# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**AN APPLICATION OF TECHNOLOGICAL MATURITY ASSESSMENT TO ROKAF T-50 AIRCRAFT PRODUCTION PROGRAM**

by

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December 2005

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Second Reader: Geonwook Jeon

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# AN APPLICATION OF TECHNOLOGICAL MATURITY ASSESSMENT TO ROKAF T-50 AIRCRAFT PRODUCTION PROGRAM

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Submitted in partial fulfillment of the
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# ABSTRACT

This thesis investigates the feasibility of applying a knowledge-based approach to the problem of estimating the future success of a major defense acquisition. This thesis will model the US Government Accountability Office (US GAO) knowledge based methodology for evaluating programs. This methodology relies on three sets of knowledge, namely, technology, design, and production. In particular, the technology dimension is measured by Technology Readiness Level (TRL), as defined by NASA. In addition, the methodology relies on assessing the design readiness of a program by examining the status of the release of engineering drawings. Finally, the US GAO methodology assesses the production readiness of a program by examining the status of Statistical Process Quality Control (SPQC) procedures. This thesis also presents to the ROKAF decision maker an independent, knowledge-based estimation of the ROKAF T-50 program by applying the US GAO methodology to the T-50 program.

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# TABLE OF CONTENTS

I. INTRODUCTION .......... 1
A. BACKGROUND .......... 1
B. OBJECTIVE .......... 2
C. RESEARCH QUESTIONS .......... 2
D. SCOPE AND LITERATURE REVIEW .......... 2
1. Scope .......... 2
2. Literature Review .......... 3
3. Organization and Chapter Summary .......... 4

II. RELATED RESEARCH .......... 5
A. WEAPON ACQUISITION ENVIRONMENT .......... 5
1. Introduction .......... 5
2. The T-50 Program .......... 5
3. The US Acquisition Programs .......... 6
4. The Technology Development Phase .......... 8
B. COST ESTIMATING .......... 10
C. GAO METHODOLOGY .......... 13
1. Knowledge Point One: Technology .......... 13
2. Knowledge Point Two: Design .......... 15
3. Knowledge Point Three: Production .......... 15
*a. Process Capability Index .......... 17*
*b. Manufacturing and Product Reliability Knowledge of GAO Report .......... 21*
D. EVALUATING AFFORDABILITY INITIATIVES .......... 22
E. SUMMARY .......... 25

III. IMPLEMENTATION AND APPLICATION .......... 27
A. TRL ASSESSMENT .......... 27
1. Technology Assessment .......... 27
2. Technology Uncertainty .......... 30
3. Accuracy OF T-50 TRL Assessment .......... 31
4. US Program TRL Assessment .......... 32
5. Analysis of the TRL .......... 34
6. Summary .......... 34
B. DESIGN DRAWINGS .......... 35
1. T-50 Design Release Status .......... 35
2. US Program Design Release Status .......... 37
3. Proportion of Drawings Released at CDR .......... 39
4. R&D Cost versus Number of Drawings .......... 42
5. Regression on the Engineering Drawings .......... 44
6. Summary .......... 45
C. PRODUCTION .......... 47

1. T-50 SPC Process Plan ........................................................ 47
*a. Definition of SPC of T-50 Program ............................ 47*
*b. Measuring, Analyzing and Improving Process......... 47*
*c. Statistical Method ....................................................... 48*
2. T-50 Statistical Process Control ........................................... 48
3. US Program Production Knowledge .................................... 48
4. Summary ................................................................................ 51

IV. CONCLUSION ........................................................................................ 53
A. SUMMARY ................................................................................... 53
B. RECOMMENDATIONS FOR FUTURE RESEARCH ......................... 55

LIST OF REFERENCES ..................................................................................... 57

INITIAL DISTRIBUTION LIST ........................................................................... 59

# LIST OF FIGURES

Figure 1. The Technology Development Phase(From: DoD 5000.2, Defense Acquisition Guidebook, - 3. Procedures) .............................................. 8
Figure 2. The Specification Limits (From: http://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm accessed November 29, 2005).......................................................... 17
Figure 3. Varying Process Widths (From: http://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm accessed November 29, 2005)) ........................................................ 19
Figure 4. Actual and Allowable Upper Spread (From: http://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm accessed November 29, 2005)) ........................................................ 21
Figure 5. Development TRL................................................................................. 28
Figure 6. Design Review TRL............................................................................... 29
Figure 7. Production TRL .................................................................................... 29
Figure 8. Percentage of Drawings Released ...................................................... 37
Figure 9. Releasable Drawings before CDR of US programs............................. 39
Figure 10. Design Drawing Release versus Criteria ............................................. 41
Figure 11. CDR Drawings / Total Drawings ........................................................... 41
Figure 12. Achievement versus Expectation ......................................................... 42
Figure 13. R&D Cost/# of Drawings versus # of Drawings ................................... 43
Figure 14. Percentage Achievement at CDR versus R&D Cost ........................... 44
Figure 15. Percentage Achievement at CDR versus # Drawings ......................... 45

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# LIST OF TABLES


Table 1. Detailed Description of the Technology Development Phase (From: DoD 5000.2, Defense Acquisition Guidebook, - 3.6. Technology Development) ..... 9
Table 2. Definition of Technology Readiness Level (From: http://www.globalsecurity.org/military/intro/trl.htm, accessed November 29, 2005) ..... 15
Table 3. CPK and Probability of a Defective Part (From: GAO 02-701) ..... 16
Table 4. Activities to Capture Manufacturing Knowledge and Make Decisions (After: GAO 02-701) ..... 22
Table 5. Definitions of Maturity Sub Factors (From: Johns Hopkins APL Technical Digest, volume 21, number 3 (2000), Evaluating Affordability Initiatives) ..... 24
Table 6. TRL Assessment ..... 28
Table 7. T-50 TRL Assessment ..... 32
Table 8. T-50 Design Drawing Release ..... 36
Table 9. Design Drawing Release Status ..... 40
Table 10. R&D Cost Data ..... 43
Table 11. US Program Production Knowledge (After: GAO 05-301) ..... 50
Table 12. Observance of GAO Benchmarks ..... 54

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# EXECUTIVE SUMMARY

This thesis investigates the knowledge-based approach developed by the US GAO to estimate if the weapon acquisition program could meet requirements without cost overruns and schedule delays. To manage the major weapon acquisition program and achieve the key results, the US GAO has developed three knowledge points; technology maturity, design stability and controlled production stability. The T-50 acquisition program, the newly developed training aircraft of ROK Air Force, is subjected to an assessment by the GAO methodology to ascertain if the program would enjoy good progress in the research and development phase. The 10 US programs' data are also compared with the T-50 program to evaluate the technology maturity of those programs and judge if they are following GAO guidance.

The following shows the status of whether each program in our dataset follows the GAO guidance or not. GAO considers each of these as a "best practice" in the major weapon acquisition process

- Technology Readiness Level(TRL) above 7
- 90 percent achievement of engineering drawings at Critical Design Review (CDR)
- Production supported by Statistical Process Control (SPC)

The GAO knowledge based-methodology about T-50 program finds some conclusions with the above rules.

- Since the T-50 program achieved a TRL of 6.3 at the development stage, we believe that the T-50 program will achieve the goal of TRL 7 with the trend of technology development.
- The releasable drawings of T-50 program at CDR is not at a sufficient level to ensure design stability. T-50 has more design drawings than the advanced programs in our dataset as well as the unmanned programs in our dataset. The T-50 program's achievement of design drawing, 67%, at CDR is below the "best practice" guidance of the GAO.

- T-50 prototype production had been performed without fully developed statistical control and production is now at the beginning phase of mass production. However, there has not been an instance where SPC has been implemented directly for each component of the T-50 prototype model. On the other hand, the T-50 program has a specific plan of SPC for implementation during the Full Scale Development and Production phases.

# I. INTRODUCTION

## A. BACKGROUND

The Republic of Korea Air Force (ROKAF) Center has been studying military-force increments within the context of constraints imposed by shortfalls in the ROKAF budget allocations. The larger context is that the Korean governmental budgetary deficit acts as a severe constraint on the general ability to fund both ROK defense and improvements to ROKAF. Specifically, both new and ongoing weapons-acquisition programs are under financial pressure. In response, ROKAF has encouraged efficient cost evaluation, aiming to employ a limited budget wisely.

Some weapons-acquisition programs already in progress have failed to arrive at stated goals, compromising related programs in turn. The chronic problem of delays and overruns has boxed the ROKAF into attempting the development and fielding of ever-more-advanced capabilities, subject to increasingly rigid cost and time constraints. Despite these budgetary pressures, the master plan for defense-weapons acquisition can be expected to meet challenges such as cost increases and scheduling delays if cost evaluation is included at the beginning of each component program and as an ongoing part of the analysis of each program. Before approval is given for final investment in the Korean master weapon-acquisition program, a detailed cost estimation should be in place.

As a case in point, the ROKAF has invested in the development of the T-50 training aircraft from concept through development, beginning at the end of 1992. The T-50, a next-generation training aircraft built by Korea Aerospace Industries (KAI) and Lockheed Martin Aeronautics Company, features the power, performance, avionics, and cockpit display of the most sophisticated defense systems. Using the production of this aircraft to illustrate the value of cost and schedule estimation will demonstrate to ROKAF headquarters the importance of evaluating a weapon-acquisition program and offer insights towards application to other programs.

## B. OBJECTIVE

The objective of this thesis is to investigate the feasibility of applying a knowledge-based approach to the evaluation of a major defense-acquisition program- that of the ROKAF T-50 aircraft and to investigate options for adapting the US GAO methodology to the ROKAF T-50 aircraft program. Specifically, this thesis demonstrates how a knowledge-based approach to the problems of the master defense-weapon acquisition program can be defined and employed, and offers practical risk-assessment tools to weapons-acquisition officers.

## C. RESEARCH QUESTIONS

This thesis will investigate the following questions:

- Can U.S. GAO methodology be applied to the ROKAF T-50 program?
- What are the differences between the U.S. and ROKAF programs, as measured by GAO methodology?
- What can we learn about the forecast of success and cost overruns in ROKAF programs?

## D. SCOPE AND LITERATURE REVIEW

### 1. Scope

This thesis examines the prospects of success and the risk of cost overruns in a ROKAF T-50 aircraft development-and-procurement program.

There are two possible, and different, approaches to examining forecasted costs associated with a weapons-acquisition program:

- Focus on the affordability of system development, using the work of the advanced cost-estimating integrated-product team (IPT), as was done in the Joint Strike-Fighter (JSF) program. The IPT is then tasked with and responsible for developing methods to assess program initiatives.
- Use GAO methodology to assess technology maturity based on three knowledge points.

Because the GAO's knowledge-based methodology provides the greater insight into risks of cost overrun, this thesis applies the GAO approach.

Discovery of whether a knowledge-based approach can be applied directly to a ROKAF acquisition case will ultimately give officers in charge another tool to enhance their ability to plan appropriately for projects and procurement. Developing and advancing the US programs will be used in comparison with the ROKAF T-50 program.

This thesis requires the use of T-50 program data and assessment of technical maturity on the basis of NASA technology-readiness levels (TRLs) It also implements the latest acquisition-report information available. As part of a data-quality assurance-and-validation program, we sought data whose reliability was based upon

- Eliminating date that was anomalous or incredible
- Reliable sources, such as program managers

### 2. Literature Review

The US GAO has written extensively on ways to enhance the weapon acquisition process. For example,

> Although the weapons that the Department of Defense (DOD) develops have no rival in superiority, there still remain ways in which they can be improved. GAO's reviews over the past 20 years have found consistent problems with weapon acquisitions-cost increases, schedule delays, and performance shortfalls-along with underlying managers to promise more than they can deliver. DOD can resolve these problems by using a knowledge-based approach derived from the best practices of successful product developments.[1]

As essential parts of successful program management, the best weapons-acquisition programs take extra steps to confirm technology maturity, design stability, and production stability.

> Separating technology development from product development is important to this effort. Successful programs make a science and technology organization, rather than the program or product

1 GAO-04-248, Assessments of Major Weapon Programs, p. 2.

development manager, responsible for maturing technologies. Such steps can help to reduce costs and deliver a product on time and within budget.[2].

### 3. Organization and Chapter Summary

This section gave an overview of the thesis and the process of assessing technical maturity based on a GAO report.

- Chapter II presents information necessary to understanding theoretical cost analysis, the GAO methodology, and statistics.
- Chapter III looks at application of theory and compares data pertaining to the U.S. and T-50 master acquisition programs.
- Chapter IV provides conclusions and recommendations for further research.

2 GAO 05-301, Assessments of Selected Major Weapon Programs, p. 6.

# II. RELATED RESEARCH

## A. WEAPON ACQUISITION ENVIRONMENT

### 1. Introduction

The program manager also should consider the requirements of users in various combatant services. Though weapon acquisition program managers and decision makers have been struggling to achieve desirable technical levels within schedule and budget, the acquisition process has proved somewhat unpredictable. For example,

> the US weapons-acquisition program results in reduced quantities and increased costs. The JSF acquisition program's estimated development and procurement costs have increased. In addition, the number of aircraft it plans to deliver has been reduced. As a result, unit costs for the JSF aircraft have increased substantially, thereby reducing the program's buying power. The most significant quantity reduction occurred after system development began in 2001, when the program reduced the number of aircraft it plans to procure from 2,852 to 2,443, or by 14 percent. The Navy-concerned that it could not afford the number of tactical aircraft it planned to purchase-reduced the number of JSF aircraft for joint Navy and Marine Corps operations from 1,089 to 680 by reducing the number of backup aircraft needed.[3]

### 2. The T-50 Program

> The T-50 is a true digital aircraft with the power, performance, avionics and cockpit display of today's most sophisticated defense systems. Everything about the T-50 readies student pilots for the rigors of frontline fighters. Through the joint development team of Korea Aerospace Industries and Lockheed Martin Aeronautics Company, an all-new trainer bridges the gap between subsonic training and supersonic, next-generation fighters. The T-50 easily exceeds Mach 1 and offers the widest flight envelope of any advanced jet trainer (AJT) and lead-in fighter trainer (LIFT) available. Pilots take the controls of a smooth-handling jet that offers the exceptional maneuverability of next-generation fighters, with similarly integrated cockpit and systems.[4]

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3 GAO 05-271, Joint Strike Fighter Acquisition, p. 7.

4 ROK Air Force, http://www.airforce.mil.kr/ENG/index.html (Accessed October 24, 2005)

### 3. The US Acquisition Programs

This thesis will use the US programs for comparison with the T-50 program. A brief description to understand the general of each program follows.

