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Review and Analysis of GAO Reports on Major Weapon Systems

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by

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Abstract

DoD major weapon systems historically have been over budget, behind schedule, and typically under performing in terms of suitability. The Secretary of Defense proposed a fiscal year (FY) 2010 budget that ended or curtailed all or part of at least a half dozen major defense acquisition programs that were over cost, behind schedule, or no longer suited to meet the warfighters' current needs.

The Government Accountability Office (GAO) publishes a major DoD weapon systems report every March. The GAO spends a considerable amount of time evaluating several dozen major weapon system programs and provides a two-page analysis of the largest defense programs.

This research project examines eight major DOD weapon systems using the yearly published GAO reports from 2003–2011. The purpose of this research is to understand what risk management was being performed on those programs, how it was implemented, when it was implemented, and how effective it was. The desired outcome is to make recommendations on improvements to the risk management process recommended by the *Risk Management Guide for DoD Acquisition* (DoD, 2006)

More specifically, this research paper addresses risk mitigation activities that are considered *best practices* and that are documented in the yearly GAO *Assessments of Selected Weapon Programs* reports. Changes in cost, schedule, and performance have been tracked over time, which provides a unique perspective to understanding program execution.

It is not possible to examine every aspect of eight programs over a nine-year period. This project has focused on some key systems engineering principles that are risk-mitigation activities. The activities studied are acquisition strategy, including acquisition phases, milestones, technical reviews, and major decision reviews. Also evaluated were technical maturity, design maturity, earned value, production maturity, and software design.

An effective program acquisition strategy reduces program risks. Breaking the development into phases lowers the chances of designing or fielding a system that is immature. The milestone reviews are used to evaluate the system and to hold back programs that aren't mature enough to proceed to the next phase. Technical reviews are used to measure the progress of the program development and are event based to ensure the timely completion of the development effort. Developmental and operational tests are used to verify system performance before large sums of money are spent on production units.

Technology Readiness Levels (TRLs) are a measure used by the Department of Defense to assess the maturity of an evolving technology prior to incorporating that technology into a system. Unfortunately, this research found that they are not a good indicator of program performance. Six of the eight programs studied identified their technologies as mature even though the programs experienced significant delays and cost overruns after the technologies had been identified as mature.

In the GAO reports, design maturity was based on the number of released drawings. Some of the values are questionable because they are exact multiples of 10%. In many cases, the percent of drawings decreased after obtaining 98% or higher in a previous year. This suggests that much redesign had taken place, that the measurement of the original value was poor, and/or that the original drawing was released before the design had stabilized.

Earned value management (EVM) is a project management technique for measuring project performance and progress in an objective manner. Earned value was required on all of the programs in the GAO reports because of their size. However, only a few programs mentioned EVM in the GAO reports (only 22 times in nine years). Even when mentioned, the data were often vague. In some cases, the EVM system was identified as broken. Therefore, EVM was not an effective risk management tool.

Using Statistical Process Control (SPC) tools is a best practice for managing quality in a manufacturing environment. It is a data-driven method for monitoring and controlling the manufacturing processes that affect product quality. The GAO reports focused on the use of SPC, which was seldom used by contractors. Therefore, in most cases the risks of manufacturing problems could not be addressed. Production readiness reviews are also a best practice and should be used to address production risks. The production readiness review assesses the maturity of the design for going into production and can be an early indicator of future manufacturing problems.

The GAO reports often neglected the role of software development in an acquisition program. Design maturity is not just the number of drawings released. That is only a measure of the physical hardware design. Software is usually very important and risky on large weapon programs. Any company that claims to be CMMI Level 2 or higher will be using metrics to manage their software projects. So, theoretically, performance metrics should exist and should be reported to manage the risk of software development problems.

Keywords: DoD major weapon systems, Technology Readiness Levels (TRLs), Earned Value Management (EVM), Statistical Process Control (SPC)

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About the Author

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Table of Contents

List of Figures

List of Tables

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Glossary of Acronyms and Terms

ACQ 450 ......“Leading in the Acquisition Environment” course taught by DAU
ACQ 451 ......“Integrated Acquisition for Decision Makers” course taught by DAU
ACQ 452 ......“Forging Stakeholder Relationships” course taught by DAU
ANSI/EIA......American National Standards Institute/Electronic Industries Alliance
AT&L............Acquisition, Technology, and Logistics
CDR.............Critical Design Review
COTS...........Commercial Off-The-Shelf
C-5...............An Air Force transport aircraft
C-5 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, maintainability, and availability of the C-5 by replacing the propulsion system; modifying the mechanical, hydraulic, avionics, fuel, and landing gear systems; and making required structural modifications.
CMMI ....Capability Maturity Model Integration
DAG.............Defense Acquisition Guidebook
DAU ....Defense Acquisition University
DCMA ....Defense Contract Management Agency
DoD.............Department of Defense
DoDD...........Department of Defense Directive
DT&E ....Developmental Test and Evaluation
ECP ....Engineering Change Proposal
EDM.............Engineering Demonstration Model
EFV..............Expeditionary Fighting Vehicle (EFV)—The Marine Corps’ EFV is designed to transport troops from ships offshore to inland locales at higher speeds and from longer distances than its predecessor, the Assault Amphibious Vehicle 7A1 (AAV 7A1).
EVM.............Earned Value Management
Excalibur ......Excalibur is a family of global positioning system–based, fire-and-forget, 155-mm cannon artillery precision munitions intended to provide improved range and accuracy being developed by the Army.
FRP..............Full-Rate Production
FY ....Fiscal Year
GAO ....General Accounting Office (before July 7, 2004)
GAO ……….Government Accountability Office (after July 7, 2004)
GPQ ....Group Process Questionnaire

Global Hawk. The Air Force's Global Hawk is a high-altitude, long-endurance unmanned aircraft with integrated sensors and ground stations providing intelligence, surveillance, and reconnaissance capabilities.
H_0 ....Null Hypothesis
H_1 ....Alternate Hypothesis
IOC ....Initial Operational Capability
IPPD ....Integrated Product and Process Development
IPT ....Integrated Product Team
JSF ....Joint Strike Fighter (JSF)—The DOD's JSF program is developing a family of stealthy, strike fighter aircraft for the Navy, Air Force, Marine Corps, and U.S. allies, with the goal of maximizing commonality to minimize life-cycle costs.
JTRS ....Joint Tactical Radio System (JTRS; Cluster 1)—This DOD program is developing software-defined radios that will interoperate with selected radios and increase communications and networking capabilities.
LRIP.............Low-Rate Initial Production
MRL ....Manufacturing Readiness Level
OT&E...........Operational Test and Evaluation
PMT 401 ......Program Manager's course taught by DAU
PRR ....Production Readiness Review
SPC ....Statistical Process Control
SBIRS..........Space Based Infrared System (SBIRS) High—The Air Force's SBIRS High satellite system is being developed to replace the Defense Support Program and perform a range of missile warning, missile defense, technical intelligence, and battle-space awareness missions.
Reaper ....The Air Force's MQ-9 Reaper is a multirole, 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.
R&D ....Research and Development
RDT&E.........Research, Development, Test and Evaluation
TRL ....Technology Readiness Level
USD(AT&L)..Under Secretary of Defense for Acquisition, Technology, and Logistics

I. Introduction

The hypothesis of this research project is that when risks increase during development, they need to be continuously reflected in cost, schedule, and performance. This is not a radically new idea. The DoD and contractors treat risk as a component of cost, schedule, and performance when the government issues a request for proposal (RFP) and the contractor submits a bid.

A. Problem Statement

DoD major weapon systems historically have been over budget, behind schedule, and typically under performing in terms of suitability. The 2010 GAO report on major weapon systems (GAO-10-388SP) stated,

> The Secretary of Defense proposed a fiscal year 2010 budget that ended or curtailed all or part of at least a half dozen major defense acquisition programs—such as the Air Force’s F-22A Raptor, the Army’s Future Combat System, the Navy’s DDG 1000 destroyer, and the Missile Defense Agency’s Multiple Kill Vehicle—that were over cost, behind schedule, or no longer suited to meet the warfighters’ current needs. (p. 1)

On the subject of technical maturity, the report (GAO, 2010) stated,

> While the design knowledge of DOD programs at the system-level critical design review has increased since 2003, these programs are still not regularly demonstrating that these designs can meet performance requirements by testing integrated prototypes before the critical design review—a best practice. … Of the 33 programs that reported that they either had tested or were going to test an early system prototype and provided a critical design review date, only 4 did so before their critical design review. The remaining programs tested or will test their prototype, on average, 31 months after their critical design review. While few programs test integrated prototypes by the critical design review, DOD programs are testing prototypes earlier. … (p. 15)

On the subject of software growth,

> Many programs are at risk for cost growth and schedule delays because of software development issues. We reported in our last assessment that programs experiencing more than a 25 percent growth in software lines of code since development start had higher development cost growth and longer schedule delays than other programs. Seventeen of the 28 programs that reported data on software lines of code estimated that the number of lines of

code required for the system to function has grown or will grow by 25 percent or more—up from 14 programs in our last assessment. Overall, the average lines of code growth or planned growth for the 28 programs was about 92 percent. (p. 20)

B. Purpose of this Study

This research project examines eight major DOD weapon systems using yearly published GAO reports. The purpose of this research is to understand what risk management was being performed on those programs, how it was implemented, when it was implemented, and how effective it was. The desired outcome is to make recommendations on improvements to the risk management process recommended by the *Risk Management Guide for DoD Acquisition* (DoD, 2006). This effort is Phase I of a multi-phase research project (Naval Postgraduate School, BAA Number NPS-BAA-11-02).

C. Overview of the Research Methodology

This research project is based on the GAO's 2003–2011 reports on major weapon systems. Eight different programs were identified for study. The yearly accomplishments have been used in this research project to build a historical record of each program. The historical records have been used to assess the effectiveness of risk management activities from prior years. The data answer the questions, "What was planned and what actually happened?"

D. Research Questions

Research questions include the following:

- Can the effectiveness of risk management be improved by continuously incorporating risk in a program's cost, schedule, and performance objectives and plans?
- How is systems engineering being used to manage risk?
- How effective is risk mitigation in managing large weapon system developments?

E. Research Hypothesis

The hypothesis of this research project is that when risks increase during development, they need to be continuously reflected in cost, schedule, and performance.

F. Objectives and Outcomes

The desired outcome is to make recommendations on improvements to the risk management process recommended by the *Risk Management Guide to DoD Acquisition* (DoD, 2006).

G. Limitations of the Study

The research project is based on GAO reports for major DoD weapon system acquisition programs. It may not apply to smaller DoD programs.

H. Validity of the Research

The research is based on GAO reports that are based on an analysis of major DoD acquisition programs. The research is directly applicable for DoD programs.

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II. Literature Review

This research project is based on written reports from the Government Accountability Office (GAO) on major DoD weapon systems. The GAO reports come out in March of every year and generally provide a two-page analysis of the largest major defense programs. The GAO reports exist from 2003–2011, although the first report (GAO, 2003) covered a smaller number of programs than the reports published from 2004–2011. The following are the GAO reports reviewed in this research project:

- *Defense Acquisitions: Assessments of Major Weapon Programs*, GAO-03-476 (May 2003)
- *Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-04-248 (March 2004)
- *Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-05-301 (March 2005)
- *Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-06-391 (March 2006)
- *Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-07-406SP (March 2007)
- *Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-08-467SP (March 2008)
- *Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-09-326SP (March 2009)
- *Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-10-388SP (March 2010)
- *Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-11-233SP (March 2011)

The purpose of the GAO reports was stated in the 2011 report, GAO-11-233SP:

> The report is in response to the mandate in the joint explanatory statement to the DOD Appropriations Act, 2009. It includes observations on the performance of DOD's 2010 portfolio of 98 major defense acquisition programs; data on selected factors that can affect program outcomes; an assessment of the knowledge attained by key junctures in the acquisition process for a subset of 40 programs, which were selected because they were

> in development or early production; and observations on the implementation of acquisition reforms. To conduct this review, GAO analyzed cost, schedule, and quantity data from DOD's Selected Acquisition Reports and collected data from program offices on performance requirements and software development; technology, design, and manufacturing knowledge; and the implementation of DOD's acquisition policy and acquisition reforms. GAO also compiled one- or two-page assessments of 71 weapon programs. (p. 0)

Analysis of the GAO reports consisted of examining the write-up for each program over the nine-year period, looking for trends in the data, identifying risk-mitigation activities, and evaluating the overall effectiveness of the risk management process.

Programs that were studied in this research project had write-ups for most of the years studied (2003–2011). In addition, programs were selected to cover the following characteristics:

- the largest program ever in the DoD;
- a program with a very small number of production units (< 6);
- a large program with COTS as a critical component;
- a large joint program;
- a program that has little software; and
- several programs in which software is critical to the success of the program.

Eight programs were selected for review. One is an Army system, one is a Marine Corps system, four are Air Force Systems, and two are joint systems. The systems selected went through the acquisition life cycle from technology development until low-rate initial production and operational test and evaluation. Some reached full rate production. The programs that were selected for study are the following:

1. Excalibur (Army): Excalibur is a family of global positioning system–based, fire-and-forget, 155-mm cannon artillery precision munitions intended to provide improved range and accuracy.

2. Expeditionary Fighting Vehicle (EFV)[1]: The Marine Corps' EFV is designed to transport troops from ships offshore to inland locales at higher speeds and from longer distances than its predecessor, the Assault Amphibious Vehicle 7A1 (AAV 7A1).

3. C-5 Reliability Enhancement and Reengining 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, maintainability, and availability of the C-5 by replacing the propulsion system; modifying the mechanical, hydraulic, avionics, fuel, and landing gear systems; and making required structural modifications.

4. Joint Tactical Radio System (JTRS; Cluster 1)[2]: This DoD program is developing software-defined radios that will interoperate with selected radios and increase communications and networking capabilities.

5. Joint Strike Fighter (JSF): The DoD's JSF program[3] is developing a family of stealthy, strike fighter aircraft for the Navy, Air Force, Marine Corps, and U.S. allies, with the goal of maximizing commonality to minimize life-cycle costs.

6. Reaper: The Air Force's MQ-9 Reaper is a multirole, 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.

7. Global Hawk[4]: The Air Force's Global Hawk is a high-altitude, long-endurance unmanned aircraft with integrated sensors and ground stations providing intelligence, surveillance, and reconnaissance capabilities.

8. Space Based Infrared System (SBIRS) High: The Air Force's SBIRS High satellite system is being developed to replace the Defense Support Program and perform a range of missile warning, missile defense, technical intelligence, and battle-space awareness missions.

GAO data were available for the following years:

1. Excalibur: 2004–2011 (eight years)

[1] Called the Advanced Amphibious Assault Vehicle (AAAV) in 2003.

[2] Also called the JTRS Ground Mobile Radios (GMR).

[3] Also called the F-35.

[4] Also called Global Hawk RQ-4A/B.

2. EFV: 2003–2011 (nine years)
3. C-5 RERP: 2004–2011 (eight years)
4. JTRS: 2004–2011 (eight years)
5. JSF: 2003–2011 (nine years)
6. Reaper: 2004–2011 (eight years)
7. Global Hawk: 2004–2011 (eight years)
8. SBIRS: 2003–2011 (nine years)

An example of a GAO write-up is shown in Appendix B. Key information from the GAO reports used in this research project are the following:

1. Financial Data
    - Research & Development (R&D) cost (total estimated)
    - R&D funding needed to complete
    - Yearly R&D cost
    - Procurement cost
    - Procurement quantity
    - Unit cost
2. Schedule
    - Development start
    - Low-rate decision
    - Full-rate decision
    - Last procurement
    - IOC (initial operating capability)
    - Acquisition time
    - EDM (engineering development model)
    - Design and/or technical reviews
3. Technical
    - Technical maturity
    - Design maturity (primarily the percent of drawings released to manufacturing)

- Production maturity (primarily the use of statistical process control)
- Software development

Of these sources of information, the group called *Technical* is directly related to technical risk management. Other risk-management considerations include the overall acquisition strategy, use of prototypes (including EDMs and LRIP units), and the scheduling of design and technical reviews.

Not all of the write-ups contained all of this information. One area that was poorly documented was *software development*. As an approximation, the number of sentences in each write-up that mentioned software was counted and used as an indicator of the importance of software to the program. This assumption is not expected to be a data-driven measure of software risk.

The yearly R&D expenditures were not listed in the GAO reports, but they were derived from the yearly values for R&D costs and total R&D costs to complete. That is, by using each year's "Research and development costs" from the Program Performance table and the "R&D funding needed to complete" from the Program Essentials table, it was possible to determine the amount of R&D funds spent each year.

All financial figures were adjusted for inflation and put into 2011 dollars. The yearly inflation rates were obtained by looking at the "As of …" cost listed in the Program Performance tables and backing out the yearly inflation rates. The C-5 RERP, JSF, and SBIRS programs had nearly identical inflation rates and the values from the C-5 RERP values were used in this analysis (shown in Figure 1**Error! Reference source not found.**). Use of the inflation rates is important when trying to assess year-to-year cost increases since costs were reported in current dollars for the time period of each report.

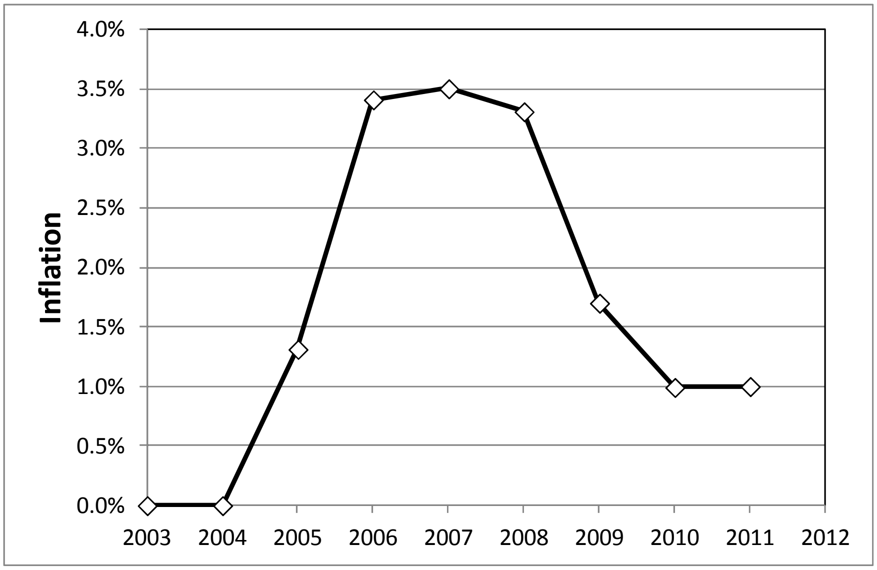

Figure 1. Inflation Rates Used for the Financial Analysis of the GAO Cost Figures

III. Research Methodology

A broad definition of research was given by Martyn Shuttleworth (2008): "In the broadest sense of the word, the definition of research includes any gathering of data, information and facts for the advancement of knowledge."

Another definition of research was given by J.W. Creswell (2008) who stated, "Research is a process of steps used to collect and analyze information to increase our understanding of a topic or issue." According to Creswell, research consists of three steps: pose a question, collect data to answer the question, and present an answer to the question.

Research can be defined as the search for knowledge, or as any systematic investigation, with an open mind, to establish novel facts, solve new or existing problems, prove new ideas, or develop new theories, usually using a scientific method. Scientific research relies on the application of the *scientific method*. This research provides scientific information and theories for the explanation of the nature and the properties of the world around us.

A. Research Strategy

This effort is Phase I of a multi-phase research project (Naval Postgraduate School, BAA Number NPS-BAA-11-02). The hypothesis of this multi-phase research project is that when risks increase during development, they need to be continuously reflected in cost, schedule, and performance. This is not a radically new idea. The DoD and contractors treat risk as a component of cost, schedule, and performance when the government issues a request for proposal (RFP) and the contractor submits a bid.

The overall research project will be done in phases with a separate research paper for each phase. This "incremental" approach, which in itself is a risk-mitigation strategy, will allow the researcher to focus on specific research questions and will allow timelier release of research reports. The overall research approach is as follows:

- Phase I: Conduct a review of the treatment of risk on several major weapon systems using GAO reports (this report);
- Phase II: Conduct a survey of the DoD acquisition workforce in the risk-taking behavior of the workforce under different situations (McKeon, 2012a);
- Phase III: Conduct experiments on the risk-taking behavior of the workforce under different situations (McKeon, 2012b);
- Phase IV: Develop a stochastic computer simulation to model and test the risk-taking characteristics of government workforce members; and
- Phase V: Interview DoD and industry project managers (or equivalents) in best practices of risk management.

This research paper covers Phase I of this research project.

