minutes, February 2007, Section 2.

Terrabase Corporation, LogiQuest, Version 1.78, September 21, 2007, FLIS data view.

TRADOC, Combat Development Engineering, FDSC for FBCB2 BFT System, December 2003.

Under Secretary of Defense for Acquisition and Technology, C-17A Selected Acquisition Report, December 31, 2006.

Under Secretary of Defense for Acquisition and Technology, Selected Acquisition Reports, December Reports, 1996–2004.

Watson Jr., John, Boeing Reliability Analyst, e-mail to John Stewart, November 19, 2007.

Weaver, COL Brett, TSM Force XXI (FBCB2), Force XXI Battle Command Brigade and Below (FBCB2), Computer Set, Digital, January 25, 2005.

Appendix I
Abbreviations

ACTD	advanced concept technology demonstration
AMP	Avionics Modernization Program
AMPM	AMSAA Maturity Projection Model
AMSAA	Army Material System Analysis Agency
AMT	accelerated mission testing
APUC	average production unit cost
ASM	air separation membrane
BFT	Blue Force Tracker
C2	command and control
CASA	Cost Analysis Strategy Assessment
CER	cost estimating relationship
CMC	ceramic matrix composite
DARPA	Defense Advanced Research Projects Agency
DLA	Defense Logistics Agency
DoDCAS	DoD Cost Analysis Symposium
DOT&E	Director of Operational Test and Evaluation
DT/OT	development test/operational test
DUSD(L&MR)	Deputy Under Secretary of Defense for Logistics and Materiel Readiness
ECP	engineering change proposal
EFV	Expeditionary Fighting Vehicle
EMD	engineering and manufacturing development
FBCB2	Force XXI Battle Command Brigade and Below
FDSC	Failure Definition Scoring Criteria
FMECA	failure mode, effects, and criticality analysis
FOT&E	full operational test and evaluation
GFE	government-furnished equipment
GPS	global positioning system

HALT	highly-accelerated life testing
HEMTT	Heavy Expanded Mobility Tactical Truck
IDA	Institute for Defense Analyses
IMP	improvement ratio
INU	inertial navigation unit
IOC	initial operational capability
IOT&E	initial operational test and evaluation
KPP	key performance parameter
LCC	life-cycle cost
LM	Lockheed Martin
Ln	natural logarithm
LOGSA	Logistics Support Activity
LRIP	low-rate initial production
LRU	line replaceable unit
LTU	Laser Transceiver Unit
MCMT	mean corrective maintenance time
MGS	Mobile Gun System
MIL-STD	Military Standard
MTBCF	mean time between critical failure
MTBD	mean time between demand
MTBEFF	mean time between essential function failure
MTBF	mean time between failure
MTBM	mean time between maintenance
MTBMA	mean time between mission abort
MTBOMF	mean time between operational mission failure
MTBSF	mean time between system failure
MTBUR	mean time between unit replacement
MTTR	mean time to repair
NSA	Night Sensor Assembly
NSN	national stock number
O&S	operations and support
OBIGGS	On-Board Inert Gas Generation System

OEF	Operation Enduring Freedom
OPEVAL	operational evaluation
ORD	operational requirements document
PoF	physics-of-failure
PTUR	Pilotage Sensor Turret Assembly
R&M	reliability and maintainability
RDT&E	research, development, test, and evaluation
SAR	Selected Acquisition Report
SME	subject matter expert
TAAF	test, analyze, and fix
TAC	total accumulated cycle
TNP	TVS-NSA-PTUR
TRADOC	U.S. Army Training and Doctrine Command
TVS	Television Sensor
UAV	unmanned aerial vehicle
UEU	Universal Exciter Upgrade
VSTOL	vertical/short takeoff and landing