- B-2 Radar Modernization Program (RMP): "The Air Force's B-2 RMP is designed to modify the current radar system to resolve potential conflicts in frequency band usage. To comply with federal requirements, the frequency must be changed to a band where the B-2 will be designated as a primary user. The modified radar system is being designed to support the B-2 stealth bomber and its combination of stealth, range, payload, and near precision weapons delivery capabilities."[5]
- C-130 Avionics Modernization Program (AMP): "The Air Force's C-130 AMP standardizes the cockpit configurations and avionics for 14 different mission designs of the C-130 fleet. It consolidates and installs the mandated DOD Navigation/Safety modifications, the Global Air Traffic Management systems, and the C-130 broad area review requirements. It also incorporates other reliability, maintainability, and sustainability upgrades and provides increased situational awareness capabilities and reduces susceptibility of Special Operations aircraft to detection/interception."[6]
- C-5 Avionics Modernization Program (AMP): "The Air Force's C-5 AMP is the first of two major upgrades for the C-5 to improve the mission capability rate, transport capabilities and reduce ownership costs. The AMP implements Global Air Traffic Management, navigation and safety equipment, modern digital equipment, and an all-weather flight control system."[7]
- C-5 Reliability Enhancement and Reengineering Program (RERP): "The Air Force's C-5 RERP is one of two major upgrades for the C-5. The RERP is designed to enhance the reliability of the aircraft through the replacement of engines and modifications to subsystems such as the electrical, fuel, hydraulic and flight controls systems, while the C-5 Avionics Modernization Program (AMP) is designed to enhance the avionics. These upgrades are part of a two-phased modernization effort to improve the mission capability rate, transport capabilities and reduce ownership costs."[8]
- F/A-22 Raptor: "The Air Force's F/A-22, originally planned to be an air superiority fighter, will also have air-to-ground attack capability. It is being designed with advanced features, such as stealth

5 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 31.

6 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 33.

7 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 35.

8 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 37.

characteristics, to make it less detectable to adversaries and capable of high speeds for long ranges. It also has integrated aviation electronics (avionics) designed to greatly improve pilots' awareness of the situation surrounding them. It is designed to replace the Air Force's F-15 aircraft."[9]

- Global Hawk: "The Air Force's Global Hawk system is a high altitude, long endurance unmanned aerial vehicle with integrated sensors and ground stations providing intelligence, surveillance, and reconnaissance capabilities."[10]
- Joint Strike Fighter (JSF): "The program goals are to develop and field a family of stealthy, strike fighter aircraft for the Navy, Air Force, Marine Corps, and U.S. allies, with maximum commonality to minimize costs. The carrier suitable version will complement the Navy's F/A-18 E/F. The conventional take-off and landing version will primarily be an air-to-ground replacement for the Air Force's F-16 and A-10 aircraft, and will complement the F/A-22. The short take-off and vertical landing version will replace the Marine Corps' F/A-18 and AV-8B aircraft."[11]
- Joint Unmanned Combat Air Systems (JUCAS): "The program is a combined effort of the Defense Advanced Research Projects Agency (DARPA), the Air Force, and the Navy to demonstrate the technical feasibility and operational value of a networked system of high performance and weaponized unmanned air vehicles. Expected missions include the suppression of enemy air defenses, electronic attack, precision strike, and surveillance. The program consolidates two formerly separate service projects and is to develop larger, more capable, and interoperable aircraft."[12]
- Predator: "The Air Force's MQ-9 Predator B is a multi-role, medium-to-high altitude endurance unmanned aerial vehicle system capable of flying at higher speeds and higher altitudes than its predecessor the MQ-1 Predator A. The Predator B is designed to provide a ground attack capability and will employ fused multi-spectral sensors to find and track small ground mobile or fixed targets. As envisioned, each Predator B system will consist of four aircraft, a ground control station, and a satellite communication suite."[13]

9 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 63.

10 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 67.

11 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 79.

12 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 87.

13 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 101.

- V-22 Joint Services Advanced Vertical Lift Aircraft: "The V-22 Osprey is a tilt rotor, vertical takeoff and landing aircraft being developed by the Navy for Joint Service application. It is designed to meet the amphibious/vertical assault needs of the Marine Corps, the strike rescue needs of the Navy, and the special operations needs of the Air Force and the U.S. Special Operations Command. The MV-22 version will replace the CH-46E and CH-53D helicopters of the Marine Corps."[14]

## 4. The Technology Development Phase

The figure below[15] show the phases of the weapon system development and acquisition process, as described in DoDI 500.2. The Technology Development Phase is a specific phase of this process, and the following descriptions,[16] in Table 1, provide a more detailed description of the Technology Development Phase.

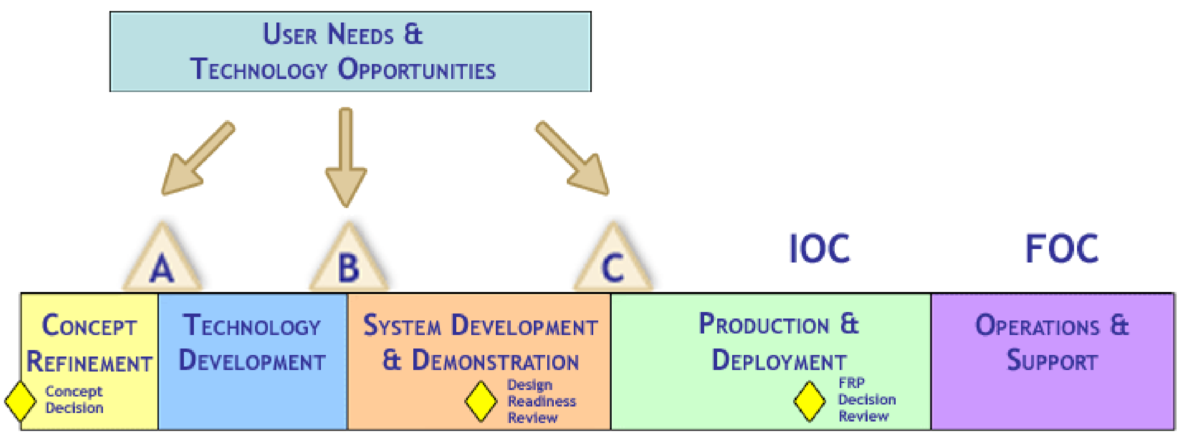


Figure 1. The Technology Development Phase(From: DoD 5000.2, Defense Acquisition Guidebook, - 3. Procedures)

14 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 117.

15 DoD 5000.2, Defense Acquisition Guidebook, - 3. Procedures, Figure 1, Framework.

16 DoD 5000.2, Defense Acquisition Guidebook, - 3.6. Technology Development.

| | |
|---|---|
| **a.** | **Purpose** |
| | The purpose of the technology-development phase is to reduce technology risk and to determine the appropriate set of technologies to be integrated into a full system. Technology Development is a continuous technology discovery and development process reflecting close collaboration between the S&T community, the user, and the system developer. It is an iterative process designed to assess the viability of technologies while simultaneously refining user requirements. |
| **b.** | **Milestone A** |
| | The project shall enter technology development at Milestone A when the MDA has approved the Technology Development Strategy (TDS). The tables in Enclosure 3 identify all statutory and regulatory requirements applicable to Milestone A. This effort normally shall be funded only for the advanced development work. A favorable Milestone A decision DOES NOT mean that a new acquisition program has been initiated. |
| **c.** | **Shipbuilding programs** |
| | Shipbuilding programs may be initiated at the beginning of Technology Development. The information required in the tables at Enclosure 3 shall support program initiation. A cost assessment shall be prepared in lieu of an independent cost estimate (ICE), and a preliminary assessment of the maturity of key technologies shall be provided. |
| **d.** | **Technology consideration** |
| | The Interim Capability Document (ICD) and the Technology Development Strategy (TDS) shall guide this effort. Multiple technology-development demonstrations may be necessary before the user and developer agree that a proposed technology solution is affordable, militarily useful, and based on mature technology. The TDS shall be reviewed and updated upon completion of each technology spiral and development increment. Updates shall be approved to support follow-on increments. |
| **e.** | **Evolutionary acquisition** |
| | If an evolutionary strategy is used, the initial capability represents only partial fulfillment of the overall capability described in the Interim Capability Document (ICD), and successive technology development efforts continue until all capabilities have been satisfied. In an evolutionary acquisition, the identification and development of the technologies necessary for follow-on increments continues in parallel with the acquisition of preceding increments, allowing the mature technologies to more rapidly proceed into System Development and Demonstration (SDD). Each increment of an evolutionary acquisition program shall have an associated MDA-approved TDS. |
| **f.** | **Exiting the phase** |
| | The project shall exit technology development when an affordable increment of militarily useful capability has been identified, the technology for that increment has been demonstrated in a relevant environment, and a system can be developed for production within a short timeframe (normally less than five years); or when the MDA decides to terminate the effort. During Technology Development, the user shall prepare the Capability Development Document (CDD) to support program initiation, refine the integrated architecture, and clarify how the program will lead to joint war fighting capability. The CDD builds on the ICD and provides the detailed operational performance parameters necessary to design the proposed system. A Milestone B decision follows the completion of Technology Development. |

Table 1. Detailed Description of the Technology Development Phase (From: DoD 5000.2, Defense Acquisition Guidebook, - 3.6. Technology Development)

## B. COST ESTIMATING[17]

Cost analysis is: (1) the act of developing, analyzing, and documenting cost estimates using analytical approaches and techniques. (2) The process of analyzing and estimating incremental and total resources required to support past, present, and future forces, units, systems, functions, and equipment. It is an integral step in the selection between alternatives by the decision maker. (3) A management tool used to help decision makers evaluate resource requirements at key management milestones and decision points in the acquisition process. Cost analysis is used to produce cost estimates for materiel systems, automated information systems, force units, training, and other Army programs and projects. Each cost analysis should contain:

(1) a clear definition of what is being costed.

(2) The specification of all assumptions, ground rules, and constraints, assumed or imposed, underlying the analysis. They must each be explained with adequate rationale.

(3) An estimate of all expected costs, directly or indirectly associated with the project over its life, including disposal. The cost estimate must include the identification of all data sources used.

(4) Risk and uncertainty analyses identifying any circumstances which could affect a course of action.

(5) Key limitations in terms of elements that were excluded.

The documentation supporting the cost analysis should describe the methodology used in developing these estimates. It also should identify all the data sources and include the computations used to estimate the costs. The documentation should be in sufficient detail to permit reviewers to follow the logic from assumptions to conclusion and to update the estimate at a later time.

Cost analysis is a critical element in the DoD acquisition process. It supports management decisions by quantifying the resource impact of alternative options. A quality analysis includes different acquisition strategies, hardware designs, software designs, personnel requirements, and operating and support concepts. As a program matures and more information becomes available, the cost estimate grows in complexity and detail. One test of the utility

17 Department of the Army Cost Analysis Manual, U.S. Army Cost and Economic Analysis Center, May 2002.

of cost analysis is its ability to respond quickly to program turbulence. Army planners must have reliable and readily available information about the cost consequences of program changes, extensions, or cancellations. Cost analysts must develop models to support these quick turnaround analyses.

Cost analysis has an on-going role in the management of base operations as well as acquisitions. Cost analysis assists installations, headquarters in determining base support requirements, developing budgets, conducting cost benefit analysis, and performing special studies. For example, the office of the Deputy Assistant Security of Army Cost and Economics (DASA-CE) develops cost factors in support of the Army Chief of Staff for Installation Management (ACSIM) for both the Installation Status Report (ISR) and the Army Installation Management - Headquarters Information (AIM-HI) model. Other ACSIM efforts supported by cost analysis include A-76 studies, Service Based Costing, and Standard Service Costing.

With the establishment of the cost/outcome oriented Government Performance Results Act (GPRA), cost analysis has taken on a larger role in to support management of base operations. The managerial costing focus, to meet GPRA mandates, requires cost analysis in the measuring and management of cost and results. Cost analysis will be needed to develop methodologies, conduct studies and analyze data of the products and services provided through base operations. The prerequisite to cost management is cost measurement. There are numerous methods of measuring costs, all of which will require cost analysis skills now and in the future. Examples of cost measurement include, full cost, job-order cost, service based cost, activity based cost, standard cost, product cost, and responsibility cost to name a few. Though there are many examples of cost measurement each demands cost analysis support to make information meaningful to DoD management. DASA-CE will prepare a managerial costing manual in the future on Activity Based Costing, Service Based Costing and Standard Service Costing.

Other uses of cost analysis in the DoD are to:

(1) Support decisions on program viability, structure, and resource requirements.

(2) Evaluate the cost implications of alternative materiel system designs.

(3) Provide credible and auditable cost estimates in support of milestone reviews during the acquisition process.

(4) Assess the cost implications of new technology, new equipment, new force structures, or new operating or maintenance concepts.

(5) Support the Planning, Programming, Budgeting, and Execution System (PPBES) process. This includes formulating and documenting Army Cost Positions (ACPs) on programs within the Program Objective Memorandum (POM) and the Budget Estimate Submission (BES) processes.

(6) Determine the funds required for a given level of training or operational activity such as miles driven per year.

Cost analysis applies scientific and statistical methods to evaluate the likely cost of a specific item in a defined scenario. In the real world, there are multiple uncertainties about the item's cost. Some "internal" uncertainties influencing cost are inadequate item definition, poor contract statement of work, optimistic proposed solutions, inexperienced management, and success-oriented scheduling. Some "external" uncertainties include funding turbulence, contractor's underestimating of complexity, contractor's changing business base, and excessive (or insufficient) Government oversight. In spite of uncertainty, the process of cost analysis is the most rigorous approach available to evaluate the costs of alternatives for the decision maker. Cost analysis does have limitations. Analysts develop cost estimating methodologies with an imperfect understanding of the technical merits and limitations of the item. The applicability of historic data is always subject to interpretation. Because of future uncertainties, there are limitations in determining the degree to which reality varies from the plan. Realistically, the cost analysis process cannot:

(1) Be applied with cookbook precision, but must be tailored to the problem.

(2) Produce results that are better than input data.

(3) Predict political impacts.

(4) Substitute for sound judgment, management, or control.

(5) Make the final decisions.

> Despite these limitations, cost analysis is a powerful tool. Rigorous and systematic analysis leads to a better understanding of the problem. It improves management insight into resources allocation problems. Because the future is uncertain our best estimate will differ from reality.