B. Data Collection

For Phase I of the overarching research project on risk management within the DoD, the yearly GAO reports on major DoD weapon systems were used in this research study.[5] The yearly GAO reports are released in March and generally provide a two-page analysis of the largest major defense programs. The reports are public-disclosure documents and include financial data and technical maturity information. The GAO reports exist from 2003–2011, although the first report (2003) covered a smaller number of programs than the reports published from 2003–2011.

Analysis of the GAO reports consisted of examining the write-up for each program over the nine-year period, looking for trends in the data, identifying risk-mitigation activities, and evaluating the overall effectiveness of the risk management process.

C. Analysis of the GAO Reports

The GAO reports were reviewed to obtain the following data:

1. Program Schedule

a) There are several values that relate to schedule. The most obvious is the "Acquisition cycle time (months)" that is in the

[5] Personnel from the programs offices were not interviewed for this study.

main table on the first page of the report. This measures the time from “development start” to “initial capability.”

b) Another schedule parameter is “development start” to “low-rate decision.” This was not reported, but it was easily determined from the schedule given on the first page of each write-up. In some cases, the time to LRIP increased but the “acquisition time” or the time to FRP did not change, which suggested a high-risk approach to planning.

c) Another schedule parameter was “development start” to “full-rate decision.” This was an important measure for programs that entered LRIP at a low maturity level. The time to FRP captured the time to mature the design and production processes.

2. **Program Costs.** There are several important cost values listed on the first page of each report.

a) R&D costs: There is a cost stated at the start of development and the most current estimate at completion. The values are adjusted for inflation. The current estimate at completion is the single most important piece of information used in this research project.

b) Procurement unit cost was also included in each GAO report.

c) Program unit cost: This value was given in each report and was used in this analysis. The value is dependent on the quantity fielded and so changes in quantity have to be considered when evaluating this cost data.

d) Funding needed to complete: R&D. This value was very important because it gave a snapshot of the technical state of the program. This value and the R&D costs were used to determine the R&D dollars spent every year.

3. **Total Quantities**

a) The total number of systems planned to be purchased for procurement was listed on the first page of each report. This information was important for understanding the program and procurement unit costs.

4. **Technical Maturity**

a) There was a chart called “Attainment of Product Knowledge” which by itself was not very useful. However, each report had a section called “Technology Maturity.” This was very useful to define the technical maturity of the program, but technical maturity rarely correlated with program success.

5. Design Maturity

There was very useful information in the section called “Design Maturity.”

a) The GAO reports listed the percent of design drawings complete. Some of the reported values were not very accurate, which will be discussed in Chapter 4.

b) The reports sometimes mentioned software development. It was very difficult to appraise the software maturity because metrics were not used. However, as a crude metric, the number of sentences that mentioned “software” were counted and used to assess the maturity of the software development effort.

6. Production Maturity.

a) There was a section on production maturity, but it did not use manufacturing readiness levels (MRLs). The write-ups often said that the assessors could not assess production maturity because statistical process controls were not being used. In some cases, other activities or accomplishments were looked at to assess production maturity.

IV. Findings

This research project is based on written reports from the Government Accountability Office (GAO) on major DoD weapon systems. The GAO reports come out in March of every year and generally provide a two-page analysis of the largest major defense programs. The GAO reports exist from 2003–2011, although the first report (2003) covered a smaller number of programs than the reports published from 2003–2011. GAO data[6] were available for the following years:

1. Excalibur: 2004–2011 (eight years)
2. EFV: 2003–2011 (nine years)
3. C-5 RERP: 2004–2011 (eight years)
4. JTRS: 2004–2011 (eight years)
5. JSF: 2003–2011 (nine years)
6. Reaper: 2004–2011 (eight years)
7. Global Hawk: 2004–2011 (eight years)
8. SBIRS: 2003–2011 (nine years)

A. Excalibur: 2004–2011 (Eight Years)

The Excalibur Precision Guided Extended Range Artillery Projectile yearly schedules and milestones from 1997–2011 are shown in Figure 2**Error! Reference source not found.**. Every published schedule is shown as a row in the table. For example, in 2004, the LRIP decision was scheduled for June 2006, the full-rate production (FRP) decision was planned for June 2008, and IOC was planned for September 2008. The 2004 schedule did not show a design review in 2005, but starting in 2006 the schedule showed a design review in either April or May of 2005.

[6] Disclaimer: Some information in the GAO reports was incomplete and some programs had significant changes in program scope that complicated the analyses of the programs.

The milestone chart is useful because it clearly shows schedule slip in FRP and IOC as a function of time. For example, IOC was originally planned to occur in September 2008 and that schedule was in place until 2008 when IOC slipped to January 2009. In 2009, the forecasted IOC slipped 13 months. Overall IOC slipped 29 months in the three years from 2009–2011.

Figure 3**Error! Reference source not found.** is another way to look at the program milestones. Three curves are plotted: time to LRIP, time to FRP, and total acquisition cycle time (all measured in months from the start of program development). The first two datasets are derived from the yearly schedules, while the last one is from the “Program Performance” table in every GAO write-up. The schedule data looks very favorable through 2008, then starts to show significant schedule delays. The overall program schedule delay was 35 months in a four-year period.

Error! Reference source not found. shows the R&D costs for the program. All costs have been adjusted for inflation. The GAO reports did not report a yearly R&D spending, so it was derived[7] from the reported cost data. In the figure, the planned total program cost is shown as the black line with squares. There was a large program cost increase in 2005. The “R&D funding needed to complete” the program, listed in the “Program Essentials” block in each GAO report, is shown as the green line with triangles.

The red line with asterisks is the actual R&D spending for each year. The red curve clearly shows the drop in R&D funding from 2007 to 2008. Spending was flat to 2007 and then it was flat, but at a lower level, until 2010. The blue line with diamonds is total R&D spending from the beginning of the program.

[7] The R&D spending for a year was not reported, but it could be determined from the reported R&D costs from two years of data. Mathematically, R&D spent (year *i*) = (Budgeted(year *i*) – Budgeted(year *i* – 1)) – (Needed to Complete (year *i*) – Needed to complete(*i* – 1)).

Figure 5 shows the total production quantity, the procurement unit costs[8] and the program unit costs.[9] There are large quantity changes in 2005, 2006, and 2011. The procurement and program unit costs increased significantly in 2011. The program unit cost increased by 193% and the procurement cost increased by 93%. There was a Nunn-McCurdy[10] breach in 2010 when the production quantity dropped and the procurement unit cost increased from $47,000 to $99,000.

Figure 6 shows the technical maturity for each year based on the GAO reports. Three critical technologies were identified for the program and it was reported that all technologies were mature starting in 2006.

Figure 7 shows the percent of drawings completed. It shows a flat trend at 100% from 2006 until 2010 and then a decrease to 90% in 2011. The percent drawings completed is not a good measure of design maturity because $257 million (est.) was spent on R&D from 2007 until 2010, even though it was reported that 100% of the design drawings had been completed. Design problems were not recognized until 2011.

None of the yearly Excalibur write-ups mentioned software. There is undoubtedly software or firmware being developed or modified, such as system operation, operation, targeting, and so forth. The GAO reports do not indicate that software was an issue for the program.

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[8] The procurement unit cost is the total procurement cost divided by the total quantity, which are both identified in the "Program Performance" block of each GAO write-up. Procurement unit cost does not include R&D costs.

[9] The program unit cost is the total program cost divided by the total quantity, which are both identified in the "Program Performance" block of each GAO write-up. The total program costs are the R&D costs plus the procurement costs.

[10] The Nunn–McCurdy Amendment or Nunn–McCurdy Provision, introduced by Senator Sam Nunn and Congressman Dave McCurdy in the United States 1982 Defense Authorization Act, is designed to curtail cost growth in American weapons procurement programs. It requires notification of the United States Congress if the cost per unit grows more than 15% beyond what was originally estimated, and calls for the termination of programs with total cost growth greater than 25%, unless the Secretary of Defense submits a detailed explanation certifying 1) the program is essential to national security, and that no suitable alternative of lesser cost is available; 2) new estimates of total program costs are reasonable; and 3) management structure is (or has been made) adequate to control costs.

Project	1997	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Excalibur	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
1997	•Prog S	•ReX						•LRIP		•IOC	•FRP		
2000	•Prog Start												
2001	•Prog Start												
2002	•Prog Start												
2003	•Prog Start												
2004	•Prog Start	•ReX					•DR	•LRIP		FRP• •IOC			
2005	•Prog Start			•ReX			•DR	•LRIP		FRP• •IOC			
2006	•Prog Start			•ReX			DR ••LRIP			FRP ••IOC			
2007	•Prog Start						DR ••LRIP			FRP ••IOC			
2008	•Prog Start						DR ••LRIP			FRP•	•IOC		
2009	•Prog Start						DR ••LRIP				FRP•	•IOC	
2010	•Prog Start						DR ••LRIP					FRP•)C	
2011	•Prog Start						•DR		•LRIP				•FRI •IOC

Figure 2. Excalibur: Milestones Based on GAO Reports

Note. Each yearly schedule from the GAO reports is shown as a row in the table. Milestones such as DR (design review), LRIP, FRP, IOC, Nunn (Nunn-McCurdy breach), and ReX (restart) are shown. The white cells are the year of the report and milestones shown in the white cells are planned to occur during the year. The milestones shown in the green cells had already occurred[11] at the time of the GAO report. The milestones shown in the yellow cells were planned milestones at the time of the report for the years after the GAO report.

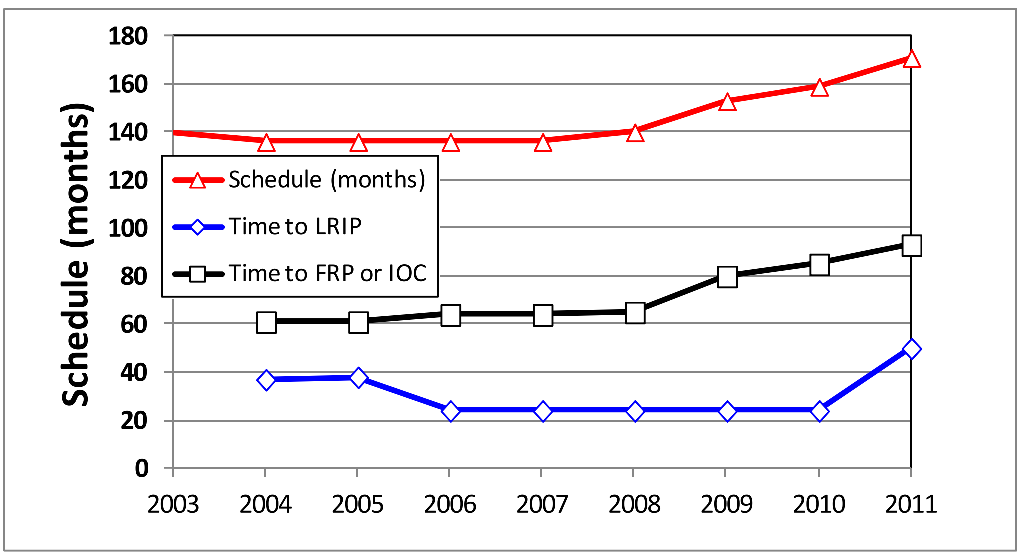

Figure 3. Excalibur Milestone Schedule

Note. The red line with triangles is the program acquisition cycle time listed in the GAO write-ups (in months). The blue line with diamonds is the time from development start to LRIP (in months). The black line with boxes is the time from development start to FRP (in months).

[11] In theory, the milestones in green should not change from year to year; however, in some cases there are minor differences.

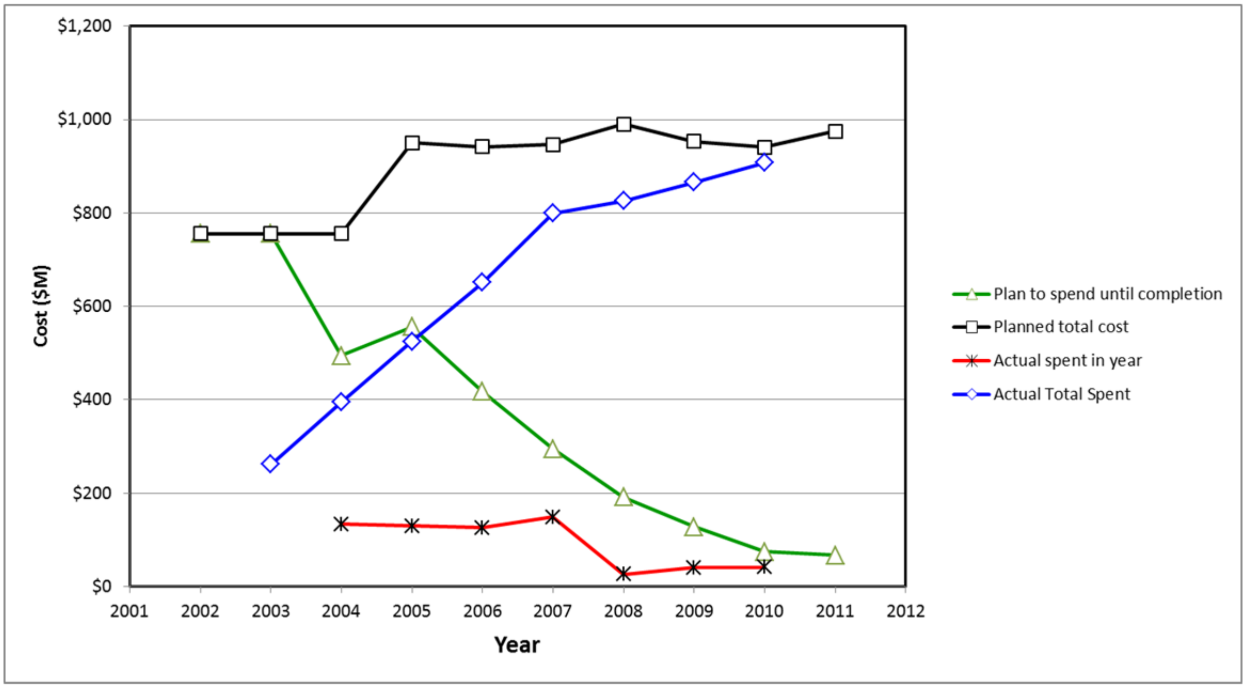

Figure 4. Excalibur R&D Cost Profile

Note. The green line with triangles is the "R&D funding needed to complete" the program and is from the "Program Essentials" section of each GAO report. The black line with boxes is the planned total R&D cost taken from the "Program Performance" section of each report. The red line with black asterisks is the R&D spending during the year. The blue line with diamonds is the Total R&D spending from the beginning of the project. It is derived from the "funding needed to complete" and the "R&D cost" categories from the reports.

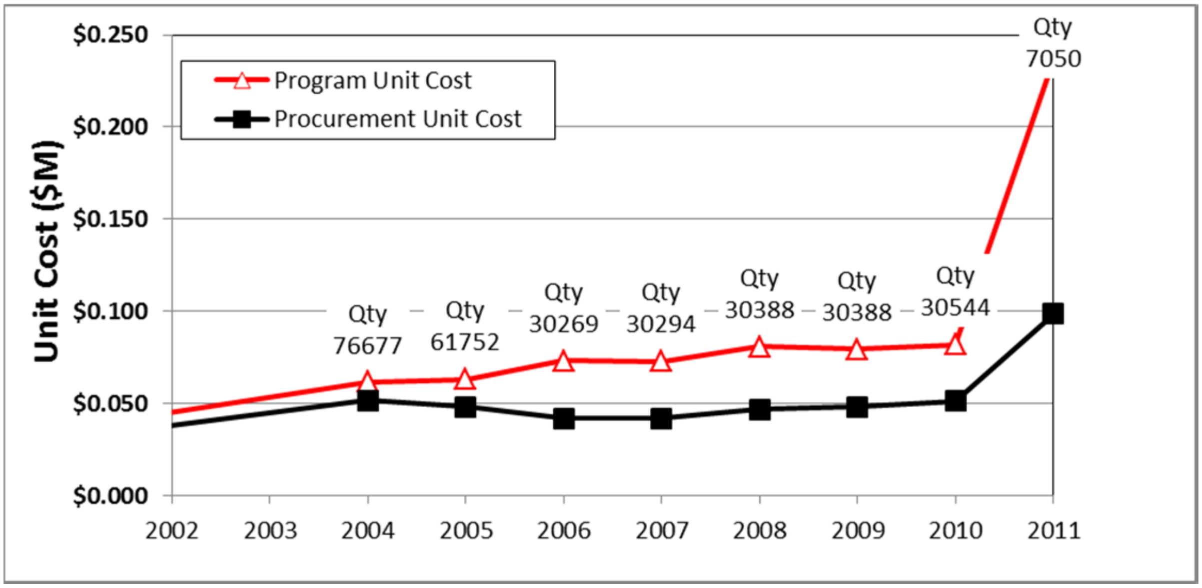

Figure 5. Excalibur: Production Quantity and Unit Costs

Note. The black line with squares is the *procurement* unit cost adjusted for inflation. The red line with triangles is the *program* unit cost adjusted for inflation (the program unit cost includes the R&D costs amortized over the total production lot).

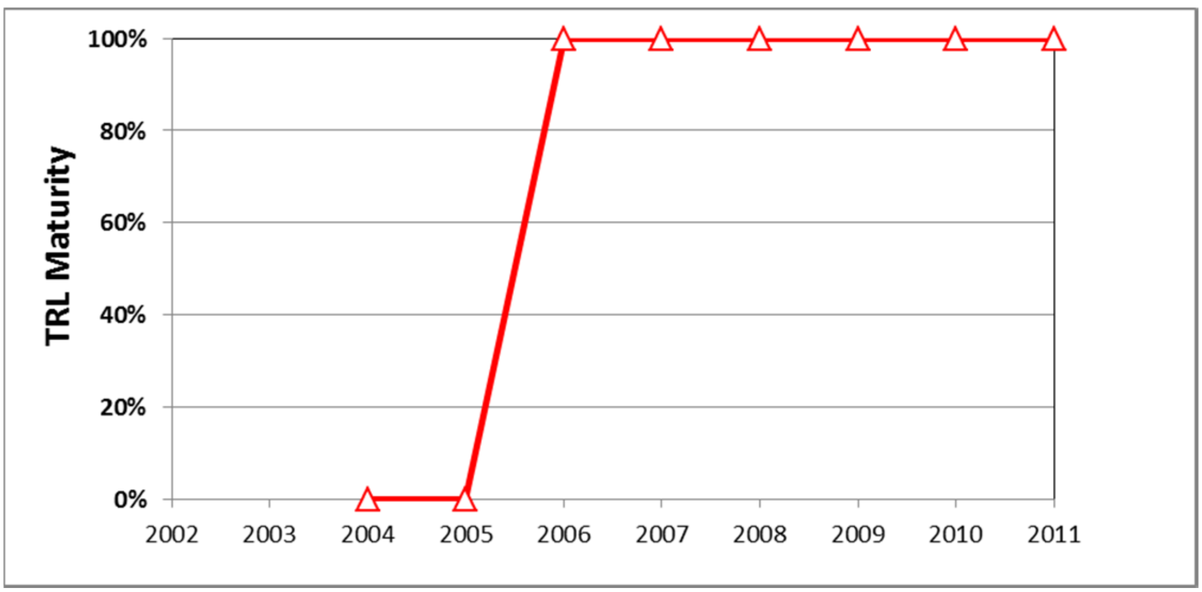

Figure 6. Excalibur: Technical Maturity

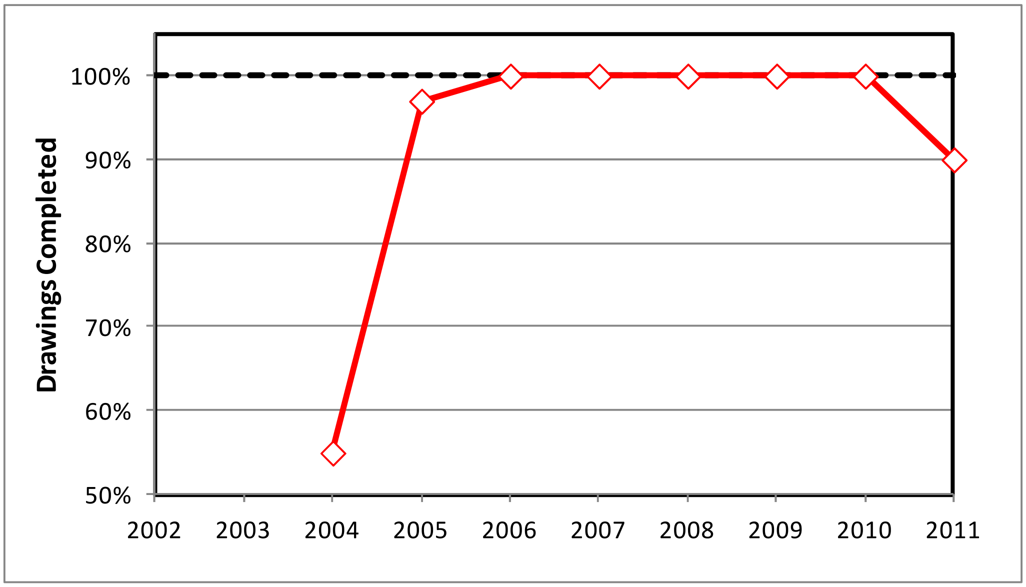

Figure 7. Excalibur: Drawings Completed

B. Expeditionary Fighting Vehicle (EFV): 2003–2011

The EFV (formerly the AAAV) program was in the GAO reports from 2003–2011. The program was cancelled in 2011 after the GAO report was issued. Even though the program has been terminated, the past data is useful for understanding program risks.