## C. GAO METHODOLOGY

Our review of the "best practices" literature in weapons-acquisition programs provides the lesson that three considerations are critical for sound progress in the weapons-acquisition process. These are

- Technology maturity
- Design stability
- Controlled production stability

Technology development is the key factor in determining whether a weapons-development program could meet requirements without cost overruns and schedule. Acquisition-program management also relies on the knowledge-based approach in developing new weapon programs and ensures key results through high levels of knowledge.

The US GAO methodology implements three knowledge points, as discussed below, and the GAO writes that

> The attainment of each successive knowledge point builds on the preceding one. While the knowledge itself builds continuously without clear lines of demarcation, the attainment of knowledge points is sequential. In other words, production maturity cannot be attained if the design is not stable, and design stability cannot be attained if the critical technologies are not mature.[18]

These knowledge points are described in the paragraphs below.

### 1. Knowledge Point One: Technology

Technology Readiness Levels (TRLs), used in the US National Aeronautics and Space Administration's (NASA) planning for many years, are measured on a scale of nine levels of technological maturity, as shown in Table 2.[19] Knowledge point one occurs when the weapon-acquisition requirements

18 GAO 05-301, Assessments of Selected Major Weapon Programs, p. 7.

19 Technology Readiness Level Definitions, http://www.globalsecurity.org/military/intro/trl.htm (accessed November 29, 2005)

meet the developer's available resources in terms of knowledge, time, and budget. The availability of mature technology on which to base development provides enhanced probability of achieving project success from the beginning. TRLs have been adapted to facilitate comparison between TRLs at the acquisition level and TRLs at the parts level. To identify critical levels of technology, GAO attempts to find the key technologies in which information availability may be a concern. As shown in the GAO report, "our best practices work has shown that a technology readiness level of 7—demonstration of a technology in an operational environment—is the level of technology maturity that constitutes a low risk of starting a product development program."[20]

| Technology Readiness Level | Description |
|---|---|
| 1. Basic principles observed and reported | Lowest level of technology readiness. Scientific research begins with to be translated into applied research and development. Example might include paper studies of a technology's basic properties. |
| 2. Technology concept and/or application formulated | Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies. |
| 3. Analytical and experimental critical function and/or characteristic | Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. |
| 4. Component and/or breadboard validation in laboratory environment | Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory. |
| 5. Component and/or breadboard validation in relevant environment | Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components. |
| 6. System/subsystem model or prototype demonstration in a relevant environment | Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment. |

20 GAO 05-301, Assessments of Selected Major Weapon Programs, p. 130.

| Technology Readiness Level | Description |
|---|---|
| 7. System prototype demonstration in a operational environment | Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft. |
| 8. Actual system completed and 'flight qualified' through test and demonstration | Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications. |
| 9. Actual system 'flight proven' through successful mission operations | Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions. |

Table 2. Definition of Technology Readiness Level (From: http://www.globalsecurity.org/military/intro/trl.htm, accessed November 29, 2005)

### 2. Knowledge Point Two: Design

This knowledge point occurs at the point when a product's design drawings are released from the engineer to the manufacturer. Successful programs obtain design stability at the time of critical design review (CDR), and CDR results serve as criteria for estimating the stability of engineering drawings released. The benchmark that the US GAO has set is that engineering-drawing stability is achieved if it is true that at least 90% of engineering drawings are completed (or at least releasable) before the CDR.

### 3. Knowledge Point Three: Production

Products manufactured with statistical process controls in place to govern costs, and schedules represent maturity in the production process. To evaluate such maturity, critical manufacturing processes are monitored for statistical data and fractions of statistical process control. To ascertain status of production, two concepts should be considered: quality and product testing.

- Quality in the manufacturing processes requires a repeatable statistical approach to ensure that standards for the system have been defined and are being monitored. Production must be on time, meet schedules, and keep in cost.

- Product test is needed to guarantee that the system operates reliably, without failure or repair during the some period. Production tests require many trials and processes.

Due to the typical shortage and high cost of the personnel needed to perform such tests, we focus only on the critical processes necessary to meet the reliability and performance standards. To measure the performance of the process, a process-capability index (CPK) is used to determine how a process is running compared to its specification limits and to measure production-process capability within specified limits.

> GAO used the Process Capability Index which is a process performance measurement that quantifies how closely a process is running to its specification limits. The index can be translated into an expected product defect rate, and GAO has found it to be a best practice.[21]

The CPK and probability of a defective part are shown in the table below.[22] A standard of less than 1.33 indicates that the manufacturing process lacks statistical control and acceptable consistency. Satisfactory cost, schedule, and product quality could be obtained during the manufacturing process prior to production.

| **Manufacturing process capability index** | **Associated defect rate** |
|---|---|
| Cpk - .67 (not capable) | 1 in 22 parts produced |
| Cpk – 1.0 (marginally capable) | 1 in 370 parts produced |
| Cpk - 1.33 (industry standard) | 1 in 15,152 parts produced |
| Cpk – 2.0 (industry growth goal) | 1 in 500,000,000 parts produced |

Table 3. CPK and Probability of a Defective Part (From: GAO 02-701)

21 GAO 05-301, Assessments of Selected Major Weapon Programs, p. 131.

22 GAO 02-701, Best Practices, p. 39.

#### *a. Process Capability Index*[23]

Process capability compares the output of an in-control process to the specification limits by using capability indices. The comparison is made by forming the ratio of the spread between the process specifications (the specification "width") to the spread of the process values, as measured by six process standard-deviation units (the process "width"). A process capability index uses both the process variability and the process specifications to determine whether the process is "capable." A capable process is one where almost all the measurements fall inside the specification limits. This can be represented pictorially by the plot below.

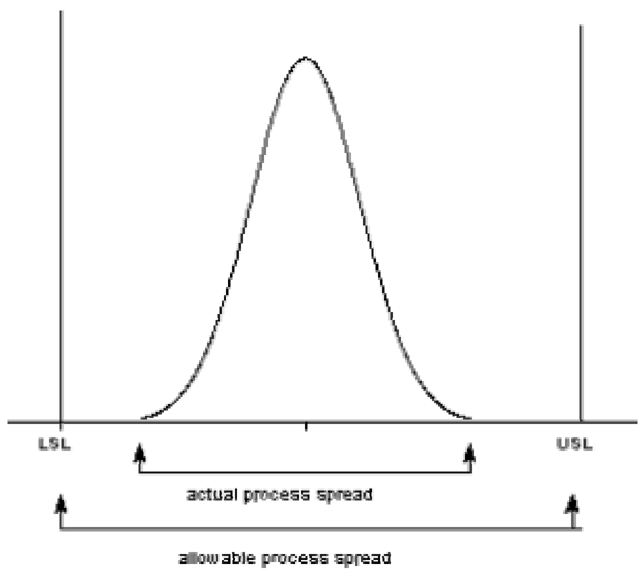


Figure 2. The Specification Limits (From: http://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm accessed November 29, 2005)

There are several statistics that can be used to measure the capability of a process: $C_p$, $C_{pk}$, $C_{pm}$.

Most capability indices estimates are valid only if the sample size used is large enough, generally thought to be about 50 independent data values.

23 Engineering Statistics Book, http://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm (accessed November 29, 2005).

The $C_p$, $C_{pk}$, and $C_{pm}$ statistics assume that the population of data values is normally distributed. Assuming a two-sided specification, if $\mu$ and $\sigma$ are the mean and standard deviation, respectively, of the normal data and USL, LSL, and T are the upper and lower specification limits and the target value, respectively, then the population capability indices are defined as follows:

$$C_p = \frac{USL - LSL}{6\sigma}$$

$$C_{pk} = \min\left[\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right]$$

$$C_{pm} = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}}$$

Sample estimators for these indices are given below. (Estimators are indicated with a "hat" over them).

$$\hat{C}_p = \frac{USL - LSL}{6s}$$

$$\hat{C}_{pk} = \min\left[\frac{USL - \bar{x}}{3s}, \frac{\bar{x} - LSL}{3s}\right]$$

$$\hat{C}_{pm} = \frac{USL - LSL}{6\sqrt{s^2 + (\bar{x} - T)^2}}$$

The estimator for $C_{pk}$ can also be expressed as $C_{pk} = C_p(1\text{-}k)$, where k is a scaled distance between the midpoint of the specification range, m, and the process mean, $\mu$.

Denote the midpoint of the specification range by m = (USL+LSL)/2. The distance between the process mean, $\mu$, and the optimum, which is m, is $\mu$- m, where $m \leq \mu \leq LSL$. The scaled distance is

$$k = \frac{|m - \mu|}{(USL - LSL)/2}, \qquad 0 \leq k \leq 1$$

(the absolute sign takes care of the case when $LSL \leq \mu \leq m$). To determine the estimated value, $\hat{k}$, we estimate $\mu$ by $\bar{x}$. Note that $\bar{x} \leq USL$.

The estimator for the $C_p$ index, adjusted by the k factor, is

$$\hat{C}_{pk} = \hat{C}_p(1 - \hat{k})$$

Since $0 \leq k \leq 1$, it follows that $\hat{C}_{pk} \leq \hat{C}_p$.

To get an idea of the value of the $C_p$ statistic for varying process widths, consider the following plot:

| | | | | |
|---|---|---|---|---|
| *USL - LSL* | *6σ* | *8σ* | *10σ* | *12σ* |
| *$C_p$* | *1.00* | *1.33* | *1.66* | *2.00* |
| *Rejects* | *.27%* | *64 ppm* | *.6 ppm* | *2 ppb* |
| *% of spec used* | *100* | *75* | *60* | *50* |

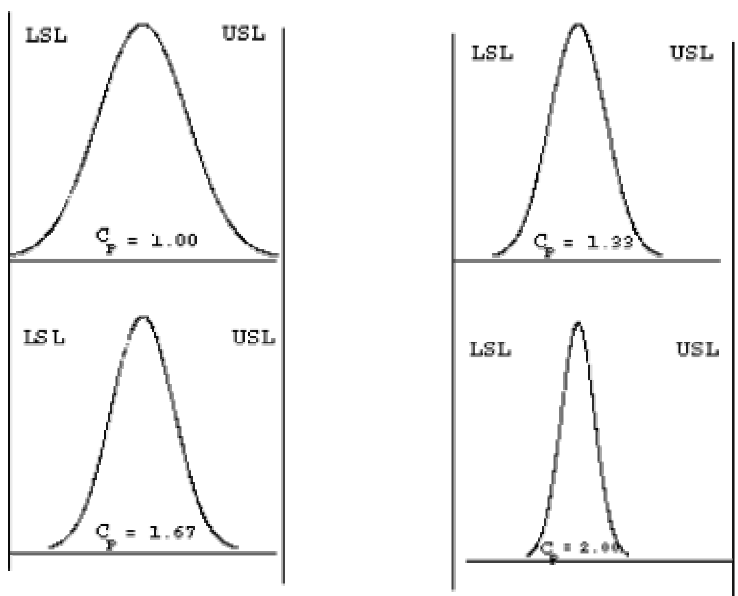


Figure 3. Varying Process Widths (From: http://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm accessed November 29, 2005))

This can be expressed numerically by the table below where ppm = parts per million and ppb = parts per billion. Note that the reject figures are based on the assumption that the distribution is centered at $\mu$.

We have discussed the situation with two spec limits: the USL and LSL. This is known as the bilateral or two-sided case. There are many cases where only the lower or upper specifications are used. Using one spec limit is called unilateral or one-sided. The corresponding capability indices are

$$C_{pu} = \frac{\text{allowable upper spread}}{\text{actual upper spread}} = \frac{USL - \mu}{3\sigma}$$

and

$$C_{pl} = \frac{\text{allowable lower spread}}{\text{actual lower spread}} = \frac{\mu - LSL}{3\sigma}$$

where $\mu$ and $\sigma$ are the process mean and standard deviation, respectively. We would like to have $\hat{C}_{pk}$ at least 1.0. Below 1.0 means this is not a good process. If possible, reduce the variability or/and center the process. We can compute the $\hat{C}_{pu}$ and $\hat{C}_{pl}$. Estimators of $C_{pu}$ and $C_{pl}$ are obtained by replacing $\mu$ and $\sigma$ by $\bar{x}$ and s, respectively. The following relationship holds $C_p = (C_{pu} + C_{pl}) /2$.

This can be represented pictorially by:

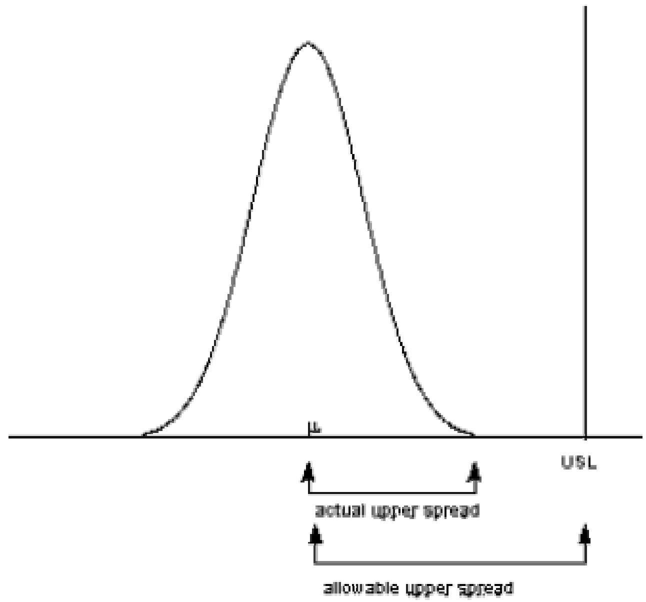


Figure 4. Actual and Allowable Upper Spread (From: http://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm accessed November 29, 2005))

Note that we also can write: $C_{pk} = min \{C_{pl}, C_{pu}\}$."

#### *b. Manufacturing and Product Reliability Knowledge of GAO Report*

The decision maker must decide whether the weapons-acquisition program is ready to make the transition from development into production. The below Table 4[24] would provide the guidance necessary to making a successful, data-driven, decision process in the weapon-acquisition program, thereby reducing the possibility of delaying the schedule and increasing costs.

| | |
|---|---|
| **Identify key system characteristics and critical manufacturing processes.** | Key product characteristics and critical manufacturing processes are identified. Because there can be thousands of manufacturing processes required to build a product, companies focus on the critical processes—those that build parts that influence the product's key characteristics such as performance, service life, or manufacturability. |
| **Determine processes in control and capability**. | Statistical process control is used to determine if the processes are consistently producing parts. Once control is established, an assessment is made to measure the process's ability to build a part within specification limits as well as how close the part is to that specification. A process is considered capable when it has a defect rate of less than one out of every |

24 GAO 02-701, Best Practices, p. 38.

| | |
|---|---|
| | 15,152 parts produced. |
| **Conduct failure modes and effects analysis**. | Bottom-up analysis is done to identify potential failures for product reliability. It begins at the lowest level of the product design and continues to each higher tier of the product until the entire product has been analyzed. It allows early design changes to correct potential problems before fabricating hardware. |
| **Set reliability growth plan and goals**. | A product's reliability is its ability to perform over an expected period of time without failure, degradation, or need of repair. A growth plan is developed to mature the product's reliability over time through reliability growth testing so that it has been demonstrated by the time production begins. |
| **Conduct reliability growth testing**. | Reliability growth is the result of an iterative design, build, test, analyze, and fix process for a product's design with the aim of improving the product's reliability over time. Design flaws are uncovered and the design of the product is matured. |
| **Conduct executive level review to begin production.** | Corporate stakeholders meet and review relevant product knowledge, including manufacturing and reliability knowledge, to determine whether a product is ready to begin production. The decision is tied to the capture of knowledge. |

Table 4. Activities to Capture Manufacturing Knowledge and Make Decisions (After: GAO 02-701)

## D. EVALUATING AFFORDABILITY INITIATIVES

There are different approaches to determining technology maturity. For example, there are those developed by the Joint Strike Fighter (JSF) Program Office's (PO) Advanced Cost Estimating (ACE) Integrated Product Team (IPT) to clarify their technology initiatives. The description below[25] shows the status and definition of technology maturity factors, as well as the sub-factors[26] that support them.

> Definitions for maturity factors were considered carefully by IPT members. All scales range from very easy (a known, presently operational technology, design, or process) to extremely difficult (purely theoretical concept or laboratory research yet to be attempted in a production environment).
>
> The state-of-technology sub-factor measures each initiative in terms of availability and promise of the technology required for

25 Johns Hopkins APL Technical Digest, volume21, number 3 (2000), Evaluating Affordability Initiatives, pp. 429-430.

26 Johns Hopkins APL Technical Digest, volume 21, number 3 (2000), Evaluating Affordability Initiatives, p. 430.

success. Ability to attain the required level of technological sophistication within known schedule constraints, as well as hardware and testing maturity, is considered. Although assessments were performed on a “system” basis, participants were also asked to consider and comment on the technological requirements of key subsystems. The scale ranges from technology that is already operational and deployed to that which still requires significant scientific research

The design and engineering sub-factor measures each initiative in terms of difficulty in advancing the state of the art to that required for the JSF Program. Thus, design and engineering focuses on implementation, separate from technology. For example, an item previously engineered and production-qualified may require extensive form, fit, and function changes or modifications for JSF application. Key subsystems are also considered. The scale ranges from off-the-shelf items meeting all requirements to ones requiring new, breakthrough design or engineering efforts.

The manufacturing process sub-factor measures each initiative in terms of the process capability needed to produce required quantities for the JSF Program. Process attributes considered are metrics such as number of allowable defects, yield or throughput requirements, tolerance or precision requirements, overall process capability to be maintained, and allowable failure rates. Evaluation includes assessment of advances required to move from current to proposed manufacturing and assembly processes. The scale ranges from an existing demonstrated process that satisfies all key attributes to one that exceeds the state of the art for at least one key attribute.

The resource availability sub-factor grades an initiative on the availability of all resource elements necessary for implementation at production quantities and rates specified for the JSF Program. Resources include parts or subassemblies, tools and fixtures, test equipment and facilities, personnel (including their skills and training levels), materials (quantity and quality), production equipment and facilities, and funding. The scale ranges from all required resources being readily available through at least one dependable source to an initiative for which resources have not yet been specified.

| Level | State of technology | Design and engineering | Manufacturing process | Resource availability [a] |
|---|---|---|---|---|
| A | Initiative presently operational and deployed | "Off-the shelf" hardware requirements | Existing, demonstrated process | Readily obtainable through at least one source; successful past experience |
| B | Process in limited operation | Design required; existing components, specs | Modified; within demonstrated norms | All but one resource obtainable from at least one source |
| C | Process passed acceptance; approved for limited operation | Design required; beyond present specs | New combination of demonstrated processes | All but two resources obtainable from at least one source |
| D | Process passed qualification tests | Some development effort required | Demonstrated, but one key attribute new | More than two resources obtainable from at lest one source |
| E | Process passed performance tests/in qualification testing | Moderate development effort required | Demonstrated, but two or more new attributes | Only one resource obtainable from at least one source |
| F | Process feasibility demonstrated | Major development effort required | New process; within state of the art | Resources have been specified |
| G | Prototype system tested; significant scientific research required | "Breakthrough" development effort required | New process; exceeds state of the art | Resources have not been specified |

[A] Resource include tools/futures, test equipment, personnel, materials, and facilities.

Table 5. Definitions of Maturity Sub Factors (From: Johns Hopkins APL Technical Digest, volume 21, number 3 (2000), Evaluating Affordability Initiatives)

## E. SUMMARY

This chapter highlighted the features of the related research. The technology-development phase reflecting the technology discovery processes, addresses technology risk and stage of development needed to satisfy the user requirements. GAO methodology also suggests the three points in time at which to judge technology maturity, and these judgments play a significant role in judging the technological risk in the weapons-acquisition program.

- First, estimate the technology maturity from the development start to design review and production. The technology readiness levels originally developed by the National Aeronautics and Space Administration may be used as criteria.
- The second technology part, design stability, will be estimated by the releasable design drawings at the critical design review. Releasable design drawings mean the completed engineering drawings, which can be released to the manufacturing stage.
- The third, and last, technology part, production maturity, means that critical manufacturing processes are under control of statistical process and the Process Capability Index is used to quantify the statistical process of the product.

The manufacturing and product reliability knowledge of the GAO report shows the ideal decision process to meet the schedule, budget limitation, and user's requirements concerning all weapon acquisition program. Yet there are different approaches to determining the level of technology maturity by examining the affordability of weapons-system development. There is also some criticism about GAO methodology. Even though GAO methodology could be used with the knowledge-based approach, Department of Defense disagrees with GAO's March 05 assessment of JSF technical maturity as stated in GAO reports GAO-05-271 and GAO-05-301. Although the knowledge points provide excellent indicators of potential risks, they do not by themselves cover all elements of risk that a program encounters during development, such as funding instability. Our detailed reviews on individual systems normally provide for a fuller treatment of risk elements.[27]

27 GAO 05-301, Assessments of Selected Major Weapon Programs, p. 132.

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# III. IMPLEMENTATION AND APPLICATION

## A. TRL ASSESSMENT

### 1. Technology Assessment

Tardy arrival of key technologies can significantly delay the development of a weapon system. Testing delays and cost increases in the F-22 program, for example, can be partly traced to inadequate maturity of Avionics, as measured by TRLs. To prevent a similar outcome in the ROKAF T-50 program, program data has been examined and GAO knowledge sets applied, and the resulting assessment will be compared against the US program. Because judging TRLs may be difficult at best, gathering up-to date information about the program as a whole is critical. We requested such data from program managers and made use of confidential TRL data provided to NPS about the U.S. program. Institute reports on the T-50 will rate the program according to a nine-level technology-maturity scale, estimating thirteen critical issues and 649 technological elements and applying GAO standards, by which "a technology readiness level of 7-demonstration of a technology in an operational environment - is the level of technology maturity that constitutes a low risk of starting a product development program,"[28] to TRL findings. The following TRL of B-2RMP, F-22 and Predator were derived by mapping the descriptions of technologies from GAO reports. These mappings represent the author's own views. They are not meant to be an endorsement of any official views and others may view the matter differently. The others are the reliable data from program manager and reports. The assessment of T-50 TRLs comes from "Analytic evaluation on technology acquisition of T-50 program" and is described in part 2 of this chapter.

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28 GAO 05-301, Assessments of Selected Major Weapon Programs, p. 130.

| Aircraft | Development | Design review | Production | criteria |
|---|---|---|---|---|
| B-2 RMP | 6.5 | 9 | 9 | 7 |
| C-130 AMP | 7.7 | 7.7 | 8.5 | 7 |
| C-5 AMP | 9 | 9 | 9 | 7 |
| C-5 RERP | 8.1 | 8.1 | 8.1 | 7 |
| F-22 | 4 | 4 | 4 | 7 |
| Global Hawk | 5.8 | 5.8 | 5.8 | 7 |
| JSF | 4.9 | 4.9 | 4.9 | 7 |
| JUCAS | 3.7 | 4.7 | 4.7 | 7 |
| Predator | 6.8 | 6.8 | 6.8 | 7 |
| V-22 | 8 | 8 | 9 | 7 |
| T-50 | 6.3 | 6.3 | 6.3 | 7 |