The schedules for the period 2001–2011 are shown in Figure 8. Every published schedule is shown as a row in the table. The columns represent the different years in each yearly schedule. For example, in 2003 the LRIP decision was scheduled for September 2005, the full-rate production decision was planned for August 2007, and IOC was planned for September 2008. This chart is useful because it clearly shows schedule slip as a function of time. There was a Nunn-McCurdy breach in 2007, which shows up as a large schedule slip between 2007 and 2008.

Figure 9 is another way to look at the program milestones. Three curves are plotted: time to LRIP, time to FRP, and total acquisition cycle time (all measured in months from the start of program development). The first two datasets are derived from the yearly schedules, while the last one is from the “Program Performance” table in every GAO write-up. The chart shows the large increase in schedule in 2008.

Figure 10 shows the R&D costs for the program. All costs have been adjusted for inflation. The GAO reports did not report a yearly R&D spending, so it was derived from the reported cost data. In the figure, the planned total program cost is shown as the black line with squares. The “R&D funding needed to complete” the program, listed in the “Program Essentials” block in each GAO report, is shown as the green line with triangles.

The red line with asterisks is the actual R&D spending for each year. Spending was flat throughout the program. The blue line with diamonds is the actual R&D spending from the beginning of the program.

The “planned total cost” (black curve) shows a step increase every other year, which may be an artifact of the data collection or budget reporting and is not a change in scope of the program. There was a steady increase in planned total cost throughout the life of the program, with a large step increase in 2008 due to the Nunn-McCurdy re-baseline. It is interesting to note that the cost increases were about equal to the expenditures, so the program was not getting closer to completion.

Figure 11 shows the total production quantity, the procurement unit costs,[12] and the program unit costs.[13] There was a large quantity change in 2008 (a 42% decrease) and large increases in the procurement and program unit costs. The program unit cost increased by 107% and the procurement cost increased by 88%.

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[12] The procurement unit cost is the total procurement cost divided by the total quantity, which are both identified in the “Program Performance” block of each GAO write-up. Procurement unit cost does not include R&D costs.

[13] The program unit cost is the total program cost divided by the total quantity, which are both identified in the “Program Performance” block of each GAO write-up. The total program costs are the R&D costs plus the procurement costs.

Figure 12 shows the technical maturity for each year based on the GAO reports. Initially, the program reported five critical technologies, but then it dropped to four starting in 2008. It was reported that all technologies were mature starting in 2005.

Figure 13 shows the number of design drawings completed for each year. The data show that the program did not have a good handle on the quality and/or number of drawings completed. The data showed that 100% of the drawings had been completed in 2005, although R&D spending was still on the order of $300 million, which implies that some redesign of critical components was underway. Starting in 2006, there was a recognition that redesign was necessary although the magnitude of the redesign effort was underestimated.

The GAO write-ups do not have a specific measure of software maturity. As an approximation, the number of sentences in each report that mentioned software was counted as a gauge of the software development. Figure 14 shows the number of lines in the EFV GAO reports that mention software. The GAO write-ups mentioned software 10 times in 2007, but software wasn't mentioned from 2008–2010.

Project	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
EFV	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
1995	•Prog Start		•Dev Start											
2000														
2001	•Prog Start		•Dev Start				•LRIP		•FRP	•IOC				
2002	•Prog Start		•Dev Start											
2003	•Prog Start		•Dev Start				•LRIP		•FRP	•IOC				
2004	•Prog Start		•Dev Start				•LRIP			FRP• •IOC				
2005	•Prog Start		•Dev Start					•LRIP		FRP•	•IOC			
2006	•Prog Start		•Dev Start					•LRIP				FRP• •IOC		
2007	•Prog Start		•Dev Start											
2008	•Prog Start		•Dev Start						•Nunn				•LRIP	
2009	•Prog Start		•Dev Start						•Nunn	•Restart				•LRIP
2010	•Prog Start		•Dev Start						•Nunn	•Restart			•OT	•LRIP
2011	•Prog Start		•Dev Start						•Nunn	•Restart			•OT	•LRIP

Figure 8. EFV Schedule

Note. Each yearly schedule from the GAO reports is shown as a row in the table. Milestones such as DR (design review), LRIP, FRP, IOC, Nunn (Nunn-McCurdy breach), and Dev Start (development start) are shown. The white cells are the year of the report and milestones shown in the white cells are planned to occur during the year. The milestones shown in the green cells had already occurred at the time of the GAO report. The milestones shown in the yellow cells were planned milestones at the time of the report for the years after the GAO report.

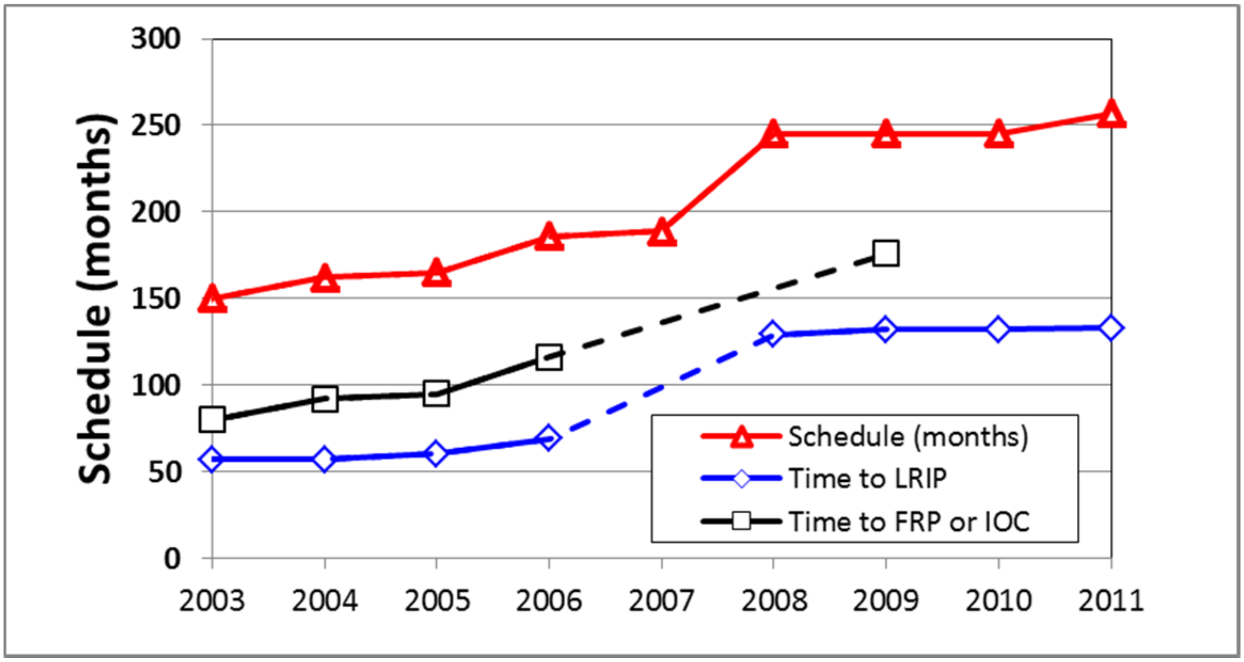

Figure 9. EFV Schedule (Months From Development Start)

Note. The red line with triangles is the program acquisition cycle time listed in the GAO write-ups (in months). The blue line with diamonds is the time from development start to LRIP (in months). The black line with boxes is the time from development start to FRP (in months). When data points are missing, a dashed line is drawn between points. The dashed lines are for visual purposes only.

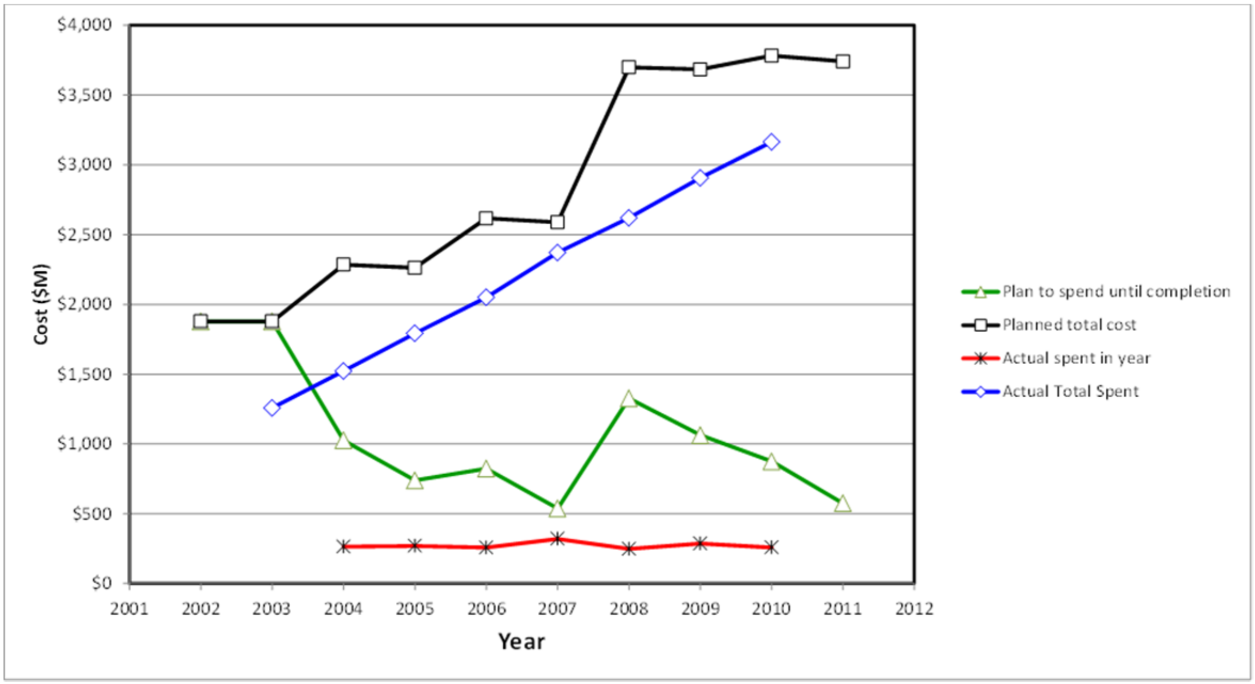

Figure 10. EFV R&D Cost Profile

Note. The green line with triangles is the "R&D funding needed to complete" the program and is from the "Program Essentials" section of each GAO report. The black line with boxes is the planned total R&D cost taken from the "Program Performance" section of each report. The red line with black asterisks is the R&D spending during the year. The blue line with diamonds is the Total R&D spending from the beginning of the project. It is derived from the "funding needed to complete" and the "R&D cost" categories in the reports.

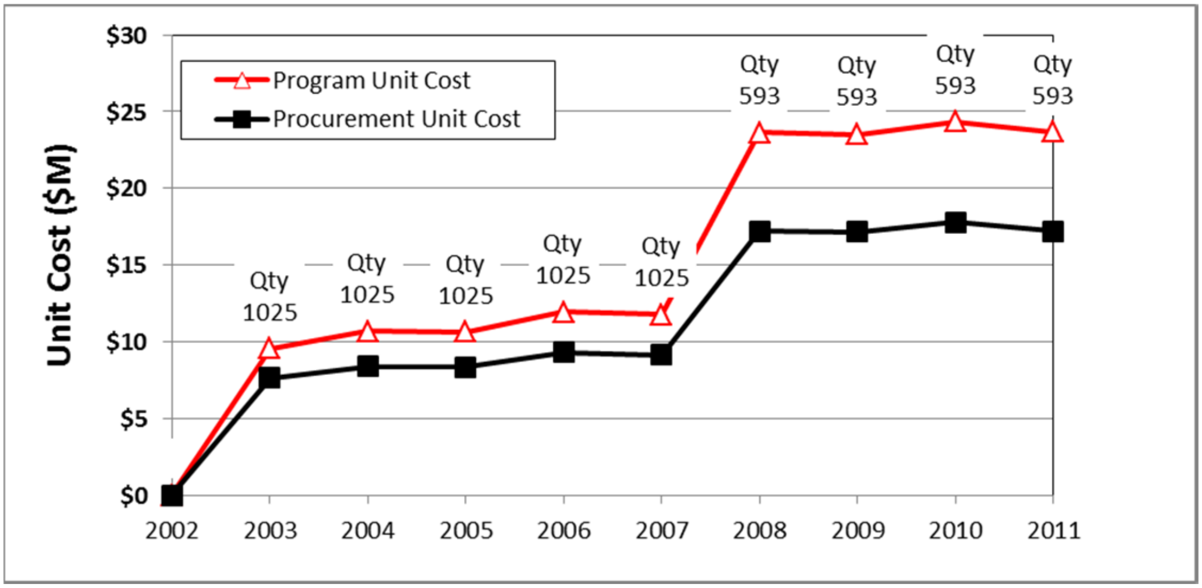

Figure 11. EFV Production Plan and Unit Cost

Note. The black line with squares is the *procurement* unit cost adjusted for inflation. The red line with triangles is the *program* unit cost adjusted for inflation (the program unit cost includes the R&D costs amortized over the total production lot).

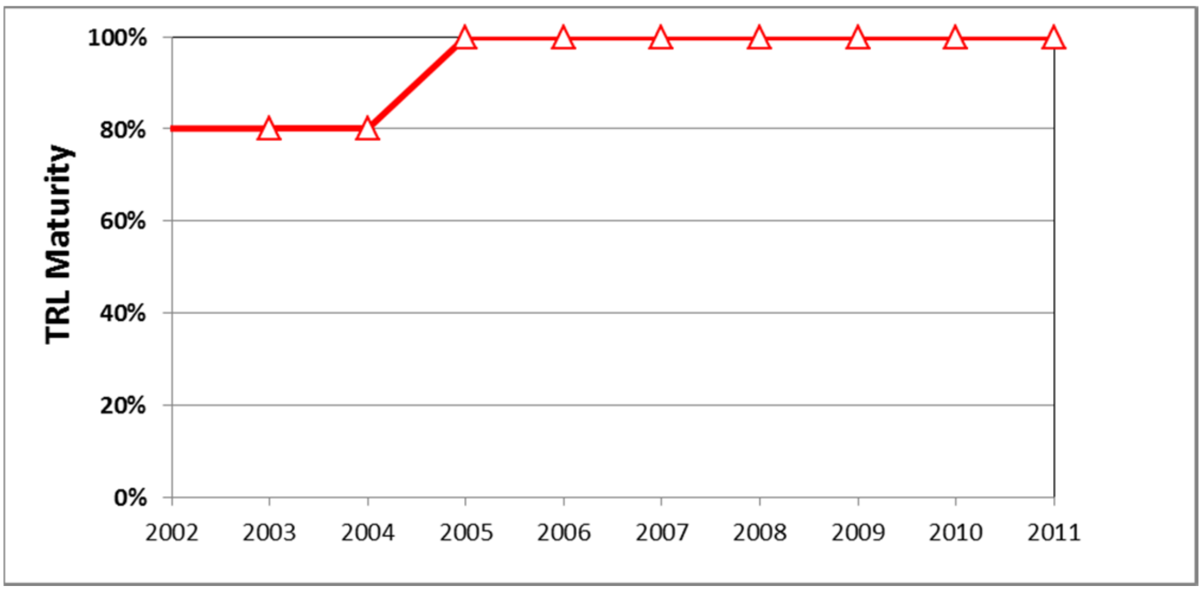

Figure 12. EFV: Technical Maturity

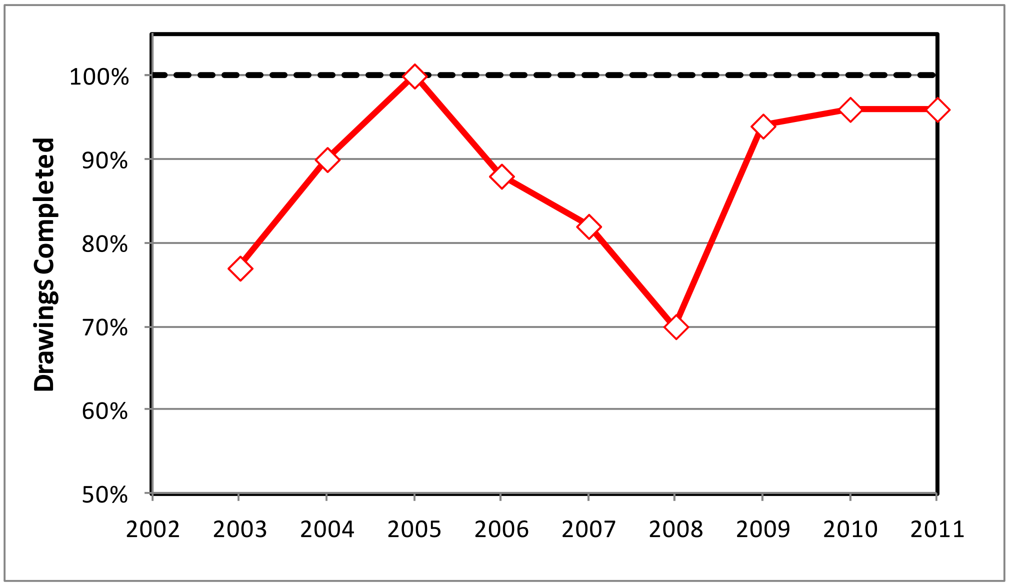

Figure 13. EFV: Design Maturity Based on the Number of Drawings Completed

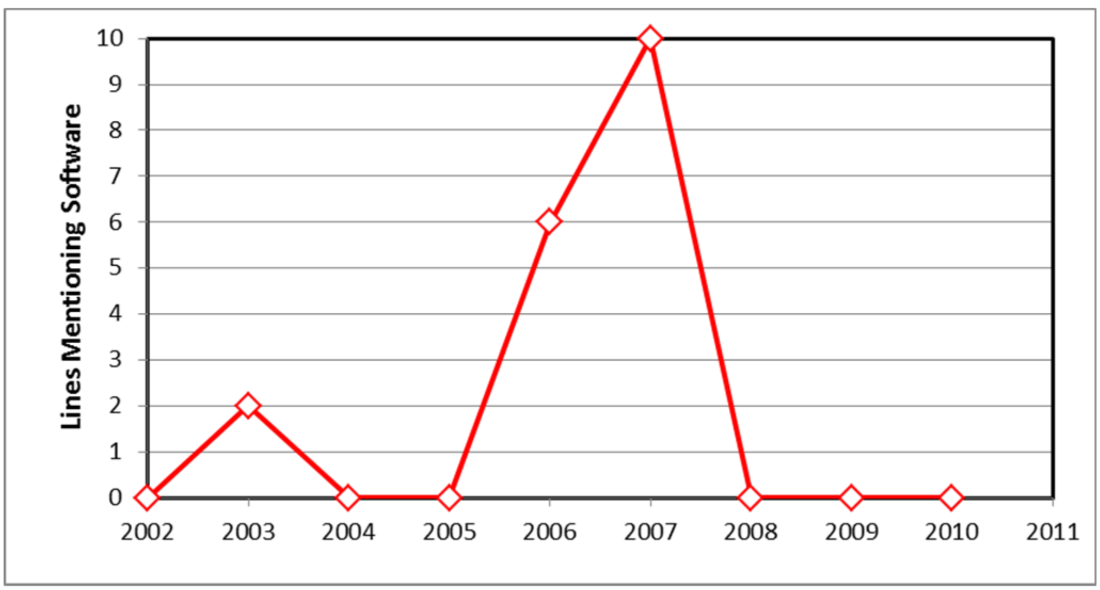

Figure 14. EFV: Number of Lines in the GAO Reports That Mentioned Software

C. C-5 Reliability Enhancement and Reengining Program (RERP): 2004–2011 (Eight Years)

Figure 15 shows the published C-5 RERP yearly schedules and milestones from 2004–2011. Every published schedule is shown as a row in the table. The columns represent the different years in each yearly schedule. The yearly schedules are very misleading. Looking at the data, only year 2008 shows a big change in schedule. There was a Nunn-McCurdy breach in 2008.