Table 6. TRL Assessment

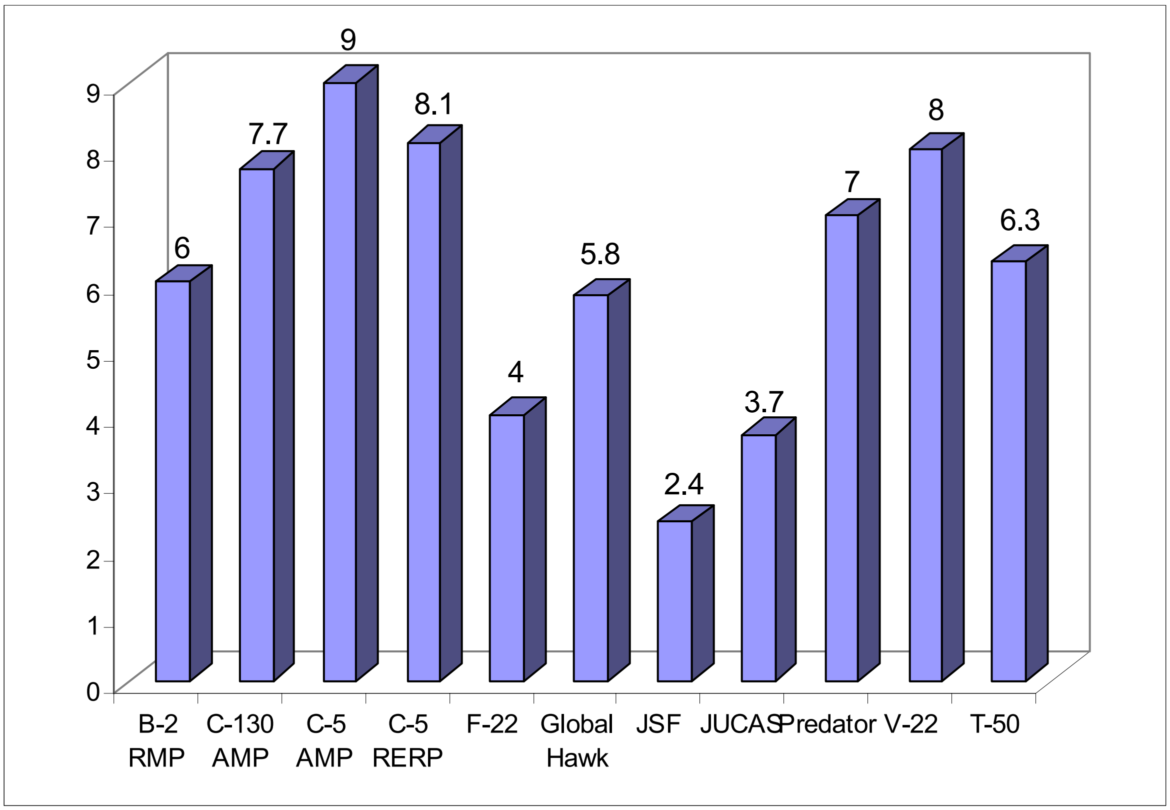


Figure 5. Development TRL

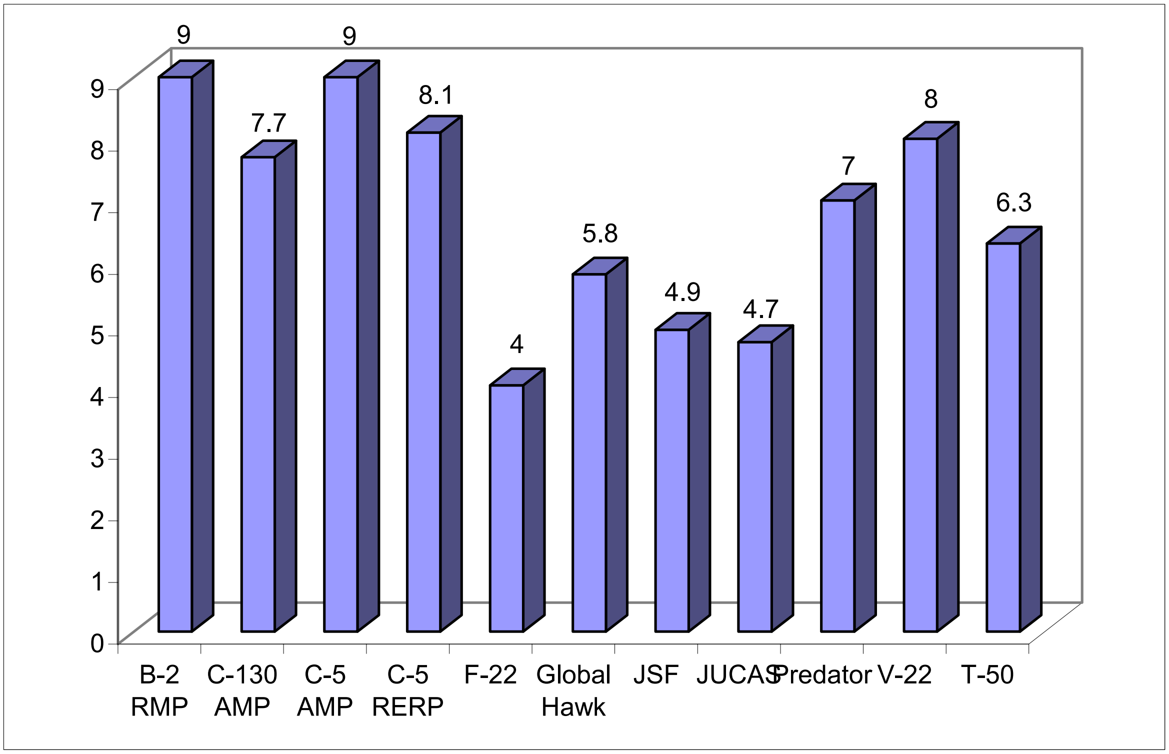


Figure 6. Design Review TRL

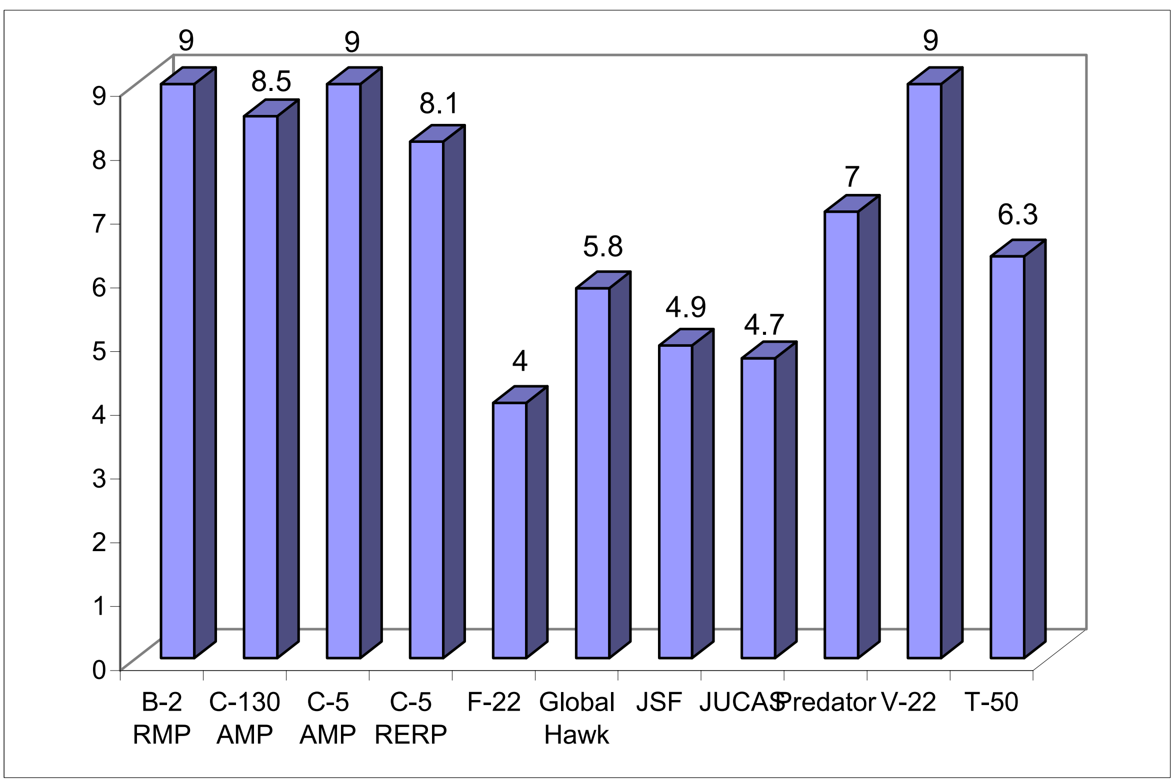


Figure 7. Production TRL

### 2. Technology Uncertainty

Program managers of weapon acquisition try to judge the level program risk by using TRLs. Sometimes, in the rapidly growing technology environment, a low level of technology in the beginning of the development phase will be sufficient to achieve the desired TRL in the design review and production phases. The difficult aspect of using this methodology in this environment is the challenge of estimation future TRL. “The higher the level of technological advancement, the higher the level of opportunity costs for a successful decision. Greater technological complexity implies a greater degree of uncertainty or ambiguity for the key decision maker”[29] In this respect, the US programs also have to accommodate uncertainty in forecasting reasonable, future values of TRLs.

The data given by US program managers also shows the difficulty of estimating the TRL in the design review and production period. The same challenge is true in the case of T-50 program. There is some literature which provides a method for estimation future values of TRLs. For forecasting the maturation of technology through TRLs, we reviewed the report by Kirby and Mavris. Unfortunately, this paper applies only to TRL 1~5, which is below the range of interest in this thesis. Still, the conclusions of this report are of interest.

> This paper described research in the area of probabilistic technology assessments and techniques to forecast the impact of any emerging technology in the conceptual and preliminary phases of aircraft design. The thrusts of the techniques developed were focused on the description of technology development programs, and the various milestones encountered during a successful program. The identification of sources of uncertainty associated with an immature technology were described and applied to the determination of frequency distributions of a technology’s impact on an aerospace system.[30]
>
> Two broad categories of forecasting exist: exploratory and normative. Exploratory forecasting techniques consider historical trends and extrapolate into the future to see what may happen. The

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29 A Methodology for Assessing Acquisition Technical Risk, Harrison, William, Gerald, Jr., p. 62.

30 Forecasting Technology Uncertainty in Preliminary Aircraft Design, Michelle R. Kirby and Dimitri N. Mavris, p. 11.

> feasibility of this process depends upon an assumption that progress is evolutionary and does follow a regular pattern. The normative method begins with future goals and works backward to identify the levels of performance needed to obtain the desired goals, if at all achievable with the resources available. Either perspective utilizes one, or combinations, of four traditional forecasting techniques: S-curves, trend extrapolation, the Delphi method, or scenario development. The first two techniques assume a functional form of previous technological growth and extrapolate to a future time. Again, sufficient information must exist for the forecast to be accurate and of value to the decision-maker. The Delphi method is a structured means of incorporating expert opinions (usually subjective) through questionnaires and controlled feedback to estimate a technology impact and the confidence of achieving that impact.[31]

It is also true in the case of US programs that, as in the Kirby and Mavris report, that TRL data is often derived subjectively, relying on the subject matter expert opinion of program managers, using a method like the Delphi method.

### 3. Accuracy OF T-50 TRL Assessment

Based on the report, “Analytic evaluation on technology acquisition of T-50 program” published by the Seoul University Aerodynamic Institute, the T-50 program has 13 critical technology parts. This report lists these critical technology parts, and it provides some conclusions.

- Eight parts (Aerodynamic, Structure, Detail System, Test and Evaluation, Cockpit, Design of Shape, Summary of System, Training System) have made fairly good progress and could achieve the expected goal until the time of weapon research and development
- Four parts (Avionics, Prototype Manufacturing, Flight control, Thrust system) have not enough technology and especially avionic parts need continuing effort because it has a little chance of achieving the goal. Even though flight control part does not make good progress, the ongoing effort will achieve the goal.
- Supply and support system does not have enough technology because of a late start.

31 Forecasting Technology Uncertainty in Preliminary Aircraft Design, Michelle R. Kirby and Dimitri N. Mavris, p. 4.

| Number | Part | Significance(%) | TRL | Achieved Level |
|---|---|---|---|---|
| 1 | Aerodynamic | 8 | **7.9** | 88% |
| 2 | Structure | 8 | **7.5** | 83% |
| 3 | Flight Control | 18 | **4.9** | 54% |
| 4 | Avionics | 15 | **4.8** | 53% |
| 5 | Detail System | 5 | **6.9** | 77% |
| 6 | Prototype Manufacturing | 5 | **7.1** | 79% |
| 7 | Test and Evaluation | 8 | **6.9** | 77% |
| 8 | Cockpit | 5 | **6.0** | 67% |
| 9 | Thrust System | 5 | **6.0** | 67% |
| 10 | Design of Shape | 5 | **8.6** | 96% |
| 11 | Summary of System | 8 | **7.6** | 84% |
| 12 | Supply and Support System | 5 | **5.7** | 63% |
| 13 | Training System | 5 | **6.7** | 74% |
| | **Summary** | **100** | **6.3** | **70%** |

Table 7. T-50 TRL Assessment

### 4. US Program TRL Assessment

- B-2 RMP: the program reported having two critical technologies, but a formal technology readiness assessment conducted in February 2004 concluded that two additional technologies should be considered critical. The additional two technologies, the receiver/exciter for the electronic driver cards and aspects of the antenna designed to help keep the B-2's radar signature low, are not considered fully mature but are approaching maturity.[32]
- C-130 AMP: Five of the C-130 AMP's six critical technologies are fully mature, as the program is primarily utilizing proven commercial and modified off-the-shelf technology for all AMP capabilities. The remaining critical technology, the Terrain Following and Terrain Avoidance (TF/TA) capability, was demonstrated through the Air Force Research Lab's Quiet Knight advanced technology demonstration.[33] The program manager estimate that the technologies that make up the Improved TF/TA System were assessed as having a TRL of 6 at the time they were transitioned from AFRL.

32 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 32.

33 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 34.

- C-5AMP: we did not assess the C-5 AMP's critical technologies because the program used commercial technologies that are considered mature. Program officials stated that those technologies are in used on other aircraft.[34]
- C-5 RERP: The program manager estimate the TRL of 11 critical technologies (Auxiliary Power Unit (APU), Engine hardware, Engine software, Electrical Power System, Elevator Variable Feel Unit, Flight Controls System, Hydraulic Suction Boost Pump, Integrated Diagnostic System, Nacelle/Thrust Reverser, Pylon, Wing-to-Pylon Attachment Fitting) of the program.
- F-22: The F/A-22 did not have mature technology at the start of the acquisition program. The program included new low-observable (stealth) materials, integrated avionics, and propulsion technology that were not mature at this time. The Air Force did not complete an evaluation of stealth technology on a full-scale model of the aircraft until several years into development. It was not until September 2000, or 9 years into development, that the integrated avionics reached a maturity level acceptable to begin product development. During development, the integrated avionics was a source of schedule delays and cost growth.[35]
- Global Hawk: The program manager estimate the TRL of 11 critical technologies (Air Vehicle & Engine, Communications/Information Exchange, Enhanced Electro-optical/Infrared Sensors, Enhanced Synthetic Aperture Radar, Global Air Traffic Management, Lithium Batteries, Multiple Platform - Radar Technology Insertion Program, Open System Architecture, Signal Intelligence Phase 1, 2, and 3)
- JSF: GAO/NSIAD -00-74 “joint strike fighter acquisition” report the eight key technology levels at the start of development.
- JUCAS: The program manager estimate the TRL of six critical technologies(Signature Reduction Technologies, Advanced Tactical Targeting Technologies, Secure Robust Communications, Force Integration, Interoperability, and Global Information Grid (GIG) Compatibility, Adaptive Autonomous Operations, Operations in Carrier Controlled Airspace)
- Predator: Three of the predator B's four critical technologies, the synthetic aperture radar, the multispectral targeting system, and the air vehicle, are fully mature.[36]

34 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 36.

35 GAO-03-645T, Best Practice, p. 11.

36 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 102.

- V-22 : The program manager estimated that the results of testing the MV-22 Block A under the expected range of environmental conditions in which it is expected to operate was successfully completed. Assessment of whether it will meet its operational requirements was made. Problems were identified and corrective plans were developed and are being implemented to insure a successful Operational Evaluation

**5. Analysis of the TRL**

Our best estimate of TRL at the program development stage is based upon input from the program manager. We have some data that indicates TRL growth form stage-to-stage. From these data, we have observed the following

- The growth rate from development to design review stage is 27%.
- The growth rate the one from design to development stage is 12%.

These growth rates imply that in order to achieve the GAO benchmark of TRL 7 at the production decision stage, it is sufficient to achieve a TRL of at least 5 at the development phase. Based on this fact, we provide the following forecasts:

- JUCAS, JSF, and F-22 programs may not achieve a desirable TRL level at the production stage.
- T-50, program having TRL 6.3 at the development stage, will achieve the goal of TRL 7.

**6. Summary**

GAO and program manager assessed the TRL on 10 US major weapon acquisition programs. Each of these 10 major weapon acquisition programs has some similarity to the T-50 program.

GAO has stated that a best practice is to have a TRL of 7, and that this level indicates that the program will progress over time without potential cost and schedule growth.

We observed the following facts about JSF and F-22 from our data set

- Each had an immature technology at the development phase.
- Program acquisition unit costs were 116.5% on the F-22, and 26.2% on the JSF, These estimates were made in GAO-05-301.
- Even though GAO recommends, as a best practice, the use of the TRL approach as part of the program management for a major

weapons system acquisition, some programs proceeded without achieving these levels or doing this analysis. That is, these programs started without considering the TRL of the key technologies, and therefore failed to lay the basis for reducing cost increases and schedule delays.

On the other hand, DoD does not always agree with the GAO reports, GAO 05-271 and GAO 05-301. An example of this is the assessment of JSF technology maturity. Furthermore, US programs do not always follow the GAO guidance. Development decisions for three programs, F-22, JSF, and JUCAS were made without achieving the sufficient TRLs of the key technologies.

In a comparison between the US programs and the T-50 program, we see that the T-50 also started without fully matured TRL. Of course, TRL can be developed with the same step of the technical development in science. Some weapon development program needs their specific technology part, which have little chance of being developed in science. With the anticipation of the TRL growth rate, we could estimate that the T-50 program starting with TRL 6.3 is going to achieve the GAO benchmark of TRL 7.

## B. DESIGN DRAWINGS

### 1. T-50 Design Release Status

As integral parts of decreasing the risk of cost increases prior to production, the T-50 program implemented two processes: Concurrent Engineering (CE) and Computer Aided Design (CAD)

- **Computer Aided Design (CAD):** T-50 is designed 100% using CAD software. Specifically, T-50 was designed using Computer Aided Three-dimensional Interactive Application (CATIA), which is often used as a design tool in the aerospace industries, and plays a major role in making design drawings, and which had to be made prior to the manufacturing. “Although CATIA is a robust design tool, it did not satisfy all LMTAS integrated product development (IPD) needs. Lockheed Martin Tactical Aircraft Systems (LMTAS) integrates several design tools to serve company-specific needs. For example, LMTAS selected Computer-Aided Three-Dimensional Interface Applications (CATIA) (a solid modeling package) as the core design software. LMTAS has identified several specific design functions not available with commercial software and has chosen to customize or build software to serve these specific needs. Computer Mock-up (COMOK) provides an example of enhancing commercially available CATIA software to satisfy LMTAS specific needs. The dynamic sharing of design iterations enables concurrent, IPD. The COMOK database management system is the technology that provides centralized access to multiple configurations defined geometrically by CATIA solid models. As new programs are initiated, COMOK is used in place of metal mock-ups. Since it is available at the start of the design process, it improves design integration and quality."[37].

- **Concurrent Engineering (CE) :**In addition to the use of CATIA, T-50 used the concept of Concurrent Engineering that is "a business strategy which replaces the traditional product development process with one in which tasks are done in parallel and there is an early consideration for every aspect of a product's development process. This strategy focuses on the optimization and distribution of a firm's resources in the design and development process to ensure effective and efficient product development process."[38]

For the T-50 program, Table 8 provides design release status while Figure 8 shows the percentage of drawings released over time while using the CATIA and CE processes on the process of engineering drawings.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1999 | - | - | - | - | - | - | - | - | 9 | 4 | 67 | 170 | 250 |
| 2000 | 316 | 489 | 750 | 974 | 1504 | 2,513 | 1,443 | 934 | 931 | 893 | 654 | 639 | 12,040 |
| Total | | | | | | | | | | | | | 12,290 |

Table 8. T-50 Design Drawing Release

37 Best Manufacturing Practices, http://www.bmpcoe.org/bestpractices/internal/lmtas/lmtas_3.html (accessed November 29, 2005)

38 Concurrent Engineering, http://best.me.berkeley.edu/~pps/pps/concurrent.html#what (accessed November 29, 2005)

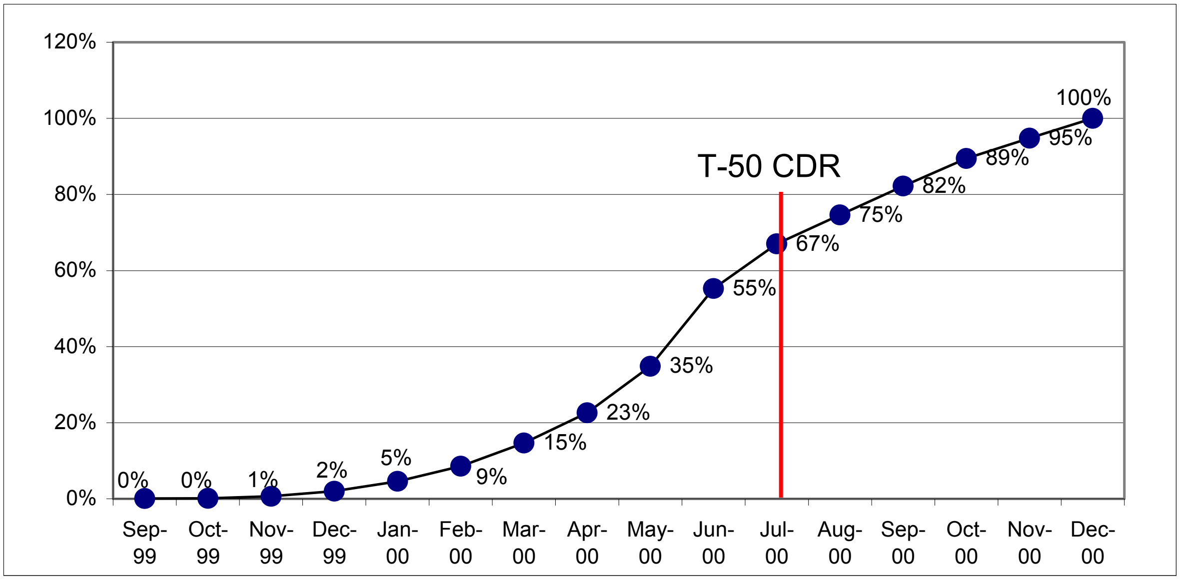


Figure 8. Percentage of Drawings Released

### 2. US Program Design Release Status

- B-2 RMP: The program has completed and released 71 percent of its engineering drawings to manufacturing. The program office has scheduled the design readiness review for June 2005 and plans to have 85 to 95 percent of its drawings released by that time.[39]
- C-130 AMP: The program office has made progress toward meeting its goal of releasing 90 percent of the design drawings by design readiness review, scheduled for August 2005. This will be nine months sooner than anticipated last year, due to the acceleration of key program dates to meet Special Operations Command requirements. Currently, 48 percent of the design drawings are complete and could be released to manufacturing.[40]
- C-5AMP: The design appears stable as the contractor has released 100 percent of the drawings for the AMP.[41]
- C-5 RERP: The program manager estimate C-5 RERP's design is stable. 3,250 out of total 3,300 were completed before the December 2003 at Critical Design Review.
- F-22 : The F/A-22 design is essentially complete, but it matured slowly, taking over three years beyond the critical design review to meet best practice standards. The late drawing release contributed

39 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 32.

40 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 34.

41 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 36.

to parts shortages, work performed out of sequence, delayed flight testing and increased costs. Design changes resulted from flight and structural tests.[42]

- Global Hawk: The program manager defined that 1,650 out of total 1,800 were completed at the April 2004 Critical Design Review.
- JSF: The program estimates 35 percent of the engineering drawing packages are expected to be released at the critical design review. Also, prototype testing will not be done prior to the design review. The design will not be stable until after production begins.[43]
- JUCAS: The program manager defined that 2,400 out of total 2,800 were completed at the September 2005 Critical Design Review.
- Predator: The program office expects 94 percent of the expected increment one drawings to be completed by the April 2006 critical design review, which has been delayed about seven months. Program officials acknowledge that additional drawings will be needed for subsequent increments.[44]
- V-22: The program manager defined that 7,230 out of total 7,490 were completed at the September 2002 Critical Design Review.

Figure 9 shows the percentage of releasable design drawings on the US programs based on the GAO report and input from program managers, before CDR.

42 GAO-02-701, Best Practices, p. 25.

43 GAO-05-271, Joint Strike Fighter Acquisition, p. 17.

44 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 101.

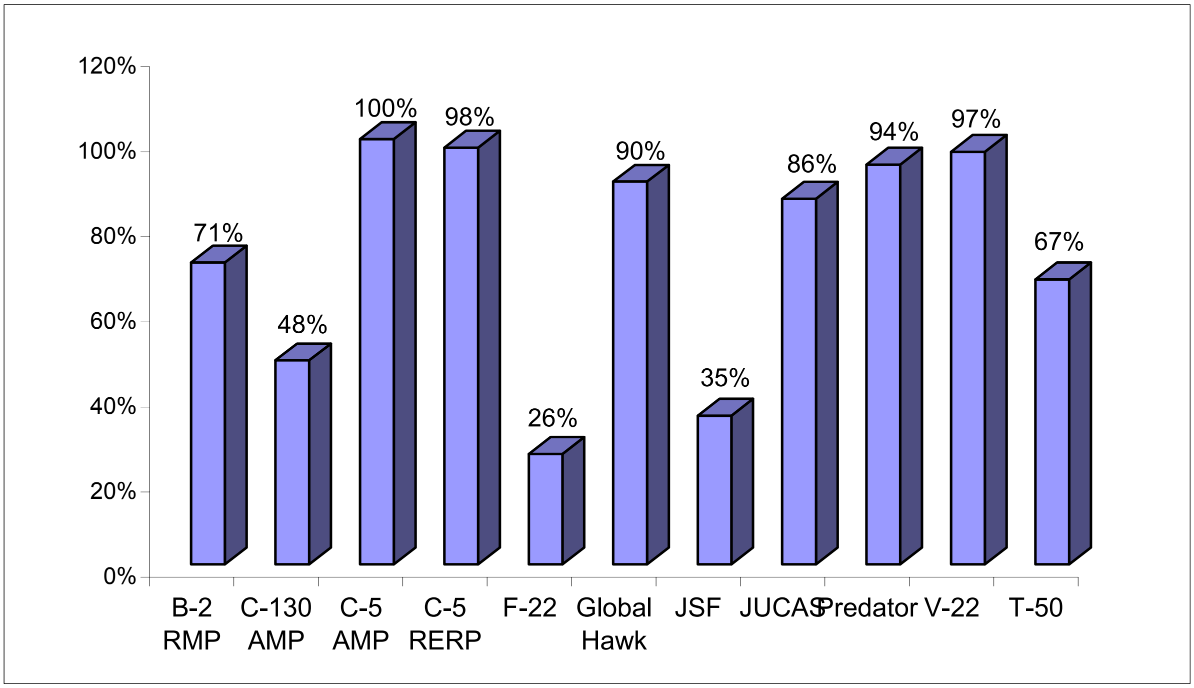


Figure 9. Releasable Drawings before CDR of US programs

### 3. Proportion of Drawings Released at CDR

To examine design stability, we reviewed the time schedule for transitioning the engineering drawings from the engineering side of the house to the manufacturing side of the house. There is a natural need to demonstrate, before beginning initial manufacturing, that the design of the product meets the stated requirements of the weapons acquisition program. To determine the design stability, and to judge whether the product is ready for the next phase of development, CDR begins to review the product from the perspective of the product's component, then continues its review at the subsystem level, and, finally, at the integrated, system level.

GAO's best practice benchmark for design stability requires at least 90% of the engineering drawings to be completed prior to Critical Design Review (CDR). The time schedule for giving the engineering drawing from engineering to manufacturing is used to examine design stability, and we developed and analyzed, as a measure of effectiveness, the percent achievement of the number of design drawings which are releasable to the manufacturing of each program.

The data of C-5RERP, Global Hawk, JUCAS(X-47), V-22 and T-50 were estimated and provided by each program manager. On the other hand, data for the other programs are based on the GAO report, which had already collected and judged the achievement. The GAO report also shows the achievement before CDR of the B-2RMP and C-130AMP programs. The Global Hawk program manager also provided the specific drawing data at the start of the program. The column of the expected value represents the expected achievement from the program start to the CDR.

The table below displays the data we have developed on engineering drawings.

| **Aircraft** | **Achievement before CDR(%)** | **Releasable drawings at CDR(%)** | **Expectation** | **Criteria (90%)** |
|---|---|---|---|---|
| B-2 RMP | 0.71 | **0.90** | 0.19 | 0.9 |
| C-130 AMP | 0.48 | **0.90** | 0.42 | 0.9 |
| C-5 AMP | - | **1.00** | - | 0.9 |
| C-5 RERP | - | **0.98** | - | 0.9 |
| F-22 | - | **0.26** | - | 0.9 |
| Global Hawk | 0.90 | **0.92** | 0.02 | 0.9 |
| JSF | - | **0.35** | - | 0.9 |
| JUCAS | - | **0.86** | - | 0.9 |
| Predator | - | **0.94** | - | 0.9 |
| V-22 | - | **0.97** | - | 0.9 |
| T-50 | - | **0.67** | - | 0.9 |

Table 9. Design Drawing Release Status

The following Figures 10 and 11 illustrate that the Matured Key technologies make the design stability keep going well during the weapon acquisition process. The seven programs, B-2 RMP, C-130 AMP, C-5 AMP, C-5 RERP, Global Hawk, Predator, and V-22, which have at least five at the development phase, have a satisfactory level of design drawings at CDR. Even if six critical technologies of the JUCAS were not matured at the development phase, the achievement of design drawing is ready to enter the stability level. The releasable drawings of T-

50 program at CDR is not at a sufficient level to assure design stability, even though it starts with TRL above 5. Two programs having the lower TRL achievement at development phase also show the lower achievement of design stability.

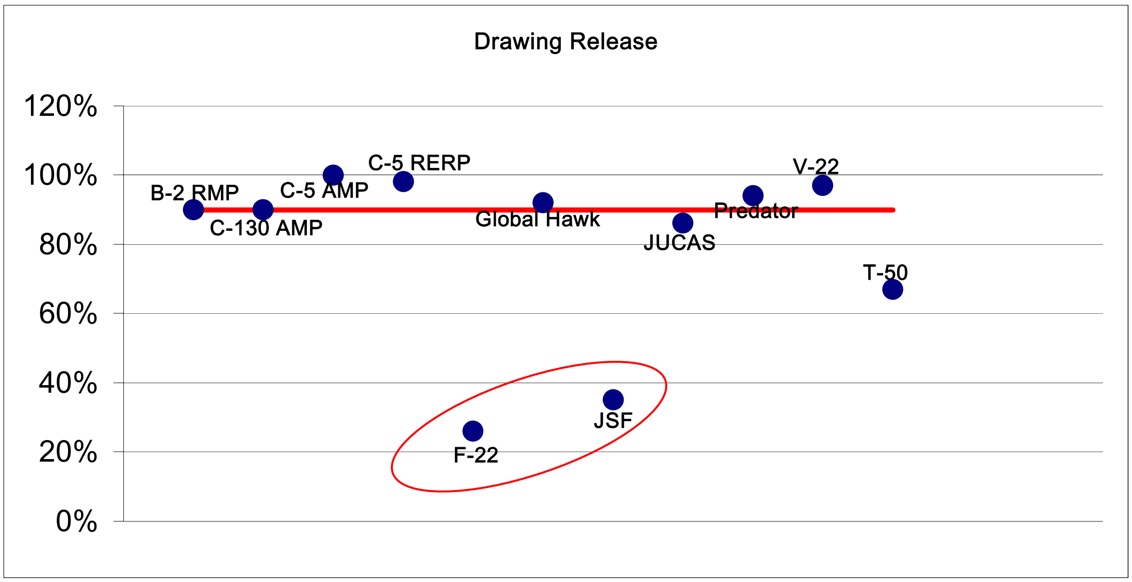


Figure 10. Design Drawing Release versus Criteria

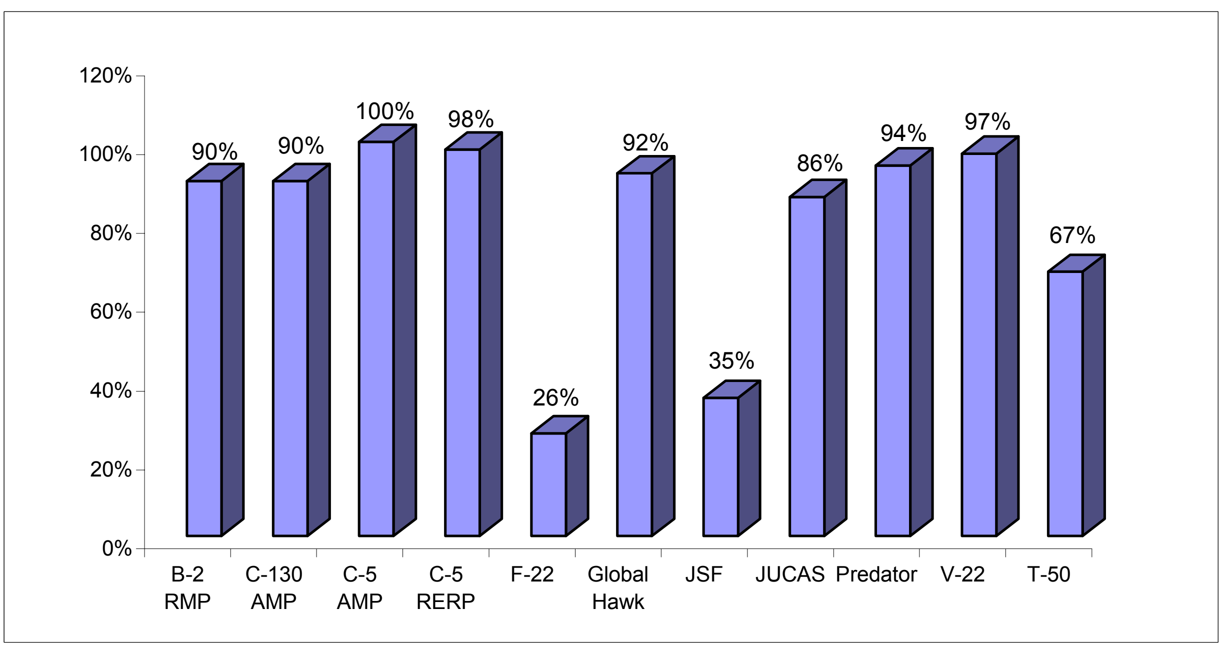


Figure 11. CDR Drawings / Total Drawings

The following figure shows the expectation of the design drawings from development to the time of CDR. As we see, the data of only three programs, B-2RMP, C-130AMP and Global Hawk, are available to represent, because each program is not managed and monitored by each program manager according to the time phase.