Figure 16 is another way to look at the program milestones. Three curves are plotted: time to LRIP, time to IOC, and total acquisition cycle time (all measured in months from the start of program development). The first two datasets are derived from the yearly schedules, while the last one is from the "Program Performance" table in every GAO write-up. The chart shows the large increase in schedule in 2008.

Figure 17 shows the R&D costs for the program. All costs have been adjusted for inflation. The GAO reports did not report a yearly R&D spending, so it was derived from the reported cost data. In the figure, the planned total program cost is shown as the black line with squares. The reason(s) for the drop in "planned total R&D costs" in 2006 and 2007 is/are unknown, but may be the result of a mathematical error in the reported data.

The "R&D funding needed to complete" the program, listed in the "Program Essentials" block in each GAO report, is shown as the green line with triangles. The red line with asterisks is the actual R&D spending for each year. R&D spending was dropping every year. The blue line with diamonds is the actual R&D spending from the beginning of the program.

Figure 18 shows the total production quantity, the procurement unit costs,[14] and the program unit costs.[15] The quantity dropped from 111 to 52 in 2009 (a 53% decrease). Unit costs (including R&D) rose from $87 million to $137 million (a 57%

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[14] The procurement unit cost is the total procurement cost divided by the total quantity, which are both identified in the "Program Performance" block of each GAO write-up. This cost does not include R&D costs.

[15] The program unit cost is the total program cost divided by the total quantity, which are both identified in the "Program Performance" block of each GAO write-up. The total program costs are the R&D costs plus the procurement costs.

increase). (The quantity and, therefore, the procurement unit cost in 2008 seem to be in error. The quantity for 2008 should have been 52.)

Figure 19**Error! Reference source not found.** shows the technical maturity for each year based on the GAO reports. One critical technology was reported for the program (the new engine) and since it was a commercially available engine, the program reported it as mature throughout the program.

In many cases, design maturity was based on the number of drawings released. There are a couple of points to consider. First, many of the quoted values seem to be arbitrary. In Figure 20, the program/contractor reported 98% for three years. On might ask if they stopped working on drawings in 2003? Then the number of drawings dropped to 90%, then 80%, then back to 90%, and then to 100%. Nothing works that predictably. The “number of drawings completed” that were reported do not seem realistic.

The GAO write-ups do not have a specific measure of software maturity. As an approximation, the number of sentences in each report that mentioned software was counted as a gauge of the software development. Figure 21 shows the number of lines in the GAO reports that mention software. Software was mentioned 15 times between 2004 and 2006, but only once between 2007 and 2011. In 2004, the write-up mentioned, “According to program officials, the greatest risk … is software development and integration activities.”

Project	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
C5 RERP	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
1999													
2000		•Prog Start											
2001		•Prog Start											
2002		•Prog Start											
2003		•Prog Start											
2004		•Prog Start	•Dev Start		•Restart				•LRIP	•FRP		•IOC	
2005		•Prog Start	•Dev Start		•Restart				•LRIP		•FRP		•IOC
2006		•Prog Start	•Dev Start		•Restart			•LRIP		•FRP			
2007		•Prog Start	•Dev Start		•Restart				Nunn• •LRIP		•FRP		
2008		•Prog Start	•Dev Start			•Restart			•EDM •Nunn			•FRP	
2009		•Prog Start	•Dev Start			•Restart			•EDM •Nunn			•FRP	
2010		•Prog Start	•Dev Start			•Restart			•EDM •Nunn			•FRP	
2011		•Prog Start	•Dev Start			•Restart			•EDM •Nunn	•LRIP		•FRP	

Figure 15. C-5 RERP Yearly Schedule

Note. Each yearly schedule from the GAO reports is shown as a row in the table. Milestones such as DR (design review), LRIP, FRP, IOC, Nunn (Nunn-McCurdy breach), and ReX (restart) are shown. The white cells are the year of the report and milestones shown in the white cells are planned to occur during the year. The milestones shown in the green cells had already occurred at the time of the GAO report. The milestones shown in the yellow cells were planned milestones at the time of the report for the years after the GAO report.

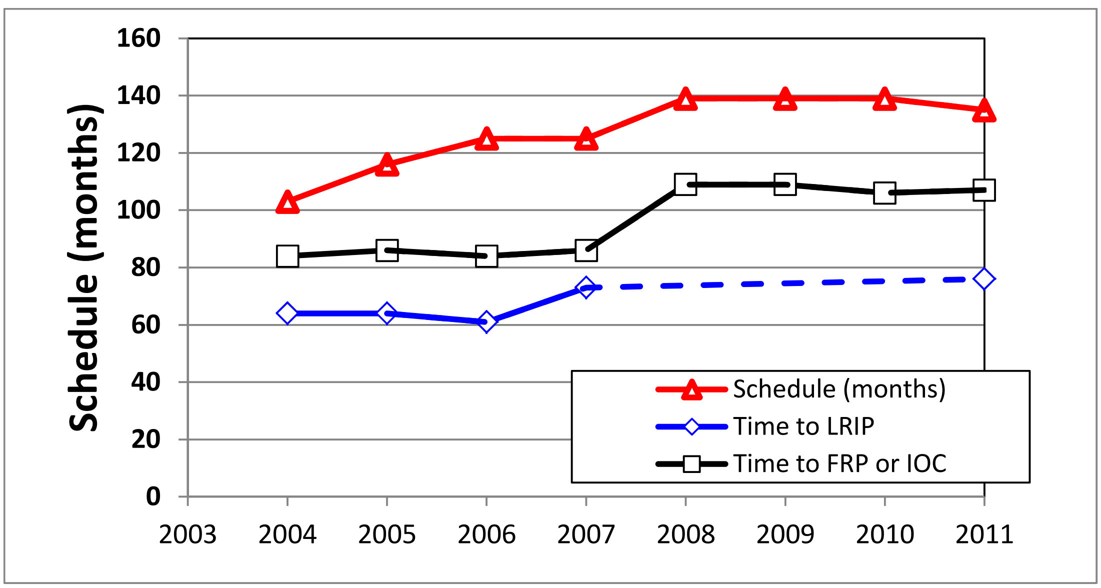

Figure 16. C-5 RERP Schedule (Months From Program Start)

Note. The red line with triangles is the program acquisition cycle time listed in the GAO write-ups (in months). The blue line with diamonds is the time from development start to LRIP (in months). The black line with boxes is the time from development start to FRP (in months). When data points are missing, a dashed line is drawn between points. The dashed lines are for visual purposes only.

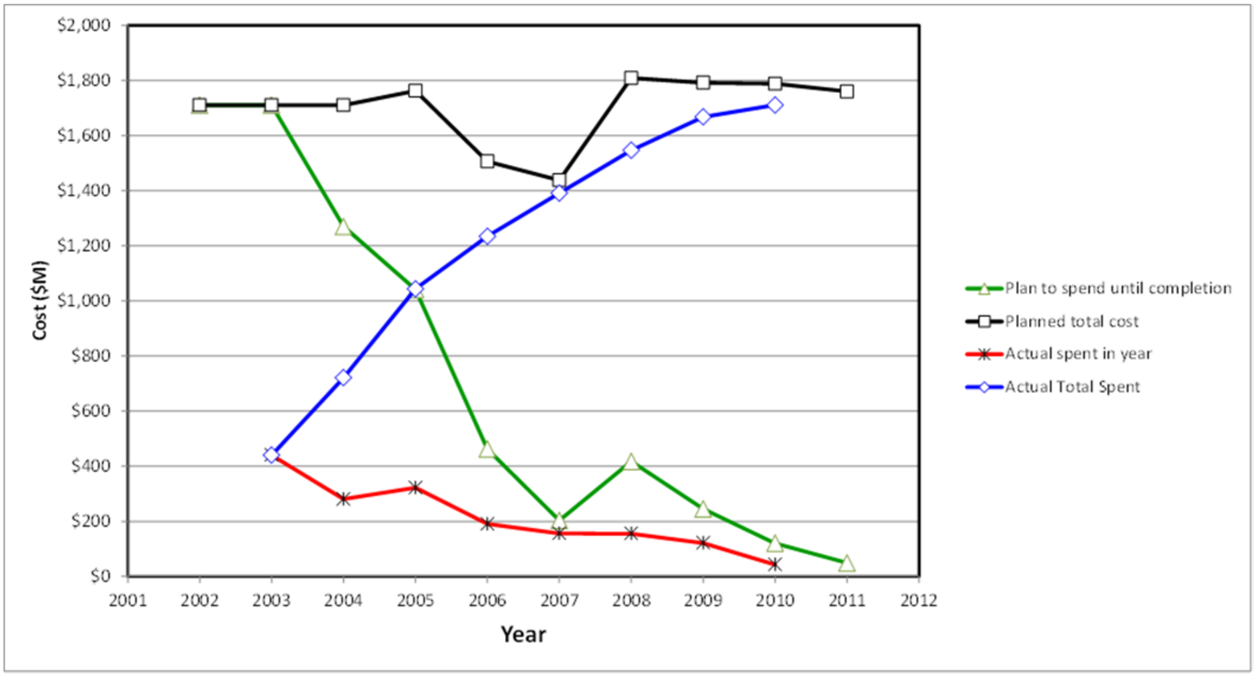

Figure 17. C-5 RERP: R&D Costs

Note. The green line with triangles is the "R&D funding needed to complete" the program and is from the "Program Essentials" section of each GAO report. The black line with boxes is the planned total R&D cost taken from the "Program Performance" section of each report. The red line with black asterisks is the R&D spending during the year. The blue line with diamonds is the Total R&D spending from the beginning of the project. It is derived from the "funding needed to complete" and the "R&D cost" categories from the reports.

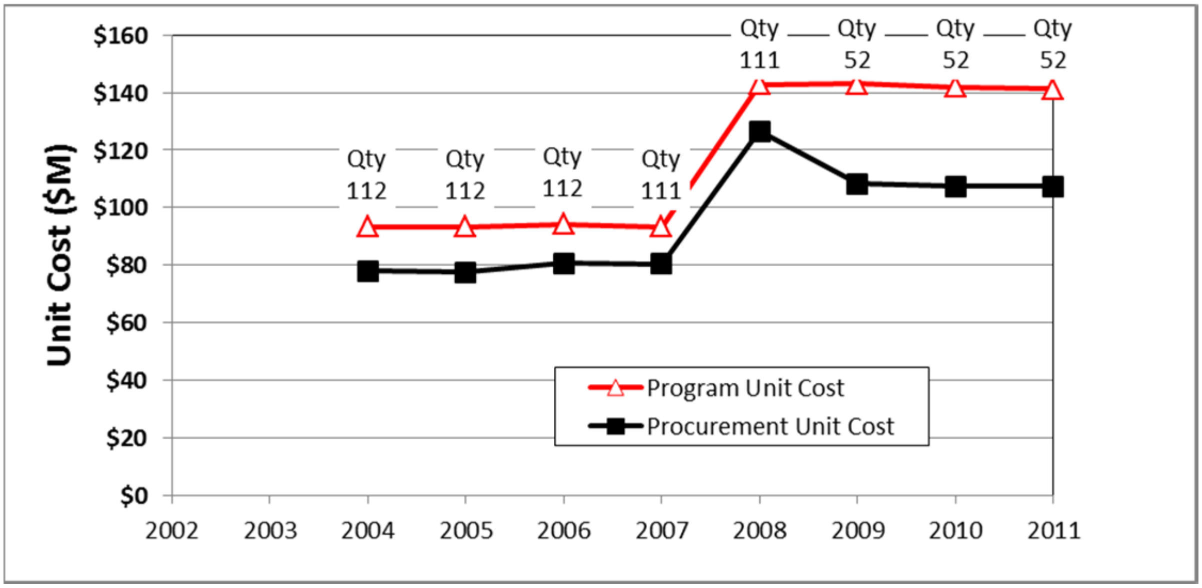

Figure 18. C-5 RERP: Total Production and Unit Cost

Note. The black line with squares is the *procurement* unit cost adjusted for inflation. The red line with triangles is the *program* unit cost adjusted for inflation (the program unit cost includes the R&D costs amortized over the total production lot).
The quantity for 2008 should have been 52.

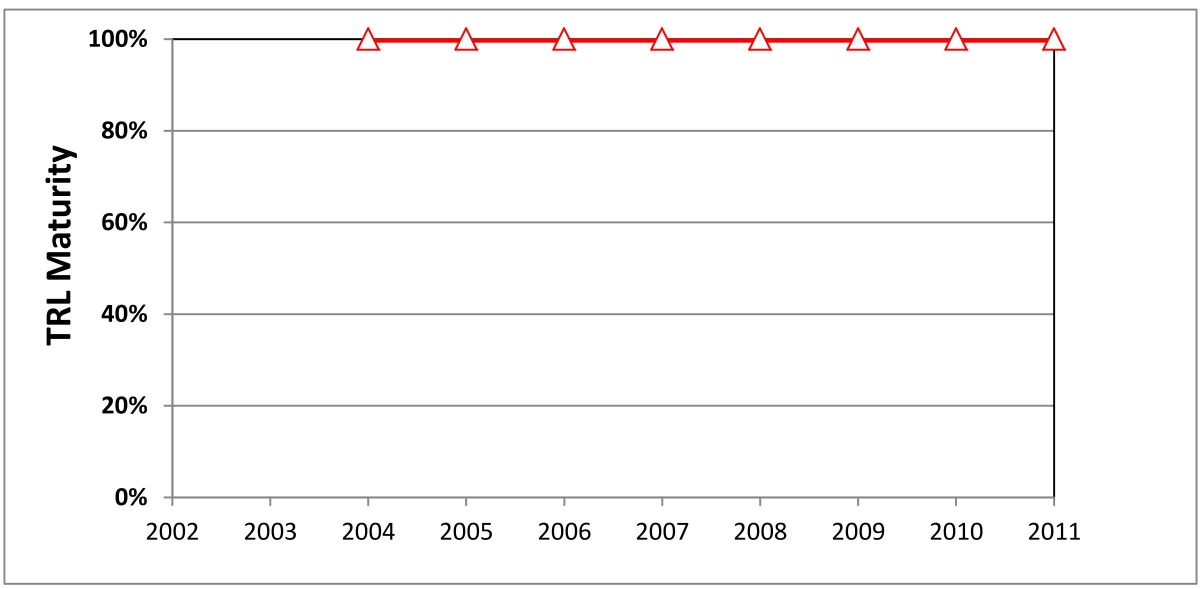

Figure 19. C-5 RERP: Technical Maturity

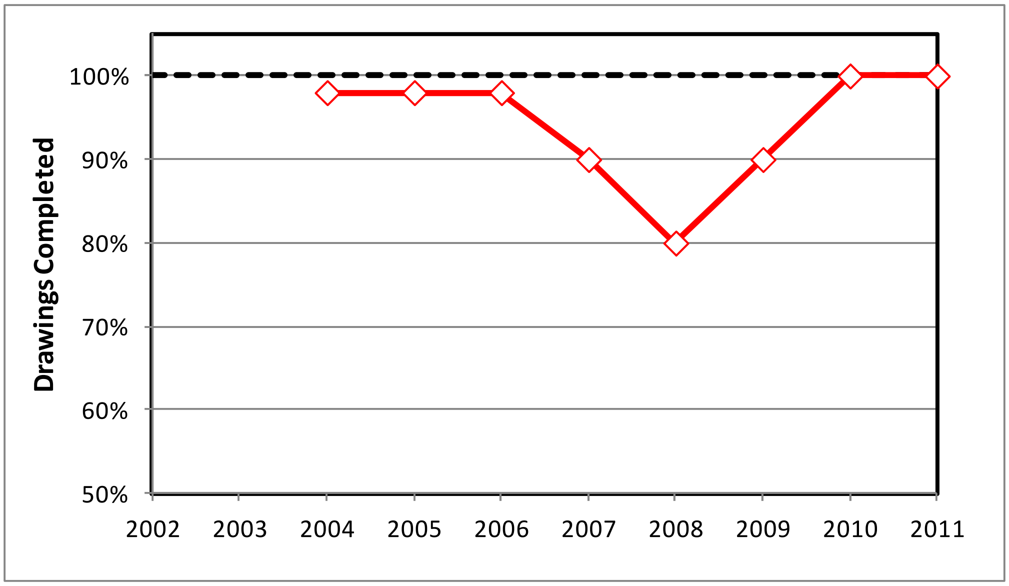

Figure 20. C-5 RERP: Design Drawings Completed

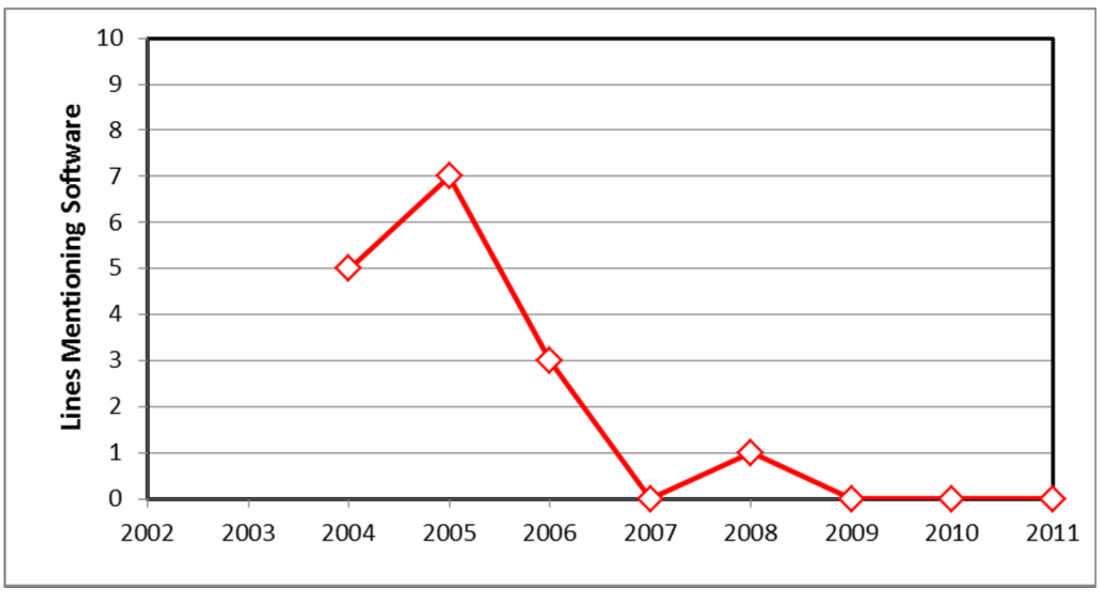

Figure 21. C-5 RERP: Number of Lines Mentioning Software

D. Joint Tactical Radio System (JTRS): 2004–2011 (Eight Years)

The JTRS program scope changed during the evaluation period. This is one program where software was mentioned repeatedly because it is a critical component of the JTRS system. Figure 22 shows the program milestones that were published each year in the GAO reports. This chart is useful because it clearly shows schedule slip as a function of time. Every published schedule is shown as a row in the table. The columns represent the different years in each yearly schedule. For example, in 2005, the LRIP decision was scheduled for April 2006 and the full-rate production decision was planned for June 2007.

The 2006 GAO write-up had the following information regarding the program structure: "The JTRS Cluster 1 program is currently being restructured due to significant cost and schedule problems that came to light in late 2004." Milestones were not given in the 2006 GAO report; however, they were given in the 2007 report. From 2005 to 2011, LRIP slipped four years and five months and the FRP decision slipped five years and five months.

Figure 23 shows the schedule based on the schedule listed in the GAO reports (red line), the schedule until LRIP (blue line) and the schedule to FRP (black line). Values are measured from the start of program development. Data were not reported for 2006 due to the restructuring. The time to LRIP and the time to FRP essentially doubled between 2005 and 2007 (a 100% increase in the schedule).

Figure 24 shows the R&D costs for the program. All costs have been adjusted for inflation. The GAO reports did not report a yearly R&D spending, so it was derived from the reported cost data. In the figure, the planned total program costs are shown as the black line with squares. The reported value for 2009 was artificially low and it was increased up by $172 million so that a realistic program total cost was given for 2009. The data show big total program cost increases for 2006 and 2007 (a total of 73% from 2005–2007).

The R&D funding needed to complete the program, listed in the "Program Essentials" block in each GAO report, is shown as the green line with triangles. In the 2010 GAO report, the "R&D funding needed to complete" data point was missing. A value of $220 million was assumed because it resulted in a linear spending profile from 2009–2011.