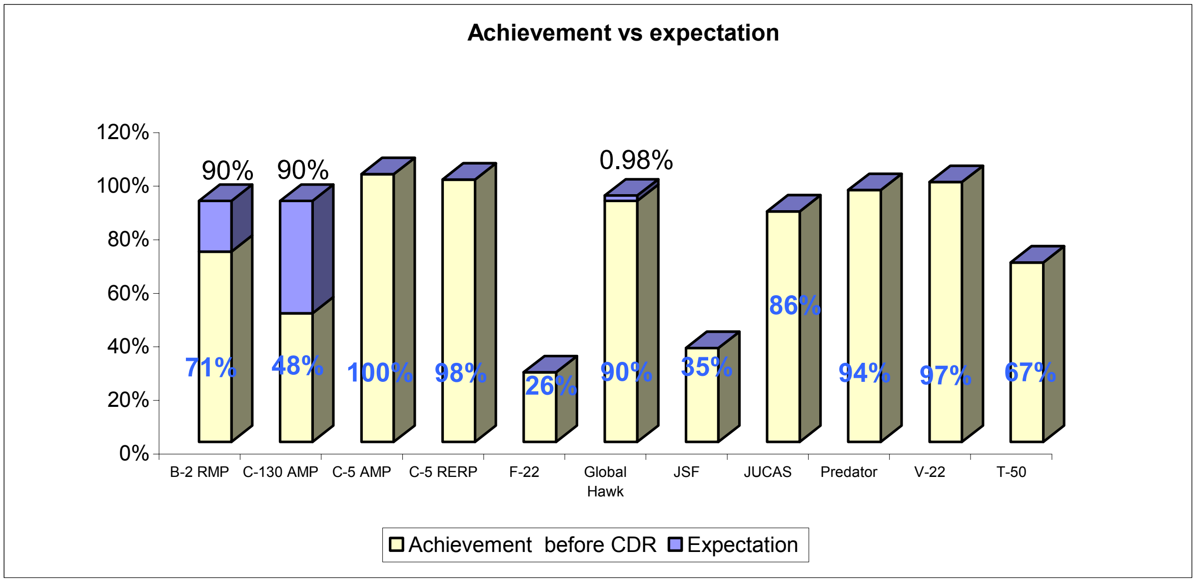


Figure 12. Achievement versus Expectation

### 4. R&D Cost versus Number of Drawings

The R&D cost for five programs except T-50 is on the basis of GAO report and R&D cost of the T-50 is from the published book for the advertisement of T-50. We can obtain the ratio of the number of drawings from the Critical Design Review (CDR) for all programs which we have analyzed, but obtaining the exact data on the number of drawings is hard to get even from the program managers. The number of drawings of each program in the table below comes from the program managers. To judge the relation between the R&D cost and number of drawings, we divided the R&D cost by the number of drawings and tried to find some results. All R&D costs are normalized to the FY2005. A five percent inflation rate is used to normalize the T-50 weapon development program. The table below display the R&D cost versus the number of drawings.

| Program | R&D cost | # of drawings | R&D/# of drawings |
|---|---|---|---|
| C-5 RERP | $1,537.4 | 3300 | 0.47 |
| Global Hawk | $2,528.9 | 1800 | 1.40 |
| V-22 | $10,723.7 | 7490 | 1.43 |
| T-50 | $2,790 | 12290 | 0.20 |
| JUCAS | $4,042.0 | 2800 | 1.44 |

■ ( FY05 dollars in millions)

Table 10. R&D Cost Data

It is analytically pleasing when three numbers are almost the same, as is the case for Global Hawk, JUCAS and V-22. It seems that $1.4 M is some sort of constant for new aircraft. We do not know what causes this constancy but perhaps it can be a topic for further research. T-50, which does not fit the pattern, is a tactical aircraft, whereas Global hawk and JUCAS are Unmanned Air Vehicle's (UAV)

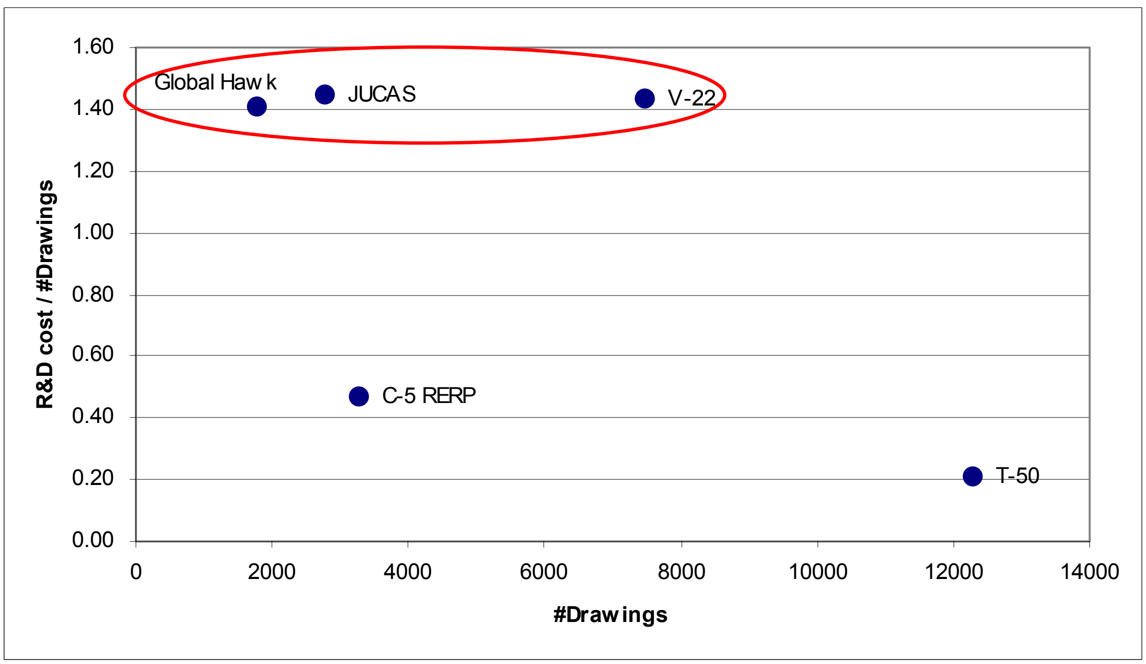


Figure 13. R&D Cost/# of Drawings versus # of Drawings

### 5. Regression on the Engineering Drawings

The figure below shows the regression line on the percent achievement of releasable design drawings at CDR versus R&D cost.

- Unmanned programs, Predator, Global hawk and Jucas, have a linear relationship along the R&D cost. These programs are identified with circles in Figure 14.
- Advancing program, C-5AMP, C-5RERP, C-130AMP and B-2RMP, have a big variation of achievement of releasable design drawings depending on each program. These programs are identified with a square in Figure 14.
- V-22 also arrived high level of drawing achievement as other advancing programs even though it has higher R&D costs than other advancing programs.
- The new and advanced program, F-22 and JSF with substantial R&D costs arrived a lower level of CDR achievement. These programs are identified with triangles in Figure 14.
- T-50 program, which is a new program, has better level than F-22 and JSF, but a low achievement when we considered the low R&D cost programs.

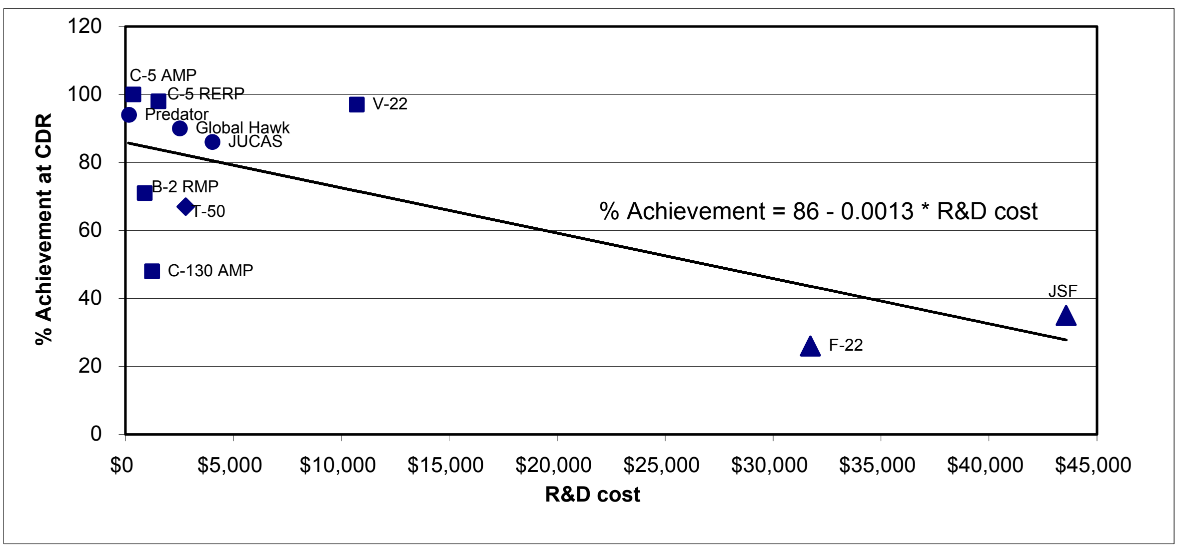


Figure 14. Percentage Achievement at CDR versus R&D Cost

Figure 13 represents the percent achievement of design drawings at CDR versus number of design drawings of the five programs. Our efforts to find the exact number of design drawings had trouble in judging whether the program manager had updated the number of each program during the whole development period. Therefore, we can obtain only reliable number of design drawings on the five programs, Global Hawk, JUCAS, C-5RERP, v-22 and T-50.

- The only regression analysis on the manned programs, C-5RERP, V-22 and T-50 result in a difficulty of finding the relationship between percent achievement and number of drawings due to the little data information.
- This regression trend shows that the uncomplicated programs (that is, those having fewer design drawings) arrived at a more satisfactory level of releasable design drawings than the programs having more design drawings.
- T-50 has more design drawings than advanced program and unmanned program. Its achievement of design drawing, 67 percent, at CDR is below the regression line. If the T-50 also achieved the about 90 percent of drawings at CDR, the regression line would be the flat line and will have very little slope of regression line.

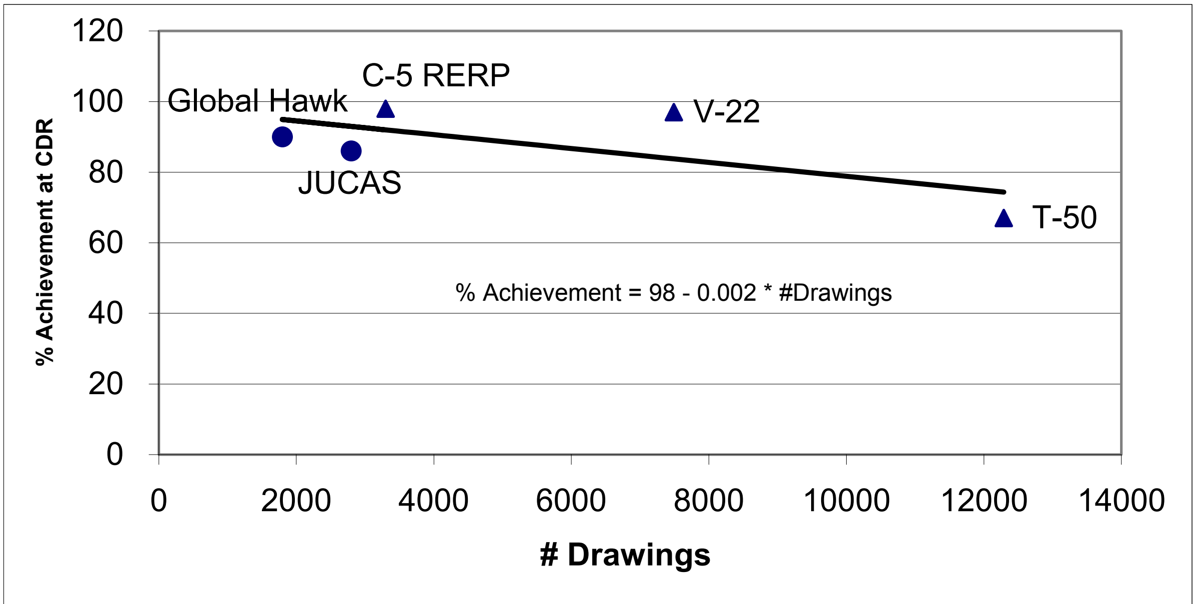


Figure 15. Percentage Achievement at CDR versus # Drawings

### 6. Summary

The US GAO had set the benchmark that the achievement of engineering drawing stability requires at least 90 percent of engineering drawings to be releasable by CDR. We observed the following from our dataset:

- Even thought this benchmark gives good guidance by which to judge the design stability of a major weapon acquisition program, some programs do not follow the GAO guidance
- The seven programs, B-2 RMP, C-130 AMP, C-5 AMP, C-5 RERP, Global Hawk, Predator, and V-22, which have achieved a TRL score of at least 5 at the development phase, also meet or exceed GAO's 90 percent engineering drawing benchmark.
- Even if six critical technologies of the JUCAS are not matured at the development phase, the program has achieved the design drawing benchmark and is stable on this dimension.
- Two programs, F-22 and JSF, having the lower TRL achievement at development phase also show the lower achievement of design stability.
- The percent of achievement is correlated with program complexity, where complexity is either research and development cost or number of design drawings.