The red line with asterisks is the actual R&D spending for each year. Spending was flat throughout the program. The blue line with diamonds is the actual R&D spending from the beginning of the program.

Figure 25 shows the total production quantity, the procurement unit costs,[16] and the program unit costs.[17] There was a large decrease in quantity in 2009 (a 17% decrease) and large increases in the procurement and program unit costs (25%).

Figure 26 shows the technical maturity for each year based on the GAO reports. Twenty critical technologies were identified for the program. Except for 2009, which seems to be in error, the highest percentage of technologies that were reported as mature was 65%.

On most programs, the GAO uses the number of released drawings to measure design maturity. Values were only provided for three years (see Figure 27). The program reported 100% in 2005, but 83% in 2007 and 2008.

The GAO write-ups do not have a specific measure of software maturity. As an approximation, the number of sentences in each report mentioning software was counted as a gauge of the software development. Figure 28 shows the number of lines in the GAO reports that mentioned software. While the write-ups discussed the software issues, the references to software were not proportional to the software problems the program faced.

[16] The procurement unit cost is the total procurement cost divided by the total quantity, which are both identified in the “Program Performance” block of each GAO write-up. Procurement unit cost does not include R&D costs.

[17] The program unit cost is the total program cost divided by the total quantity, which are both identified in the “Program Performance” block of each GAO write-up. The total program costs are the R&D costs plus the procurement costs.

Project	1997	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JTRS Cluster	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
1997														
2000	•Prog Start													
2001	•Prog Start													
2002	•Prog Start			•Dev Start										
2003	•Prog Start			•Dev Start										
2004	•Prog Start			•Dev Start		•DR			•FRP					
2005	•Prog Start			•Dev Start				•LRIP	•FRP					
2006	•Prog Start			•Dev Start		•DR								
2007	•Prog Start			•Dev Start					•DR			•LRIP		•FRP
2008	•Prog Start			•Dev Start						•DR		•LRIP	FRP •	•IOC
2009	•Prog Start			•Dev Start					DR•	•Restart		•LRIP		•IOC
2010	•Prog Start			•Dev Start						•Restart			•LRIP	•IOC
2011	•Prog Start			•Dev Start					DR•	•Restart			•LRIP	

Figure 22. JTRS: Overall Schedule

Note. Each yearly schedule from the GAO reports is shown as a row in the table. Milestones such as DR (design review), LRIP, FRP, IOC, Nunn (Nunn-McCurdy breach), and DevStart (development start) are shown. The white cells are the year of the report and milestones shown in the white cells are planned to occur during the year. The milestones shown in the green cells had already occurred at the time of the GAO report. The milestones shown in the yellow cells were planned milestones at the time of the report for the years after the GAO report.

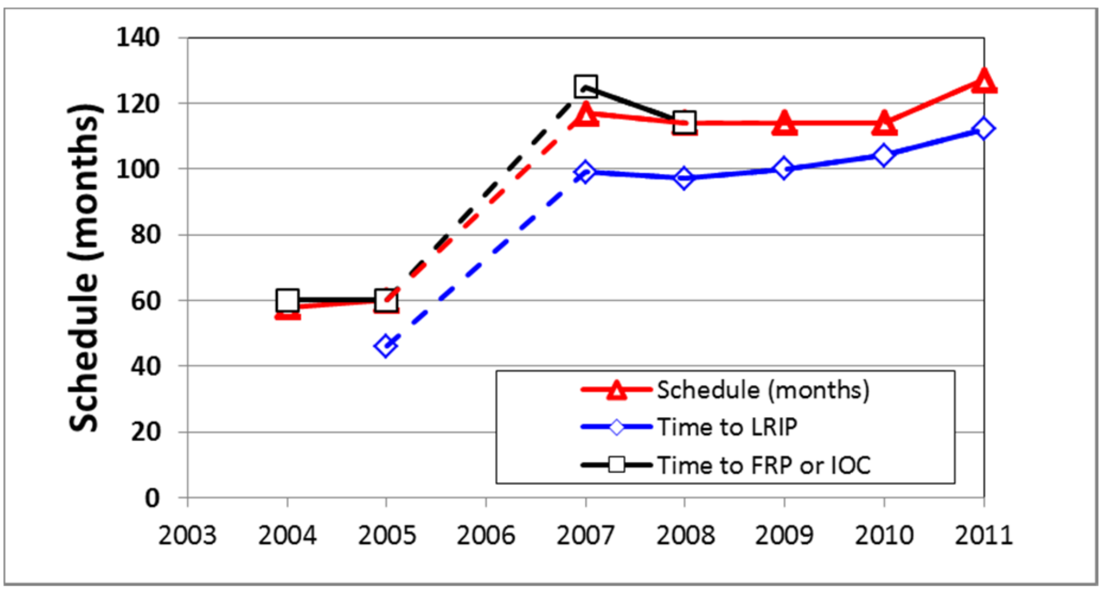

Figure 23. JTRS: Schedule to LRIP and FRP

Note. The red line with triangles is the program acquisition cycle time listed in the GAO write-ups (in months). The blue line with diamonds is the time from development start to LRIP (in months). The black line with boxes is the time from development start to FRP (in months). When data points are missing, a dashed line is drawn between points. The dashed lines are for visual purposes only.

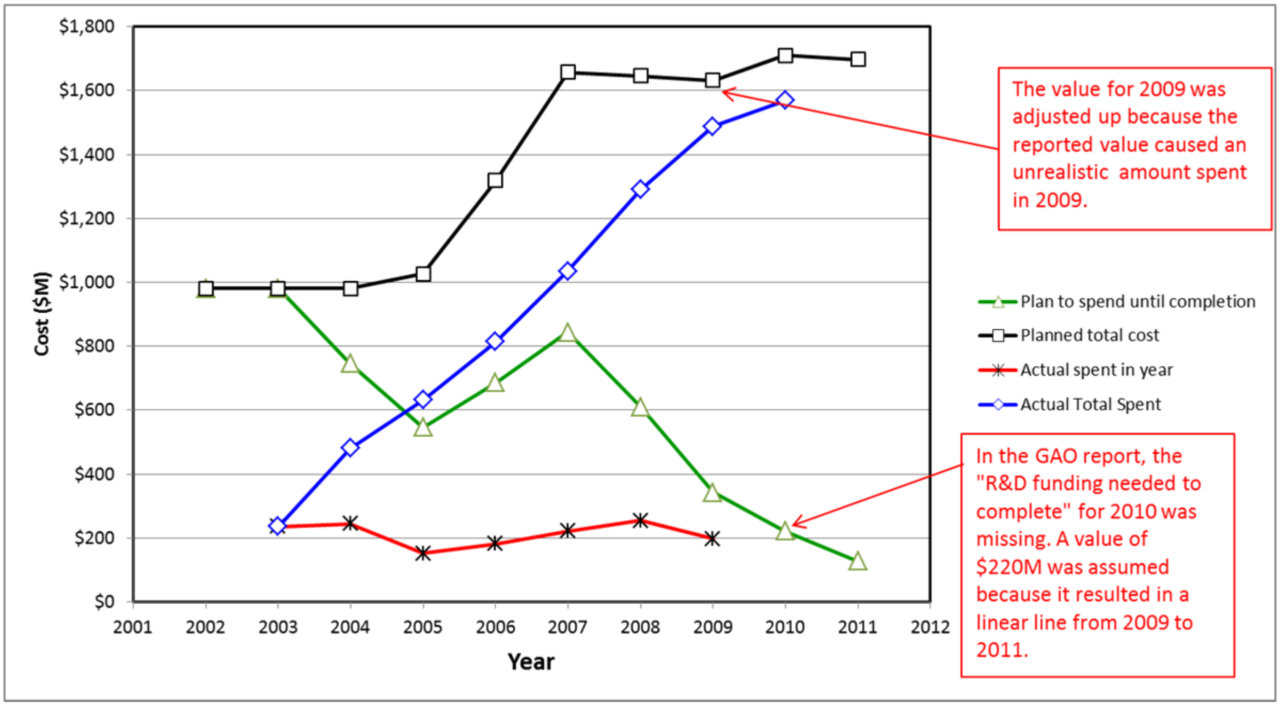

Figure 24. JTRS: Costs by Year for the JTRS Program

Note. The green line with triangles is the “R&D funding needed to complete” the program and is from the “Program Essentials” section of each GAO report. The value for 2010 was missing and a value of $220 million was used to achieve a linear spending profile from 2009–2011. The black line with boxes is the planned total R&D cost taken from the “Program Performance” section of each report. For 2009, the reported value was revised up by $172 million so that a realistic program total cost was given for 2009. The red line with black asterisks is the R&D spending during the year. The blue line with diamonds is the Total R&D spending from the beginning of the project. It is derived from the “funding needed to complete” and the “R&D cost” categories from the reports.

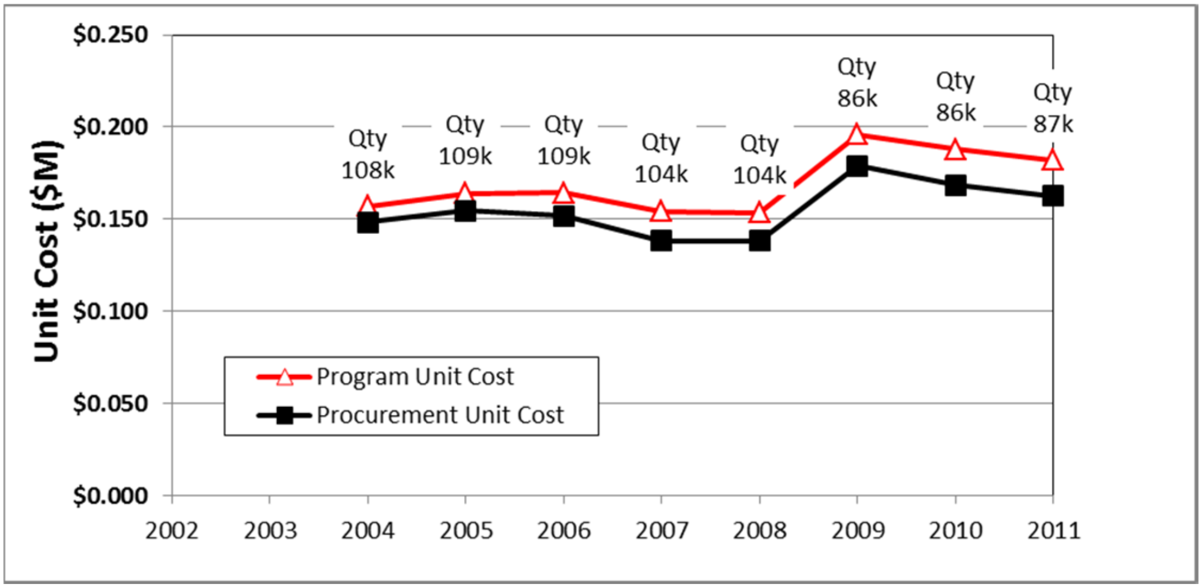

Figure 25. JTRS: Production Quantity and Unit Cost

Note. The black line with squares is the *procurement* unit cost adjusted for inflation.
The red line with triangles is the *program* unit cost adjusted for inflation (the program unit cost includes the R&D costs amortized over the total production lot).

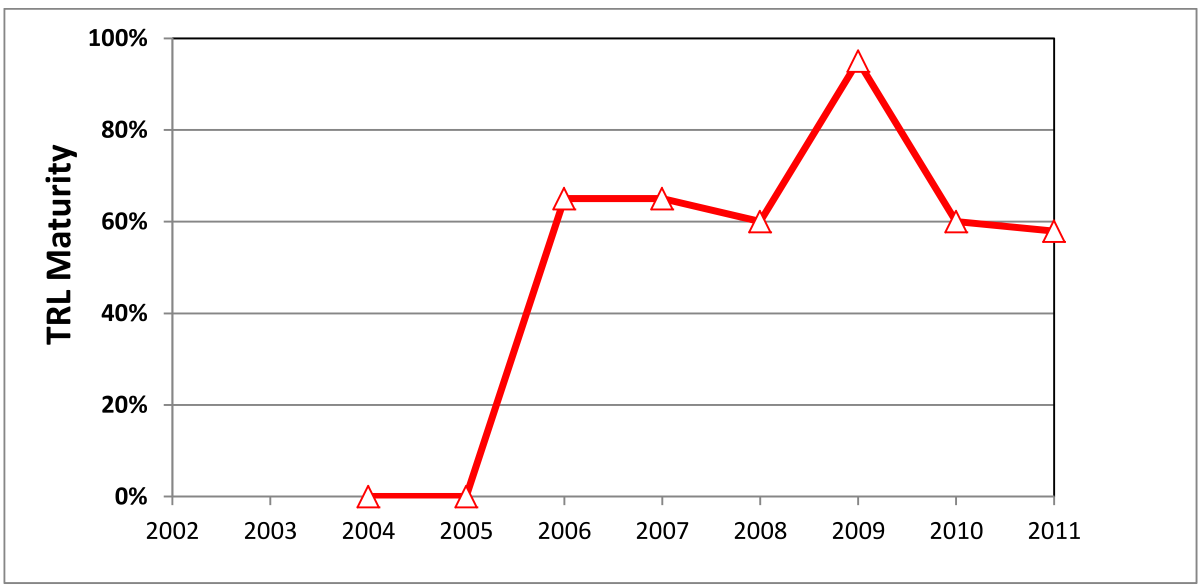

Figure 26. JTRS: Technical Maturity

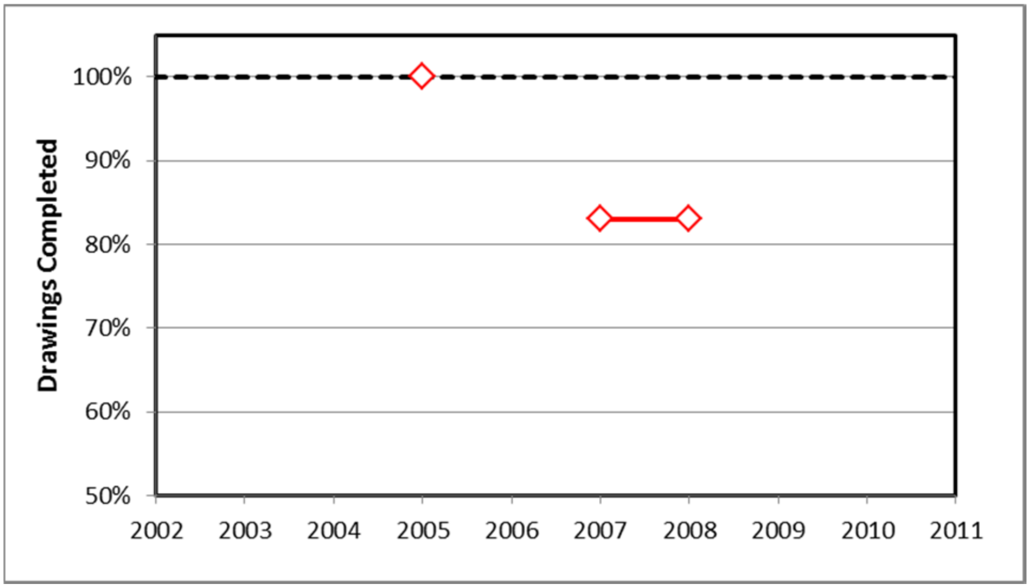

Figure 27. JTRS: Drawings Complete

Note. Data were not available for 2006 and 2009–2011.

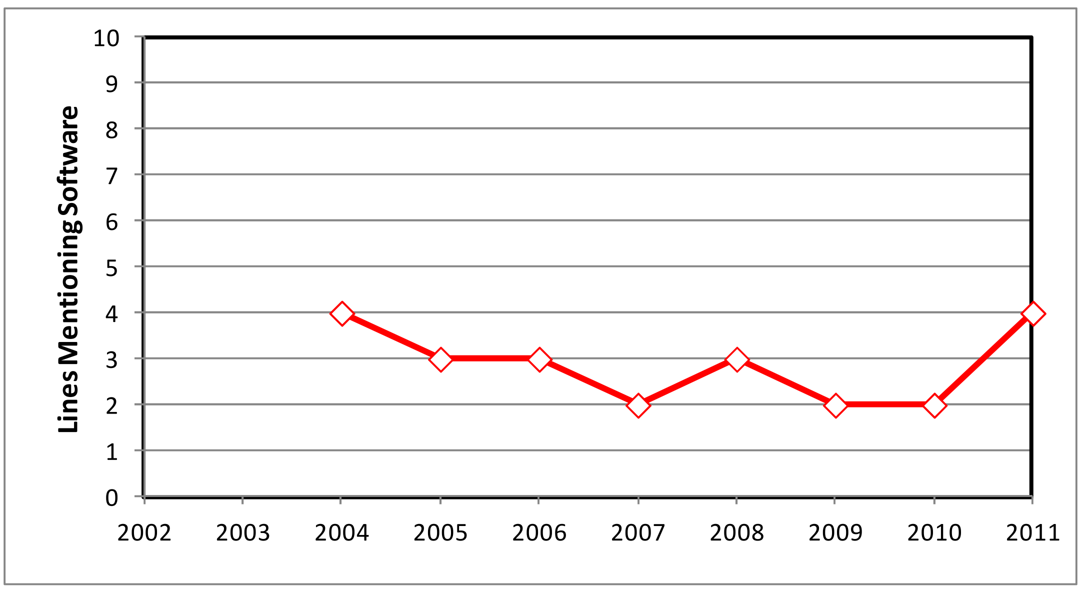

Figure 28. JTRS: Lines in the GAO Reports Mentioning Software

E. Joint Strike Fighter (JSF): 2003–2011 (Nine Years)

Figure 29 shows the program milestones that were published each year in the GAO reports. Every published schedule is shown as a row in the table. The columns represent the different years in each yearly schedule. For example, in 2004, the LRIP decision was scheduled for April 2006 and IOC was planned for April 2010 (USMC version).

The “Acquisition cycle time” is reported in every GAO report. Two values are given: the value given at program start (an historical value) and the most current estimate, which might change every year. In most programs, the planned acquisition cycle time at *program start* does not change because it is a historical value. For the JSF, the “approved” acquisition cycle time in the 2003 report was quoted as 185 months as of October 2001. However, in the 2010 GAO report, the planned acquisition cycle time was quoted as 116 months as of October 2001. That is, the historical value changed. There wasn’t an explanation for why a different value was reported. The change in acquisition cycle times is reflected in Figure 30.

Figure 30 shows the time to LRIP and the time to IOC from the GAO reports (measured from development start). There were very large changes in the “Acquisition cycle time” in 2009 and 2011.

All costs have been adjusted for inflation. The GAO reports did not report the amount of R&D money spent each year, so it was derived from the reported cost data. The RDT&E cost data is shown Figure 31. The planned total costs had significant increases in 2004 (10%), 2005 (19%), and 2011 (11%).

Figure 32 shows the total production quantity, the procurement unit costs, and the program unit costs. There was little change in the production quantity from 2004 until 2011. Program and procurement unit costs increased in 2005 (19%), 2007 (~6%), 2008 (5%), and 2011 (13%).

Figure 33 shows the technical maturity for each year based on the GAO reports. Eight critical technologies were identified for the program and only five were reported mature in 2011.

The design maturity, defined as the “percent of drawings completed”, reached 99% in 2008, but fell to 90% in 2009 (see Figure 34). It is interesting to note that the percent drawings complete is a predictor of future cost over-runs. In 2011, a 13%

increase in RDT&E costs was realized. When the “percent of drawings completed” is an exact multiple of 10%, the validity of the value comes into question.

The GAO write-up in 2006 mentioned software in eight sentences out of 33 sentences describing the program (see Figure 35). The report also had the following: “Officials consider software a high risk item.” However, in the following years, there was much less emphasis on software (an average of about two lines per write-up).

Project	1996	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	
JSF	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	
1996	•Prog Start														
2000	•Prog Start														
2001	•Prog Start		•Dev Start												
2002	•Prog Start		•Dev Start												
2003	•Prog Start		•Dev Start					•LRIP				•IOC			
2004	•Prog Start		•Dev Start					•LRIP				•IOC			
2005	•Prog Start		•Dev Start						•LRIP					•IOC	
2006	•Prog Start		•Dev Start						•LRIP					•IOC	
2007	•Prog Start		•Dev Start						•LRIP					•IOC	
2008	•Prog Start		•Dev Start						DR ••LRIP					•IOC	
2009	•Prog Start		•Dev Start						DR ••LRIP					•IOC	
2010	•Prog Start		•Dev Start						DR ••LRIP					•IOC	
2011	•Prog Start		•Dev Start						DR ••LRIP			•Restart			•IOC

Figure 29. JSF Milestones As Reported in the GAO Major Weapon Systems Report

Note. Each yearly schedule from the GAO reports is shown as a row in the table. Milestones such as DR (design review), LRIP, FRP, IOC, Nunn (Nunn-McCurdy breach), and DevStart (development start) are shown. The white cells are the year of the report and milestones shown in the white cells are planned to occur during the year. The milestones shown in the green cells had already occurred at the time of the GAO report. The milestones shown in the yellow cells were planned milestones at the time of the report for the years after the GAO report.