The relationship between the achievement of releasable design drawings and level of R&D cost shows the following:

- Unmanned programs, Predator, Global hawk and JUCAS, have a linear relationship along the R&D cost.
- Advancing program, C-5AMP, C-5RERP, C-130AMP and B-2RMP, have a big variation of achievement of releasable design drawings depending on each program
- V-22 also arrived high level of drawing achievement as other advancing programs even though it has high R&D cost than other advancing programs.
- The new and advanced program, F-22 and JSF, having a very high R&D achieved a lower level of CDR achievement.

We investigated the relationship between the achievement of releasable design drawings and the number of design drawings for the five programs for which we have data. The observations are:

- The only regression analysis on the three data points which represent manned programs, C-5RERP, V-22 and T-50, has poor statistics and we concluded that it is difficult to find a linear relationship between percent achievement and number of drawings. This is probably due to the little data information available to us. This regression shows that the less complicated programs having fewer design drawings achieved a satisfactory level of releasable design drawings than the programs having many number of design drawings.

We considered the T-50 program with the following observations:

- T-50 TRLs are above 5
- T-50 achived releasable design drawings of 67 percent at CDR, which is below GAO guidance, so that T-50 is at risk for not showing design stability.

T-50 has more design drawings than advanced program and unmanned program among five programs

## C. PRODUCTION

### 1. T-50 SPC Process Plan

This paragraph describes the T-50 SPC plan during the Full Scale Development and Production period and is translated from the T-50 SPC plan.

#### *a. Definition of SPC of T-50 Program*

Statistical Process Control (SPC) is a prevention focused process management method that is used to identify sources of malfunctions that are occurred by inherent variances, materials, workers, management methods, measuring methods and working environment, through quality characteristic analyses which separate, measure and quantify causes of malfunctions through statistical methods.

#### *b. Measuring, Analyzing and Improving Process*

SPC plans monitoring, measuring, analyzing and continuous improvement process and execute them for relevant events as follows:

- Verification of product suitability
- Ensuring suitability of quality management systems, and
- Continuous improvements of effectiveness of quality management systems. Monitoring, measuring, analyzing and continuous improvement process also include decision making process on methods and a level of implement of SPC.

#### c. *Statistical Method*

By implementing statistical methods, we can ensure continuous and stable quality of products. This is achieved through forecasting potential problems and then devising countermeasures to prevent these forecasted problems.

- Analyze collected data through statistical method and manage factors that affect product quality.
- A whole inspection of product is a general rule. However, when implementing a sample inspection, it is require to establish a sample inspection plan and get the plan approved by the government.
- During prototype production, SPC is implemented as a data collecting stage. Upon full scale production, KC's will be identified for fully implementing SPC.

### 2. T-50 Statistical Process Control

We reviewed information from the T-50 program, which is at the beginning of the full-scale production phase. T-50 prototype production was performed without fully developed statistical control. Below is information about the T-50 Statistical Process Control (SPC).

- SPC (Statistical Process Control), during the stage of Full Scale Development (FSD), was defined as a phase of data collection that is necessary to identify Key Characteristics (KC's) for the mass production.
- SPC should be fully implemented upon identifying KC's during mass production. However, according to one of our assembly engineers, there has not been an instance where SPC had been implemented directly for each component of T-50 model.
- However, there have been a number of cases where SPC had been implemented to improve the production process electronically. (i.e., reducing 'lead time' through process improvement)

### 3. US Program Production Knowledge

The third dimension of GAO's knowledge-based approach to evaluating weapons-systems acquisition is Statistical Process Quality Control (SPQC). We examined each aspect of our programs and found, surprisingly, that most programs are not doing this. The following table[45] displays the results.

| Programs | Description |
|---|---|
| **B-2 RMP** | "Production maturity metrics are planned to be formulated during development. These metrics, which may or may not include manufacturing process control data, are planned to be used as measures of progress toward production maturity during a production readiness review prior to the start of production in February 2007". |
| **C-130 AMP** | "Funding reductions in fiscal years 2003 and 2004 delayed the C-130 AMP's development program, which resulted in a rescheduling of program milestones and rebase lining of the program. The design review, low-rate initial production, and production readiness decisions were all delayed. While program officials stated that the delay in schedule would provide more time to resolve issues with the TF/TA technology and software, the delay in fielding was not acceptable to the Special Operations". |
| **C-5 AMP** | "We could not assess the production maturity because most components are readily available as commercial-off-the-shelf items. This equipment is being used on other military and commercial aircraft. In addition, the C-5 AMP is incorporating many other off-the-shelf systems and equipment, such as the embedded global positioning system, the inertial navigation system, and the multifunction control and display units. To ensure production maturity, the program office is collecting data regarding modification kit availability and the installation schedules." |
| **C-5 RERP** | "We did not assess the C-5 RERP's production maturity because the Air Force is buying commercially available items. However, we expect that production maturity would be at a high level because the engines have been commercially available for many years." |
| **F-22** | "The program office stopped collecting process control information in November 2000. The contractor estimated that nearly half of the key processes had reached a marginal level of control, but not up to best practice standards. The Air Force relies on the contractor's quality system to verify manufacturing and performance requirements are being met. However, the Air Force has not demonstrated the F/A-22 can achieve its reliability goal of three hours mean time between maintenance. It does not expect to achieve this goal until 2008 when most of the aircraft will have |

45 GAO 05-301, Assessments of Selected Major Weapon Programs, pp. 32, 34, 36, 38, 64, 68, 80, 102, 118.

| Programs | Description |
|---|---|
| | already been bought. Best practices call for meeting reliability requirements before entering production. As of the current production estimate by approximately mid-October 2004, the Air Force had only demonstrated about 22 percent of the reliability required.” |
| **Global Hawk** | “Although production experience and lessons learned on the RQ-4A will benefit the RQ-4B program, the new model requires different and more complex manufacturing processes and tooling than the original model. Officials have not implemented, and do not plan to implement, a comprehensive statistical process control program to demonstrate that new manufacturing processes are in control and capable of meeting cost, schedule, and quality targets. Officials have started to identify critical manufacturing processes and will continue to collect performance data such as defect and rework rates to measure product quality. There are continuing concerns about the quality and timeliness of several key subcontractors, which negatively affect cost and schedule of both design and production work.” |
| **JSF** | “The program office is collecting information on the JSF production processes. The contractor is currently in the process of identifying the key characteristics, critical manufacturing processes and capturing some early data. At the time of the production decision, the program will not have demonstrated that the aircraft can be produced efficiently or with expected reliability.” |
| **JUCAS** | “The J-UCAS program began in October 2003 with technologies that officials project will sufficiently mature to support a possible 2010 start of operational system development, so there is no data for production.” |
| **Predator** | “Program officials said the contractor does not plan to use statistical process controls to ensure product quality. Instead, they plan to use other quality control measures such as scrap, rework, and repair to track product quality. Also, initial operational testing of increment one, which is to demonstrate a product is ready for production, is not scheduled to be complete until September 2007. Testing for remaining increments has not been determined.” |
| **V-22** | “Process management is becoming more robust at the final assembly site on each major fixture assembly using Six Sigma. Program officials point to the delivery of aircraft as an indication of manufacturing maturity.” |

Table 11. US Program Production Knowledge (After: GAO 05-301)

### 4. Summary

The GAO benchmark suggests a standard rule for describing the production maturity and for estimating if the programs are under control during the weapon production phase. As the GAO states it:

> To determine if a product's design is reliable and producible, successful programs use statistical process control to bring manufacturing processes under control so they are repeatable, sustainable, and consistently producing parts within quality standards. The collection of process control data prior to a production decision can enable a smooth transition from product development to the production phase.[46]

One of the frequently heard comments about the difficulty of implementing SPC is the high level of training required of personnel and the high costs of these personnel. Due to the typical shortage and high cost of the personnel needed to perform such tests, we focus only on the critical processes necessary to meet the reliability and performance standards. GAO used the Process Capability Index, which can be used to compute a product defect rate that permits us to assess such critical process and the index is measured the application of statistical control.

When we focus on the critical process, the SPC data needed to judge a program's production maturity depends on the particular program manager. Based on the program manager data and some reports, most programs in our dataset do not follow the GAO's SPQC guidance. As the GAO states: "While the absence of the data does not mean that production processes were immature, it does prevent an assessment against an objective standard."[47] On the other hand, the production decision of some programs will be made later, and some programs have a plan to follow the SPC.

Our conclusions on the programs in our dataset follow.

- C-130AMP, JUCAS, V-22: the programs are under development, so it is too early to judge the SPC.

46 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 12.

47 GAO-05-301, Assessments of Selected Major Weapon Programs, p. 12.

- C-5 AMP, C-5 RERP: production maturity seems assured since many aspects of this program are readily available as commercial-off-the-shelf items.
- B-2 RMP: SPC are planned to be formulated later, as the programs enter their production phase.
- F-22, Global Hawk, JSF, Predator: we can judge that the programs do not follow the GAO guidance
- T-50: prototype production was performed without fully developed statistical control and the program has just entered the full-scale production phase. While SPC should be fully implemented upon identifying Key Characteristic(KC's) during mass production, our information from assembly engineers is that there has not been an instance where SPC has been implemented directly for any component of T-50 prototype model. On the other hand, there have been a number of cases where SPC had been implemented to improve the production time. Looking further into the future, T-50 program has a specific plan to implement SPC during the Full Scale Development and Production period.

# IV. CONCLUSION

## A. SUMMARY

Technology development is the important factor in estimating whether a weapons-development program could meet requirements without schedule delays and cost overruns. Acquisition-program management also relies on the knowledge-based approach in developing new weapon programs and it ensures achievement of key results through high levels of knowledge. To support program management, the US GAO has developed a methodology, which implements three knowledge points.

- Technology maturity

  GAO attempts to find the key technologies, which are measured on a scale of nine levels of technological maturity. Starting a product development with a technology readiness level of seven is a GAO-identified "best practice", and it appears to ensure the satisfactory progress of weapon acquisition programs.

- Design stability

  Successful programs obtain design stability at the time of critical design review (CDR), and CDR results serve as criteria for estimating the stability of engineering drawings released. The benchmark that the US GAO has set is that engineering-drawing stability is achieved if it is true that at least 90 percent of engineering drawings are completed (or at least releasable) before the CDR.

- Controlled production stability

  Products manufactured with statistical process controls in place are better able to govern costs and to stay within schedule than programs that do not have SPC in place. To evaluate such maturity, the components of statistical process control are used and critical manufacturing processes are monitored for statistical data. To measure the performance of the process, a process-capability index (CPK) is used to determine how a process is running compared to its specification limits and to measure production-process capability within specified limits. The CPK index below 1.33 indicates that the manufacturing process lacks statistical control and acceptable consistency.

To monitor and evaluate the programs' maturity and stability, we collected data from some US programs, B-2 RMP, C-130 AMP, C-5 AMP, C-5 RERP, F-22, Global Hawk, JSF, JUCAS, Predator, and V-22, relevant to the aircraft acquisition and advancing program to determine if the acquisition also follow the GAO guidance or not. These data are also compared to the T-50 acquisition program data to estimate if the program would make good progress in the research and development phase.

Interestingly, even though the US GAO had been trying to enhance the military capability and readiness, some acquisition program did not follow the guidance of the GAO. The following table shows the status of whether each program programs in our dataset follows the GAO guidance or not. In this table, we followed the following rules:

- A TRL score above 7 is considered to follow the GAO guidance
- 90 percent achievement of engineering drawings at CDR was considered to follow the GAO guidance.
- The production followed by the SPC is considered to follow the GAO guidance no matter what the CPK is. If some program is under development, we assume that SPQC is not available.

| Programs | TRL | Engineering Drawings | SPQC |
|---|---|---|---|
| B-2 RMP | Yes | Yes | No |
| C-130 AMP | Yes | Yes | N/A |
| C-5 AMP | Yes | Yes | Yes |
| C-5 RERP | Yes | Yes | Yes |
| F-22 | Yes | No | No |
| Global Hawk | No | Yes | No |
| JSF | No | No | No |
| JUCAS | No | No | N/A |
| Predator | No | Yes | No |
| V-22 | Yes | Yes | N/A |
| T-50 | No | No | No |

Table 12. Observance of GAO Benchmarks

This objective of this thesis is to investigate if the GAO knowledge based-methodology could be used in the T-50 program and, if possible, to judge the progress on the base of GAO methodology with the collected data. We can find some conclusions as follows.

- We can find the technical readiness level, releasable design drawings at CDR and Statistical Process Control plan on the T-50 program, so we can judge the T-50 program on the basis of GAO report.
- Since the T-50 program achieved a TRL of 6.3 at the development stage, we believe that the T-50 program will achieve the goal of TRL 7.
- The releasable drawings of T-50 program at CDR is not a sufficient level to ensure design stability, even though it started with a TRL above 5. T-50 has more design drawings than the advanced programs in our dataset as well as more design drawings than the unmanned programs in our dataset. The T-50 program's achievement of design drawing, 67 percent, at CDR is below the "best practice" guidance of the GAO.
- T-50 prototype production had been performed without fully developed statistical control and production is on the beginning phase of mass production. However, there has not been an instance where SPC has been implemented directly for each component of T-50 prototype model. Fortunately, T-50 program have a specific plan of SPC during the Full Scale Development and Production period.

## B. RECOMMENDATIONS FOR FUTURE RESEARCH

During this research, we identified some further research areas.

The first is to forecast the maturation of technology over time on the basis of Kirby and Mavris report describing the impact of emerging technology on the probabilistic technology maturation process. Even though this report focuses on the estimation of low level of technology maturity, if we can obtain the reliable TRL of weapon program, which is developed with TRL above 5 from the development start to production, we can compare the TRL improvement with estimation of the report.

The second is to find the relationship between the number of drawings and research and development cost. We note that the higher number of designing drawings, the higher research and development cost for the programs in our dataset. This topic needs additional data to explore and identify the statistical relationship between two items.

The third is to find the statistical process control data for the entire analysis of the GAO methodology. The environments at which most program managers do not try to follow the GAO guidance make it hard to estimate product stability. Further research should explore the SPC and CPK data. It is possible that full-scale analysis of GAO methodology would also yield good guidance to the new developing weapon acquisition program.

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