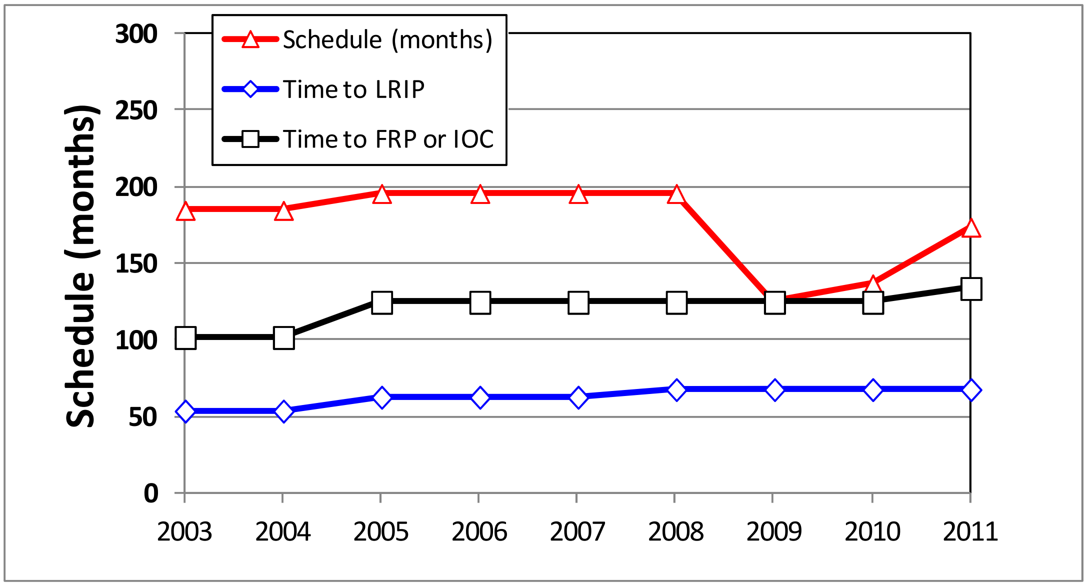

Figure 30. JSF Schedule

Note. The red line with triangles is the program acquisition cycle time listed in the GAO write-ups (in months). The blue line with diamonds is the time from development start to LRIP (in months). The black line with boxes is the time from development start to FRP (in months).

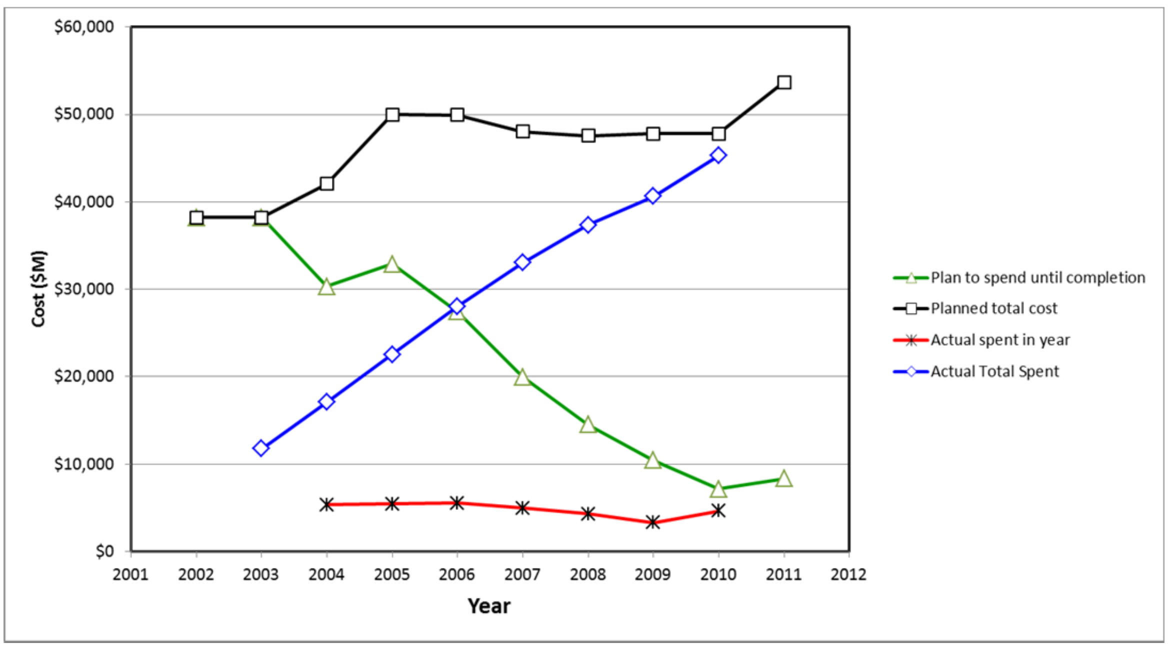

Figure 31. JSF: R&D Costs

Note. The green line with triangles is the R&D funding needed to complete the program and is from the "Program Essentials" section of each GAO report. The black line with boxes is the planned total R&D cost taken from the "Program Performance" section of each report. The red line with black asterisks is the R&D spending during the year. The blue line with diamonds is the Total R&D spending from the beginning of the project. It is derived from the "funding needed to complete" and the "R&D cost" categories from the reports.

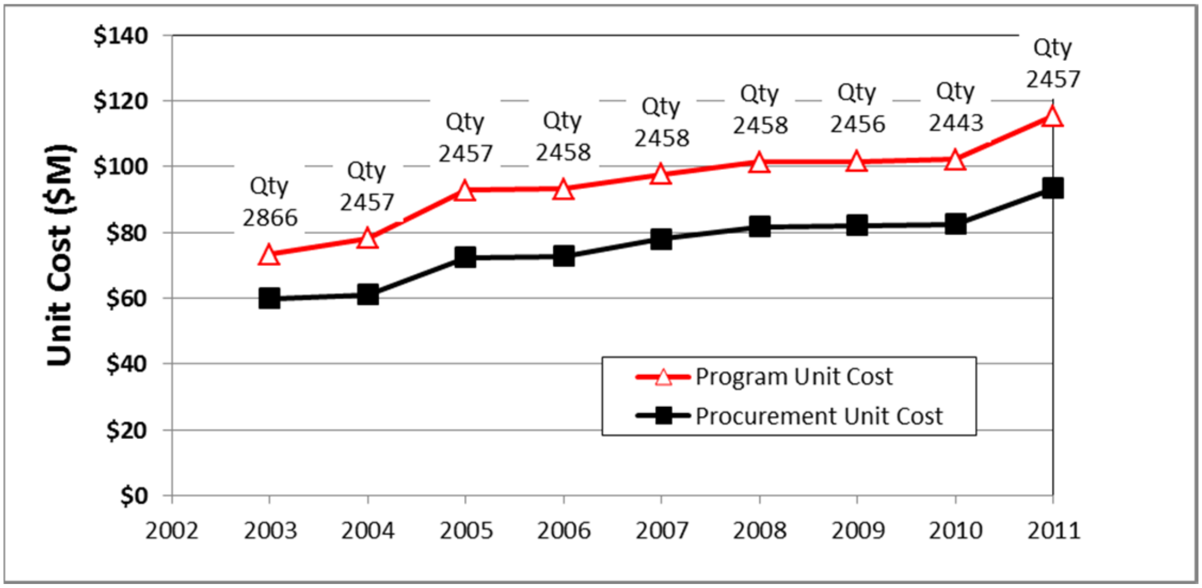

Figure 32. JSF Production Quantity and Unit Cost

Note. The black line with squares is the *procurement* unit cost adjusted for inflation. The red line with triangles is the *program* unit cost adjusted for inflation (the program unit cost includes the R&D costs amortized over the total production lot).

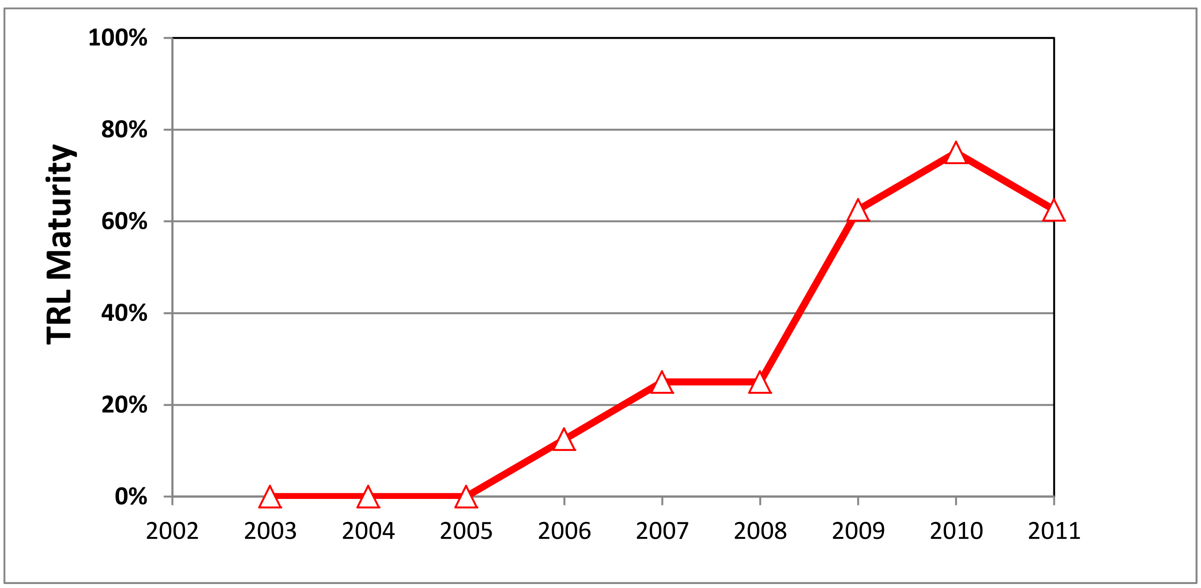

Figure 33. JSF: Technical Maturity

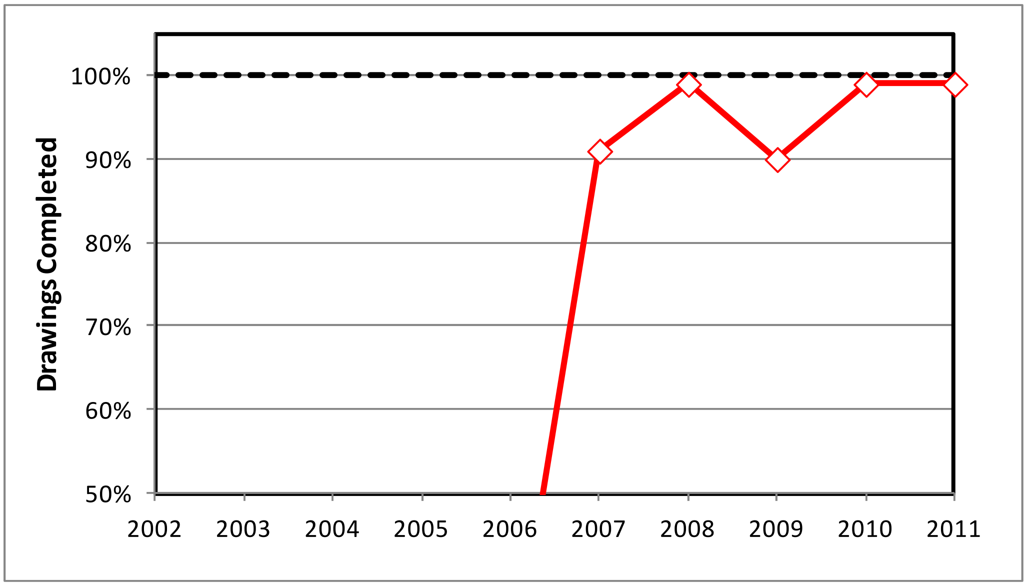

Figure 34. JSF: Design Maturity

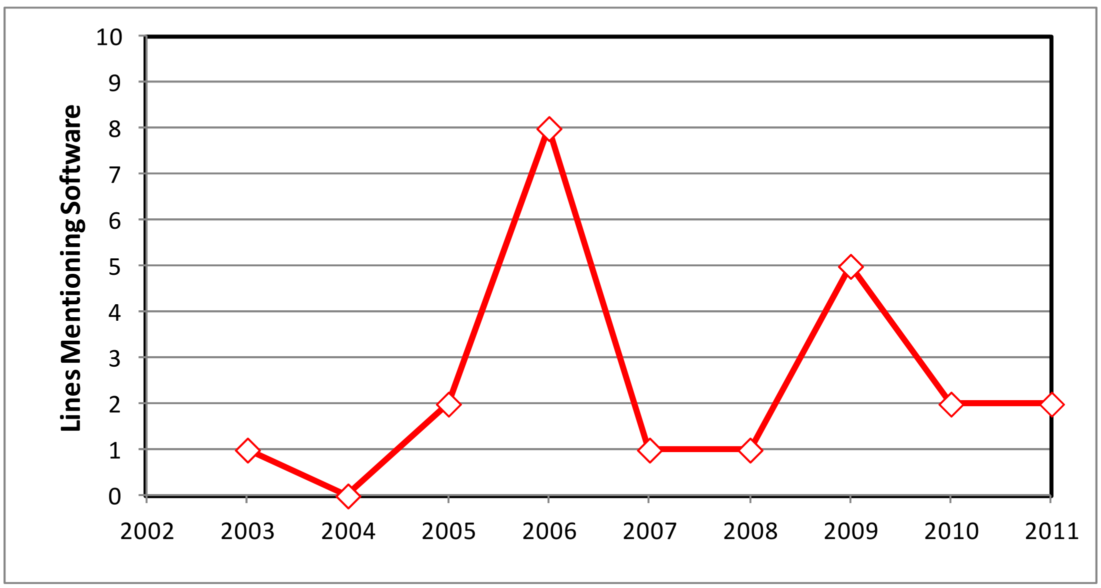

Figure 35. JSF: Number of Sentences in the GAO Write-Ups That Mentioned Software

F. Reaper: 2004–2011 (Eight Years)

The Reaper program scope changed during the study. Figure 36 shows the major milestones identified in the GAO reports. Every published schedule is shown as a row in the table. The columns represent the different years in each yearly schedule. For example, in 2004 the LRIP decision was scheduled for January 2006, the full-rate production decision was planned for January 2008, and IOC was planned for December 2009.

Figure 37 shows the time to LRIP and the time to FRP from the GAO reports. There is a two-year slip in LRIP in the four years from 2004 to 2008, and there is about an equal delay in the FRP decision. IOC did not change from 2004 to 2007, even though LRIP and the FRP decisions slipped significantly during this time period.

Figure 38 shows the R&D costs for the program. All costs have been adjusted for inflation. The GAO reports did not report a yearly R&D spending, so it was derived from the reported cost data. In the figure, the planned total program cost is shown as the black line with squares, and it increases rapidly starting in 2008 due to the increase in production units.

The R&D funding needed to complete the program, listed in the "Program Essentials" block in each GAO report, is shown as the green line with triangles. It grew over time due to the large increase in production units. The 2010 GAO report did not list a figure for this curve so $350 million was assumed.

Figure 39 shows the total production quantity, the procurement unit costs,[18] and the program unit costs.[19] There were large quantity changes in 2008, 2009, 2010, and 2011 (from 63 in 2007 to 391 in 2011). Normally the unit costs go down as quantity increases. They went up in 2008 and 2010, but went down in 2009 and 2011. From 2007 to 2011, unit procurement cost increased by 170%.

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[18] The procurement unit cost is the total procurement cost divided by the total quantity, which are both identified in the "Program Performance" block of each GAO write-up. Procurement unit cost does not include R&D costs.

[19] The program unit cost is the total program cost divided by the total quantity, which are both identified in the "Program Performance" block of each GAO write-up. The total program costs are the R&D costs plus the procurement costs.

Figure 40 shows the technical maturity for each year based on the GAO reports. Four critical technologies were identified for the program, and it was reported that all technologies were mature starting in 2008.

The GAO based design maturity on the number of drawings released. Figure 41 shows the number of design drawings completed for each year. In 2005 the “number of drawings completed” was 35%. It increased to 85% in 2005, then was 80% from 2007–2008. The GAO reports stated 95% in 2009 and 100% in 2011 (a value was not given for 2010).

The write-ups do not have a specific measure of software maturity. As an approximation, the number of sentences in each report mentioning software was counted as a gauge of the software development. Figure 42 shows the number of lines in the GAO reports that mention software. The GAO write-ups do not mention software until 2007. From 2007–2009, software was mentioned once per year. It wasn’t mentioned in 2010, but it was referenced three times in 2011.

Project	0	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Reaper	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
0													
2000													
2001													
2002				•Prog Start		•Dev Start							
2003				•Prog Start		•Dev Start							
2004				•Prog Start		•Dev Start	•DR	•LRIP		•FRP	Last •	•IOC	
2005				•Prog Start		•Dev Start		•DR		•FRP		•IOC	
2006				•Prog Start		•Dev Start		•DR		•FRP		•IOC	
2007				•Prog Start		•Dev Start			•DR		•FRP	•IOC	
2008				•Prog Start		•Dev Start			LRIP	• DR• •IOC			
2009				•Prog Start		•Dev Start				•LRIP	•DR •IOC	•FRP	
2010				•Prog Start		•Dev Start				•LRIP			
2011				•Prog Start		•Dev Start				•LRIP			•IOC

Figure 36. Reaper Schedule

Note. Each yearly schedule from the GAO reports is shown as a row in the table. Milestones such as DR (design review), LRIP, FRP, IOC, Nunn (Nunn-McCurdy breach), and DevStart (development start) are shown. The white cells are the year of the report and milestones shown in the white cells are planned to occur during the year. The milestones shown in the green cells had already occurred at the time of the GAO report. The milestones shown in the yellow cells were planned milestones at the time of the report for the years after the GAO report.

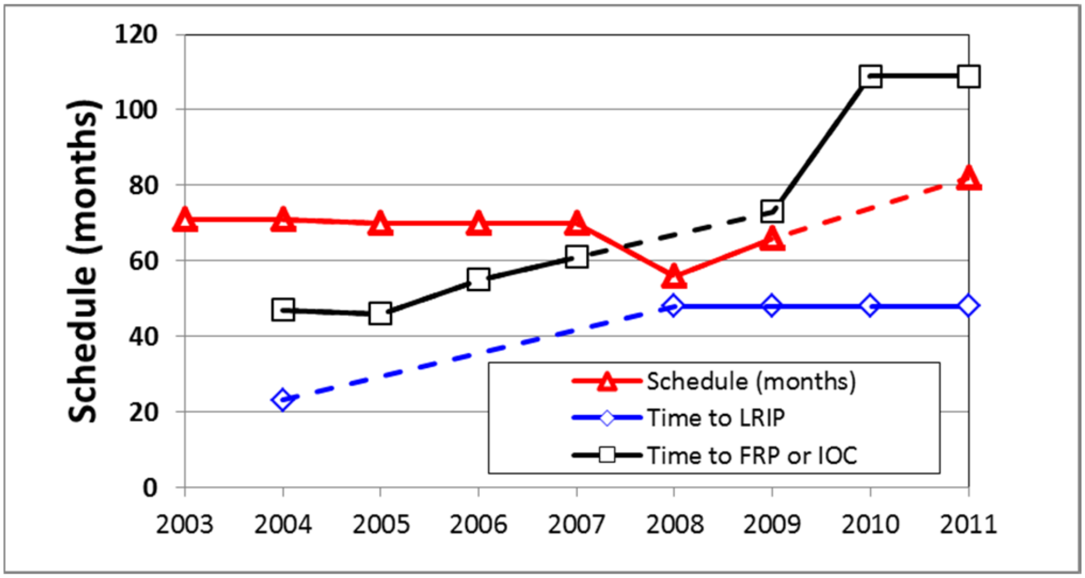

Figure 37. Reaper: Time to LRIP and Time to IOC

Note. The red line with triangles is the program acquisition cycle time listed in the GAO write-ups (in months). The blue line with diamonds is the time from development start to LRIP (in months). The black line with boxes is the time from development start to FRP (in months). When data points are missing, a dashed line is drawn between points. The dashed lines are for visual purposes only.

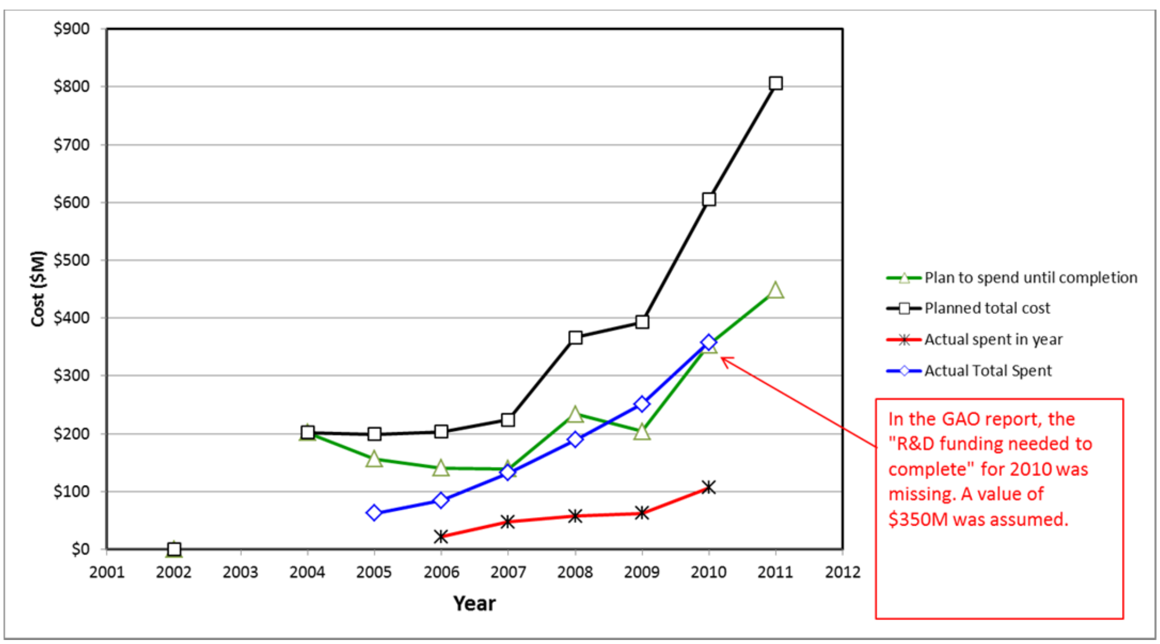

Figure 38. Reaper R&D Costs

Note. The green line with triangles is the R&D funding needed to complete the program and is from the “Program Essentials” section of each GAO report. The black line with boxes is the planned total R&D cost taken from the “Program Performance” section of each report. The red line with black asterisks is the R&D spending during the year. The blue line with diamonds is the Total R&D

spending from the beginning of the project. It is derived from the "funding needed to complete" and the "R&D cost" categories in the reports.

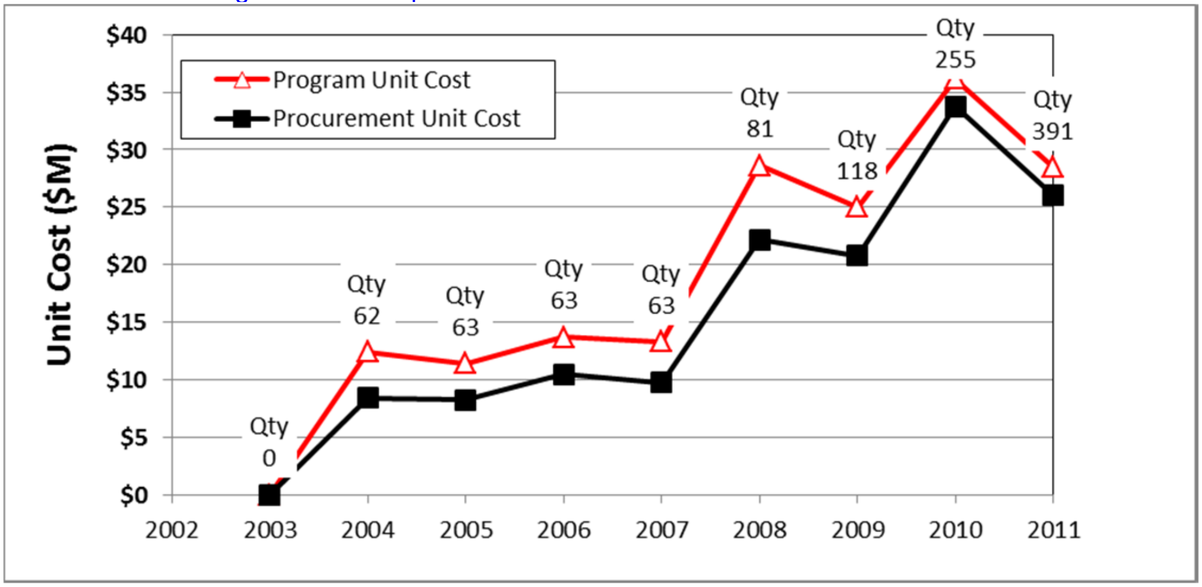

Figure 39. Reaper: Production Quantity and Unit Cost

Note. The blue line with diamonds is the total production plan by year. Values are on the left axis. The red line with triangles is the unit cost adjusted for inflation (the unit cost includes the R&D costs amortized over the total production lot). Values are shown on the right axis.

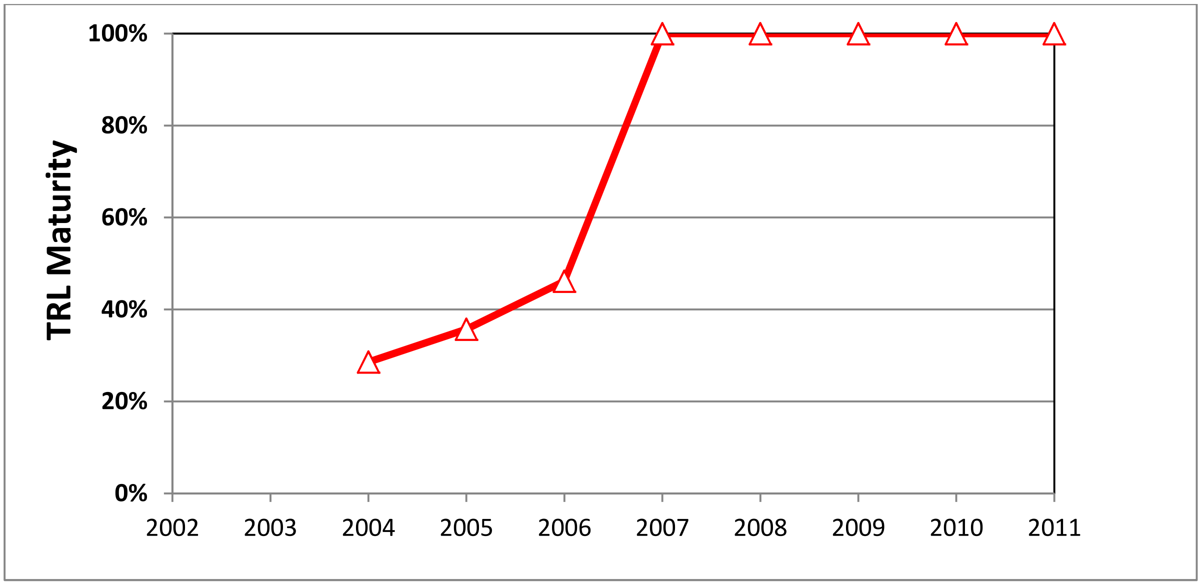

Figure 40. Reaper: Technical Maturity

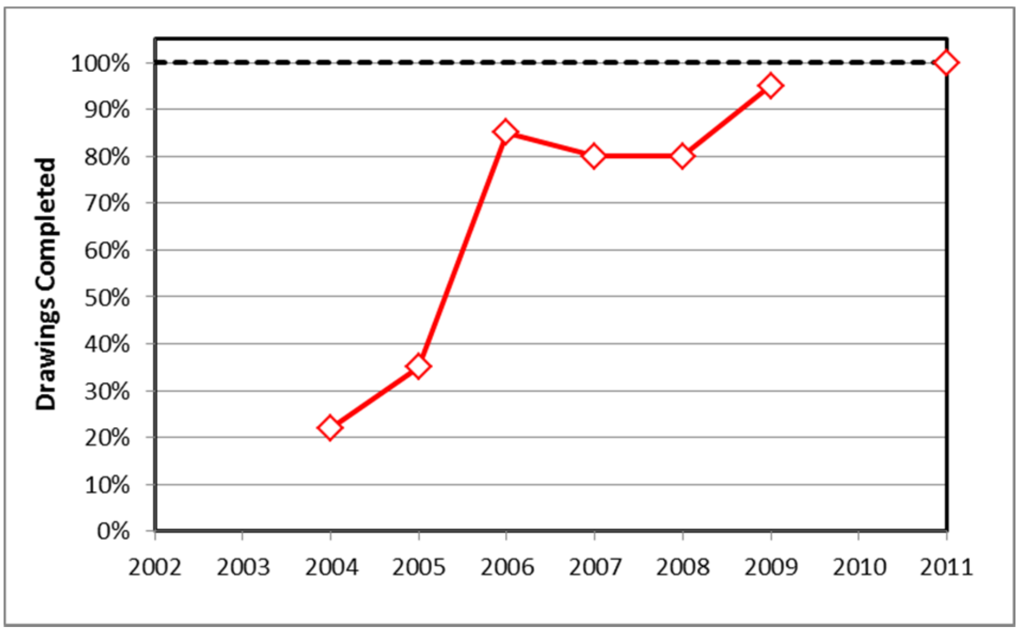

Figure 41. Reaper: Drawings Completed

Note. Data for 2010 are missing from the GAO report.

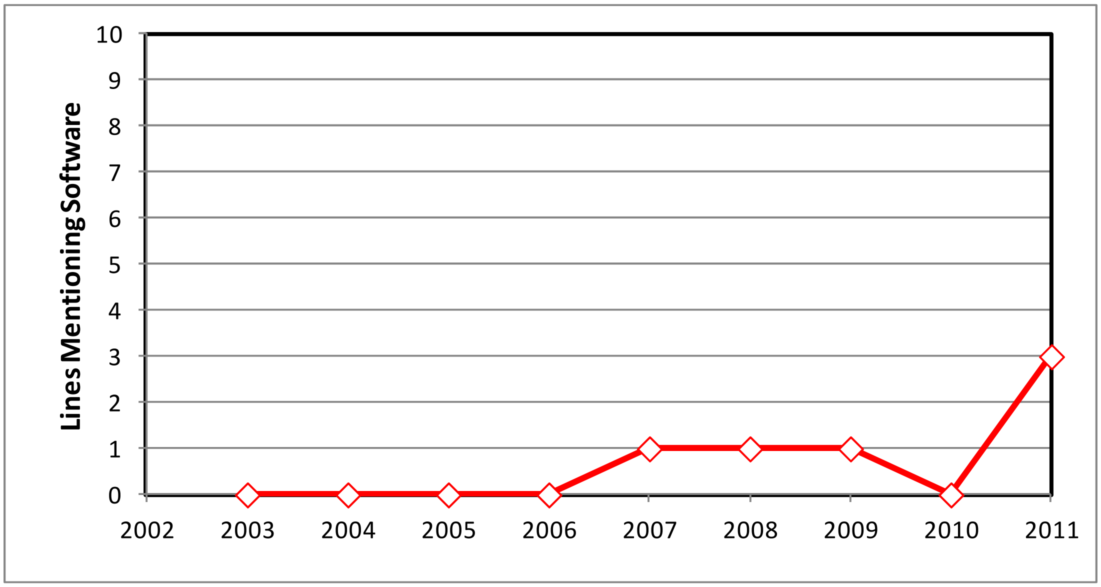

Figure 42. Reaper: Number of Sentences That Mention Software in the GAO Reports

G. Global Hawk: 2004–2011 (Eight Years)

The yearly schedules and milestones for the Global Hawk program are shown in Figure 43. Every published schedule is shown as a row in the table. The columns represent the different years from the schedules shown in the GAO reports. For example, in 2004, IOC was scheduled for December 2005 and the full-rate production decision was planned for November 2006.

This chart is useful because it clearly shows schedule slip as a function of time. There was a Nunn-McCurdy breach in 2005, but it wasn't reflected into the write-up until 2007.

Figure 44 shows the time to a major milestone measured in months from development start. The reported "acquisition cycle time" was measured from development start to IOC, which was planned to occur before the FRP decision. The acquisition cycle time remained 57 months until 2007 when it increased to 78 months. Thereafter, it was reported as TBD (to be defined).

The system was already in LRIP production (although one could argue that the planes were really EDMs). There was a very large increase in the schedule in

2007 when the time to FRP jumped from 74 months in 2006 to 97 months in 2007 (a 31% increase). There was a small increase in the schedule in 2009.

Figure 45 shows the R&D costs for the program. All costs have been adjusted for inflation. In the figure, the planned total program cost is shown as the black line with squares.

The R&D funding needed to complete the program, listed in the “Program Essentials” block in each GAO report, is shown as the green line with triangles. The GAO reports did not report a yearly R&D spending, so it was derived from the reported cost data. The red line with asterisks is the actual R&D spending for each year. The blue line with diamonds is the actual R&D spending from the beginning of the program.

Figure 46 shows the total production quantity, the procurement unit costs,[20] and the program unit costs.[21] The planned quantity was flat at 51 units from 2004–2006 and was then flat at 54 units from 2007–2010. The quantity increased 43% in 2011 to 77 units. While the program unit cost decreased 5% in 2011 due to the increase in quantity, the procurement unit cost actually rose 7%. Normally, procurement unit costs should decrease due to learning curve effects and fixed overhead expenses being spread out over more units.

Figure 47 shows the technical maturity for each year based on the GAO reports. Initially, 14 technologies were reported as critical, but the number dropped to 10 in 2007. All were identified as mature starting in 2007.

Figure 48 shows the number of design drawings completed for each year. Data for 2006 were unclear and are not plotted. The 2005 GAO report states that 90% of the engineering drawings were completed by late FY 2004. The reports

[20] The procurement unit cost is the total procurement cost divided by the total quantity, which are both identified in the “Program Performance” block of each GAO write-up. Procurement unit cost does not include R&D costs.

[21] The program unit cost is the total program cost divided by the total quantity, which are both identified in the “Program Performance” block of each GAO write-up. The total program costs are the R&D costs plus the procurement costs.

stated 100% in 2007 and thereafter, although the 2008 report stated, “however, frequent and substantive engineering changes increased development and airframe costs and delayed delivery and testing schedules.” So while the drawings were “released,” they were far from being mature.

The write-ups do not have a specific measure of software maturity. As an approximation, the number of sentences in each report mentioning software was counted as a gauge of the software development. Figure 49 shows the number of lines in the GAO reports that mention software. Software was mentioned twice per year for the years 2007–2010.

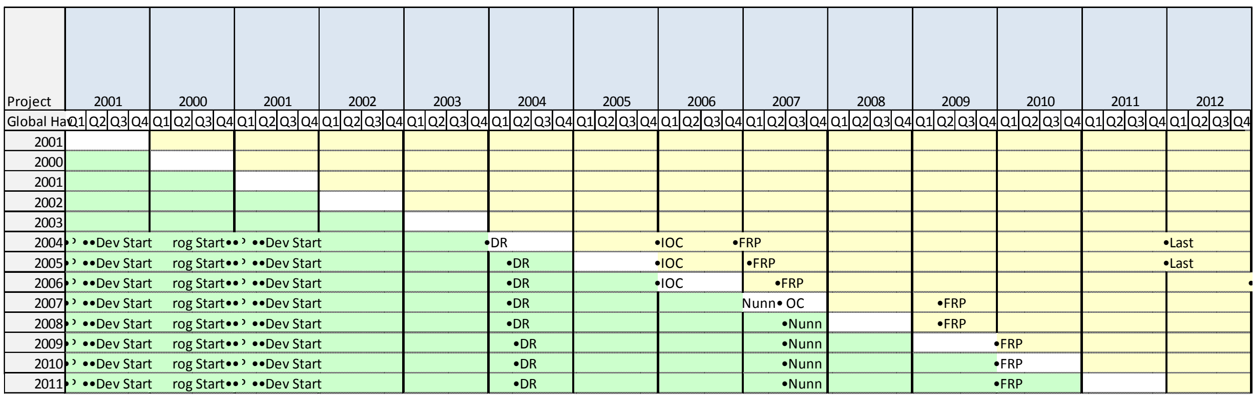

Figure 43. Global Hawk Schedules

Note. Each yearly schedule from the GAO reports is shown as a row in the table. Milestones such as DR (design review), LRIP, FRP, IOC, Nunn (Nunn-McCurdy breach), and DevStart (development start) are shown. The white cells are the year of the report and milestones shown in the white cells are planned to occur during the year. The milestones shown in the green cells had already occurred at the time of the GAO report. The milestones shown in the yellow cells were planned milestones at the time of the report for the years after the GAO report.

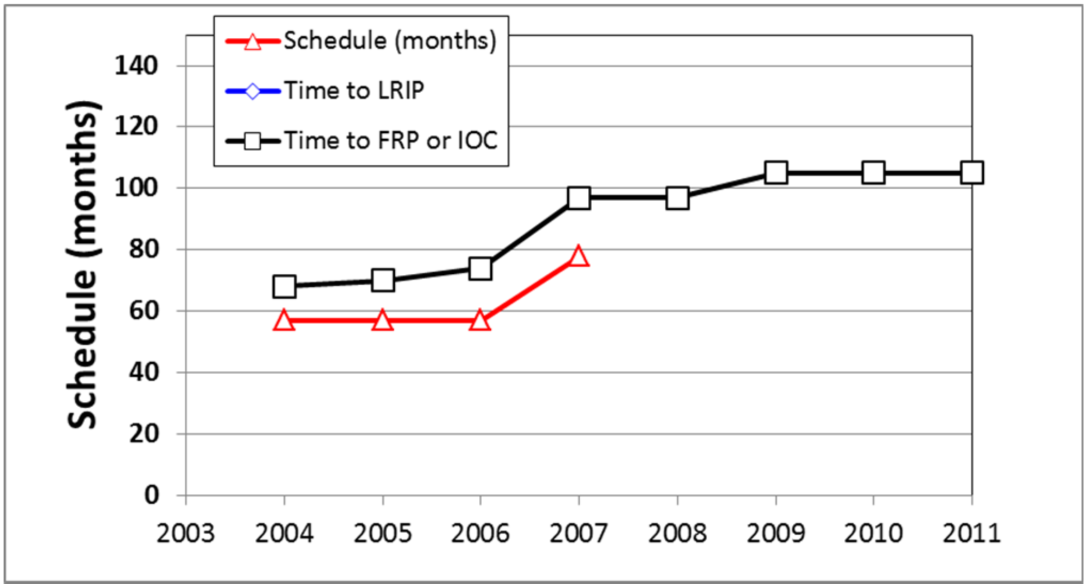

Figure 44. Global Hawk: Time to FRP

Note. The red line with triangles is the program acquisition cycle time listed in the GAO write-ups (in months). It was measured from development start to IOC, which was planned to occur before the FRP decision. After 2007, it was listed as "TBD." The black line with boxes is the time from development start to FRP (in months).

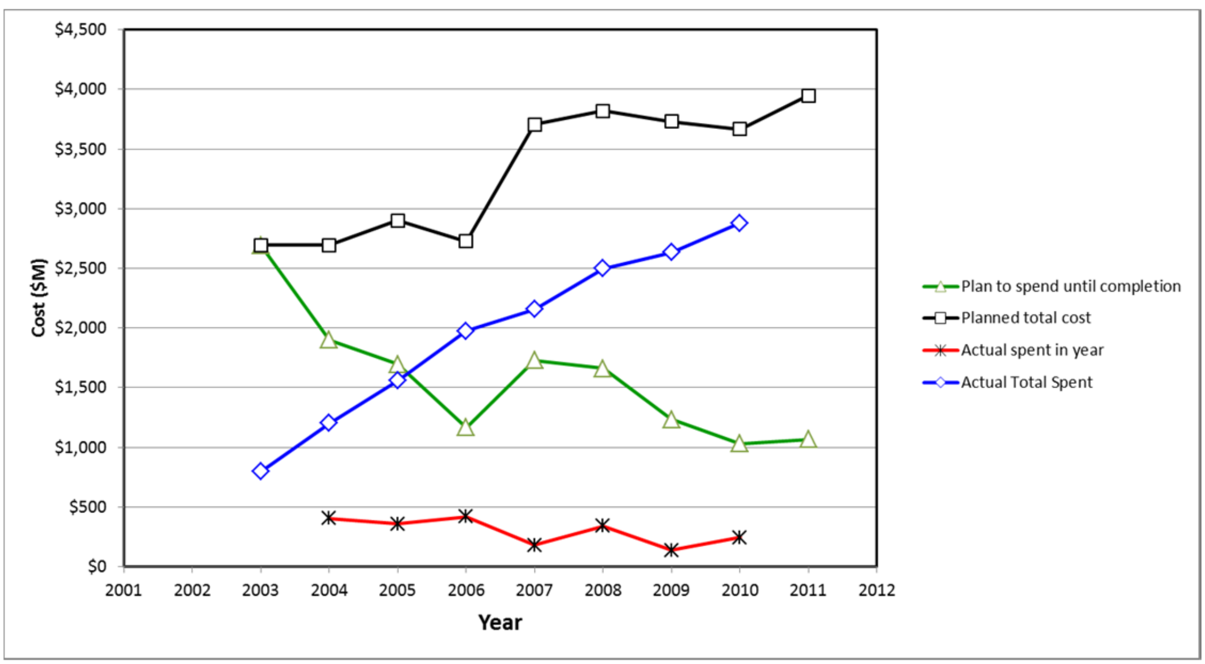

Figure 45. Global Hawk: R&D Costs By Year (Derived From the GAO Data)

Note. The green line with triangles is the R&D funding needed to complete the program and is from the "Program Essentials" section of each GAO report. The black line with boxes is the planned total R&D cost taken from the "Program Performance" section of each report. The red line with black asterisks is the R&D spending during the year. The blue line with diamonds is the Total R&D

spending from the beginning of the project. It is derived from the “funding needed to complete” and the “R&D cost” categories in the reports.

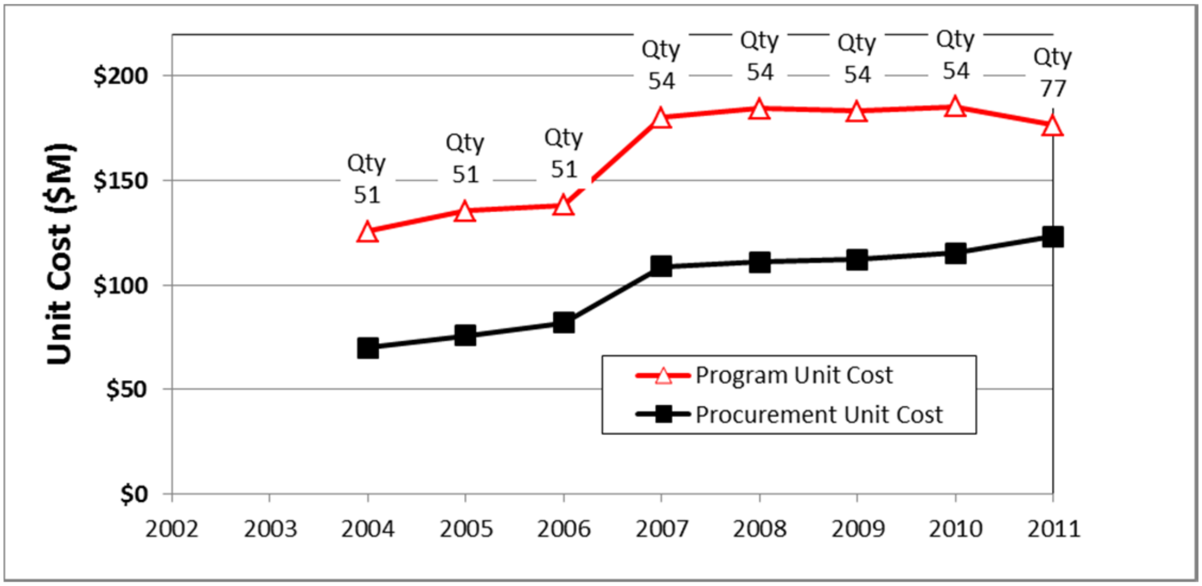

Figure 46. Global Hawk: Production Quantity and Unit Cost

Note. The black line with squares is the *procurement* unit cost adjusted for inflation. The red line with triangles is the *program* unit cost adjusted for inflation (the program unit cost includes the R&D costs amortized over the total production lot).

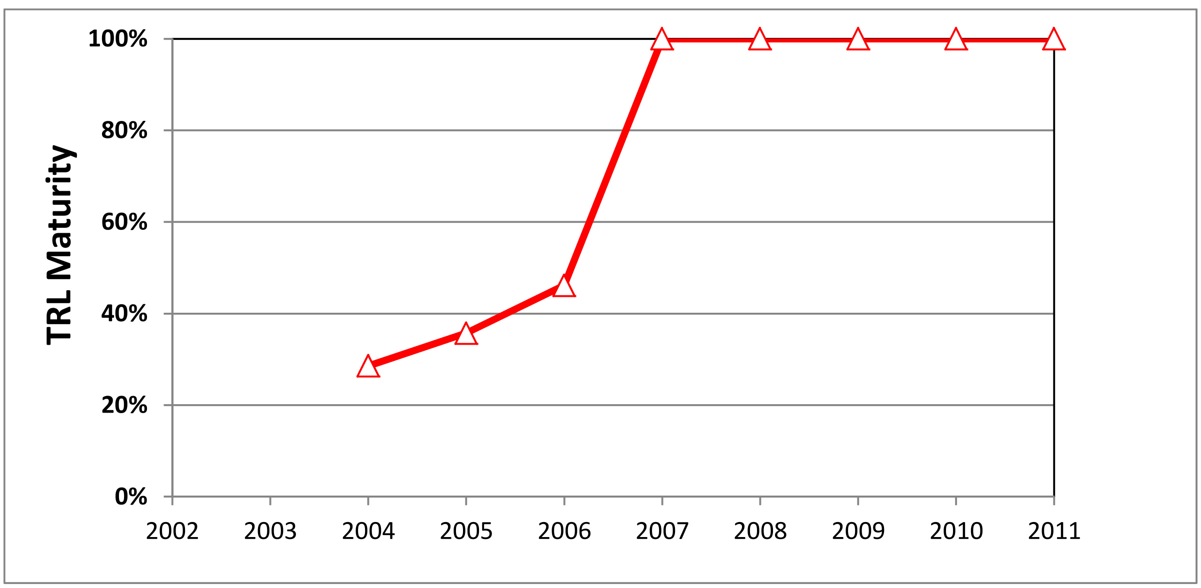

Figure 47. Global Hawk: Technical Maturity

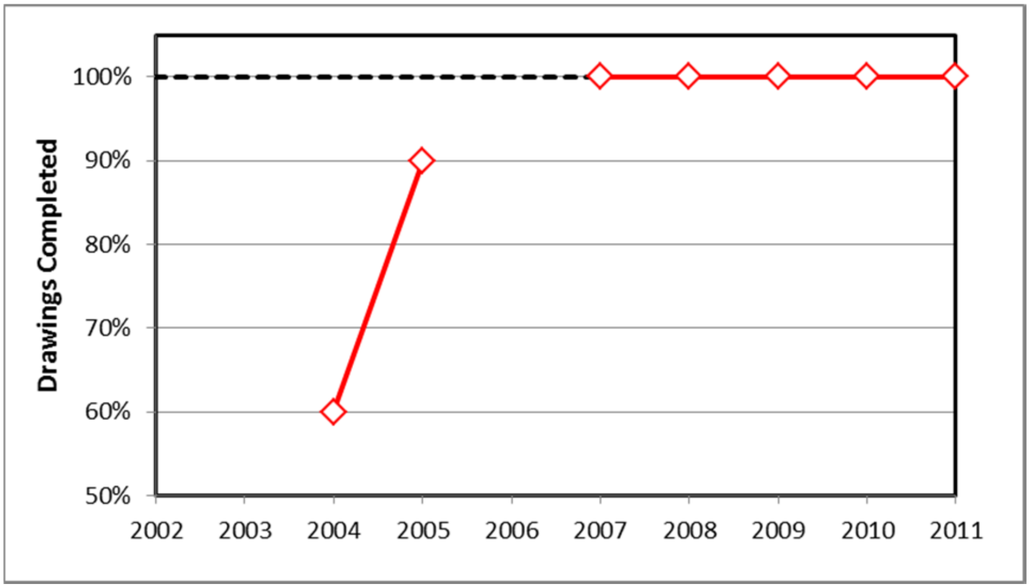

Figure 48. Global Hawk: Drawings Completed

Note. The number of drawings completed was not reported in 2006.

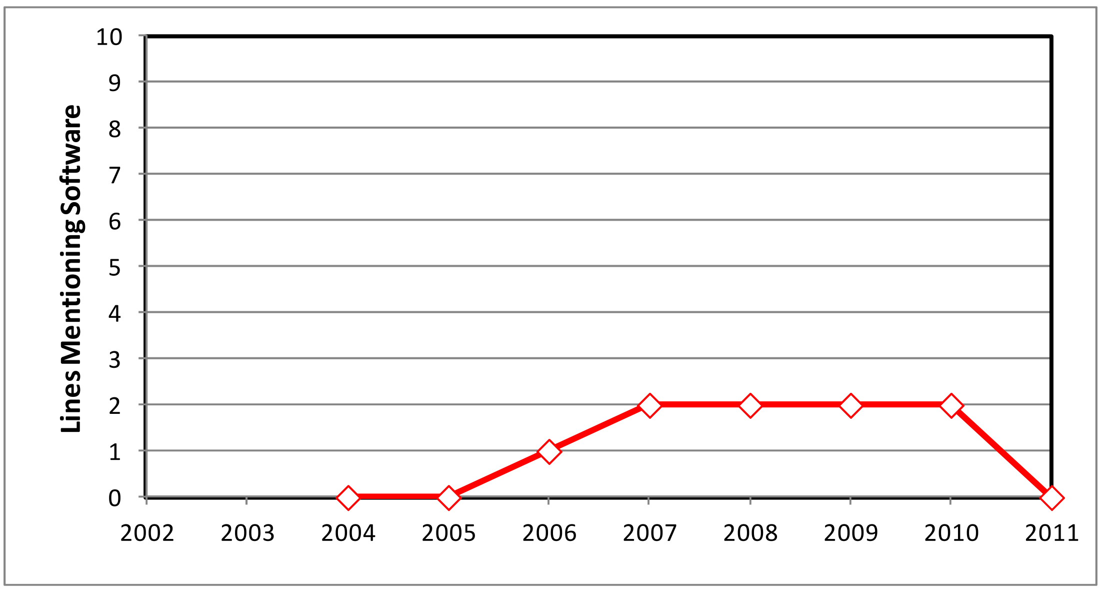

Figure 49. Global Hawk: Number of Lines Mentioning Software

H. Space Based Infrared System (SBIRS) High: 2003–2011 (Nine Years)

A historical look at the major SBIRS milestones by year is shown in Figure 50. Every published schedule is shown as a row in the table. The columns represent the different years in each program schedule from the GAO reports. In 2003, the first satellite launch was referred to as LRIP. For the following years, IOC was used to denote the first satellite delivery. For example, in 2003, satellite launch (LRIP) was scheduled for October 2006. In 2004, IOC was planned for September 2006. There was a Nunn-McCurdy breach in May 2004, which shows up as a large program unit cost increase in 2006 (the increase from 2004 to 2006 was 81%).

Figure 51 shows the R&D costs for the program. All costs have been adjusted for inflation. The GAO reports did not report a yearly R&D spending amount, so it was derived from the reported cost data. In the figure, the planned total program cost is shown as the black line with squares.

The R&D funding needed to complete the program, listed in the "Program Essentials" block in each GAO report, is shown as the green line with triangles.

The red line with asterisks is the actual R&D spending for each year. The blue line with diamonds is the actual R&D spending from the beginning of the program.

Figure 52 shows the total production quantity, the procurement unit costs,[22] and the program unit costs.[23] Because the system is a specialized satellite, the production quantity is very low and, thus, there can very large swings in the unit cost.

Figure 53 shows the technical maturity for each year based on the GAO reports. Three critical technologies were identified for the program, and it was reported that all technologies were mature for 2003-2008 and 2010. In the 2009 report, the GAO report stated that the program had split one technology into two, one of which was immature.

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[22] The procurement unit cost is the total procurement cost divided by the total quantity, which are both identified in the "Program Performance" block of each GAO write-up. Procurement unit cost does not include R&D costs.

[23] The program unit cost is the total program cost divided by the total quantity, which are both identified in the "Program Performance" block of each GAO write-up. The total program costs are the R&D costs plus the procurement costs.

Figure 55 shows the number of completed drawings. The data are not consistent with the schedule slip and the continued increase in spending from 2003–2011. RDT&E spending was $1.52 billion, even though there wasn't a change in the "number of drawings completed." The relatively flat percentage of drawings completed (from 2009–2011) is also not consistent with the continued increase in RDT&E costs during those years.

The write-ups do not have a specific measure of software maturity. As an approximation, the number of sentences in each report mentioning software was counted as a gauge of the software development. Figure 56 shows the number of lines in the GAO reports that mention software. The GAO write-ups mention software at least five times from 2008–2011, which is much more often than the typical GAO program write-up.

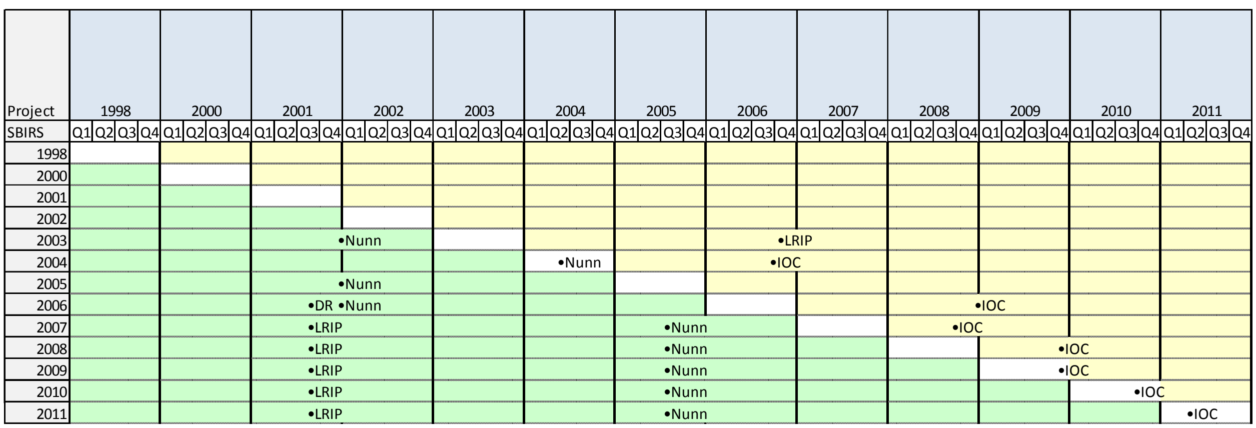

Figure 50. SBIRS Schedule

Note. Each yearly schedule from the GAO reports is shown as a row in the table. Milestones such as DR (design review), LRIP, FRP, IOC, Nunn (Nunn-McCurdy breach), and DevStart (development start) are shown. The white cells are the year of the report and milestones shown in the white cells are planned to occur during the year. The milestones shown in the green cells had already occurred at the time of the GAO report. The milestones shown in the yellow cells were planned milestones at the time of the report for the years after the GAO report.

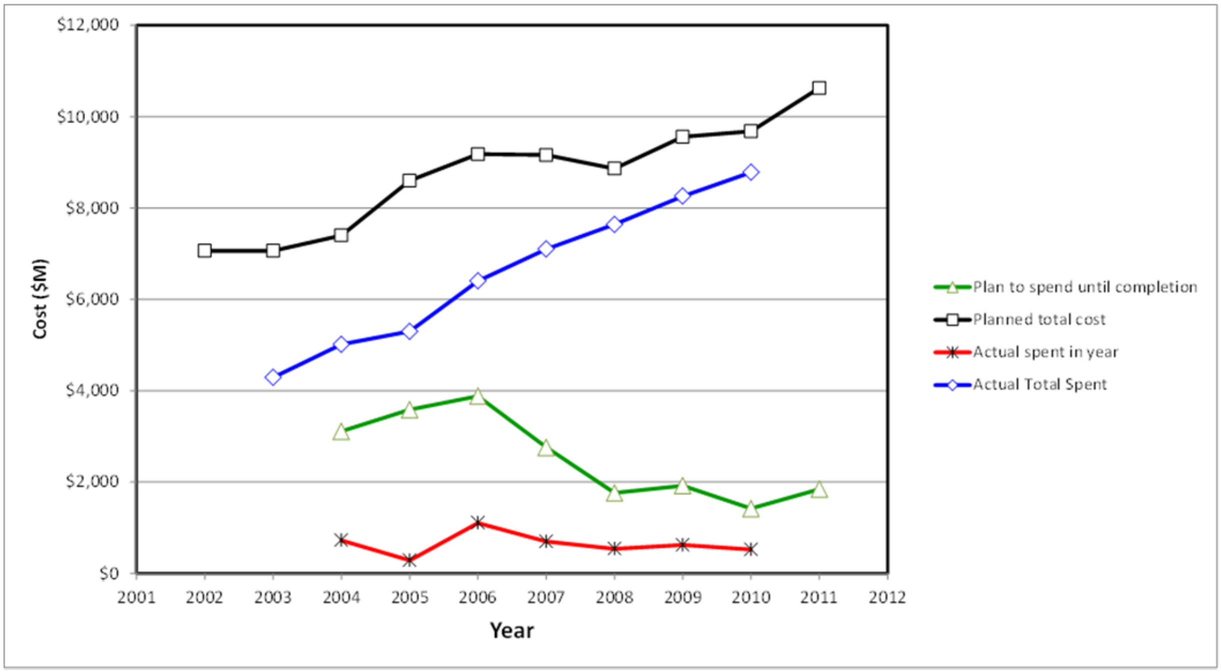

Figure 51. SBIRS: Cost Profile

Note. The green line with triangles is the R&D funding needed to complete the program and is from the "Program Essentials" section of each GAO report. The black line with boxes is the planned total R&D cost taken from the "Program Performance" section of each report. The red line with black asterisks is the R&D spending during the year. The blue line with diamonds is the Total R&D spending from the beginning of the project. It is derived from the "funding needed to complete" and the "R&D cost" categories in the reports.

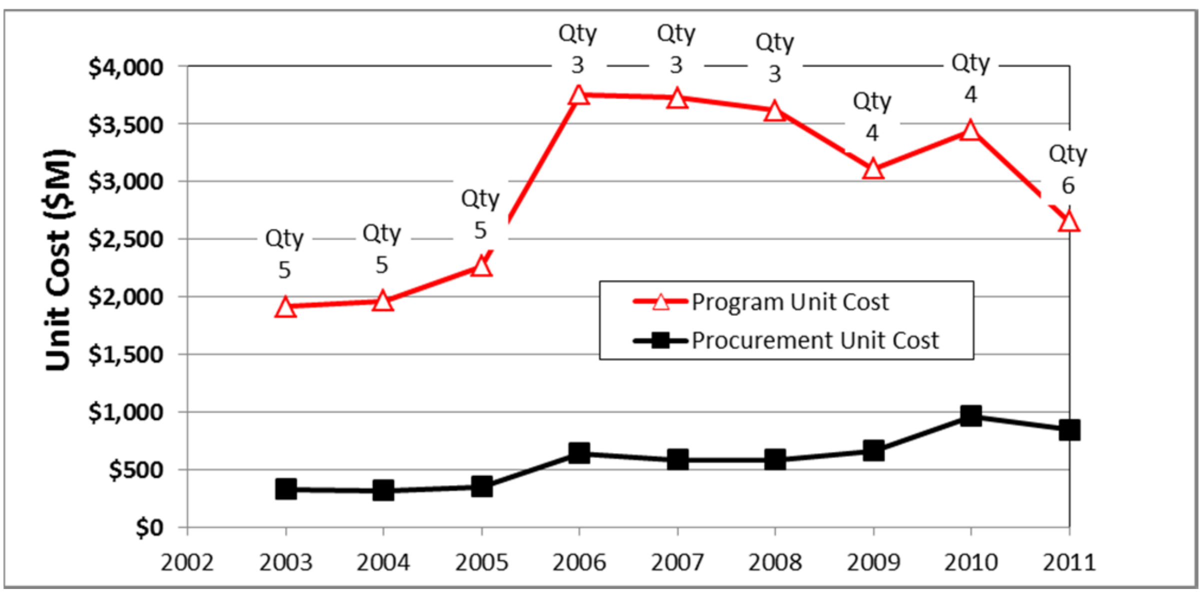

Figure 52. SBIRS: Quantity and Unit Costs

Note. The black line with squares is the *procurement* unit cost adjusted for inflation. The red line with triangles is the *program* unit cost adjusted for inflation (the program unit cost includes the R&D costs amortized over the total production lot).

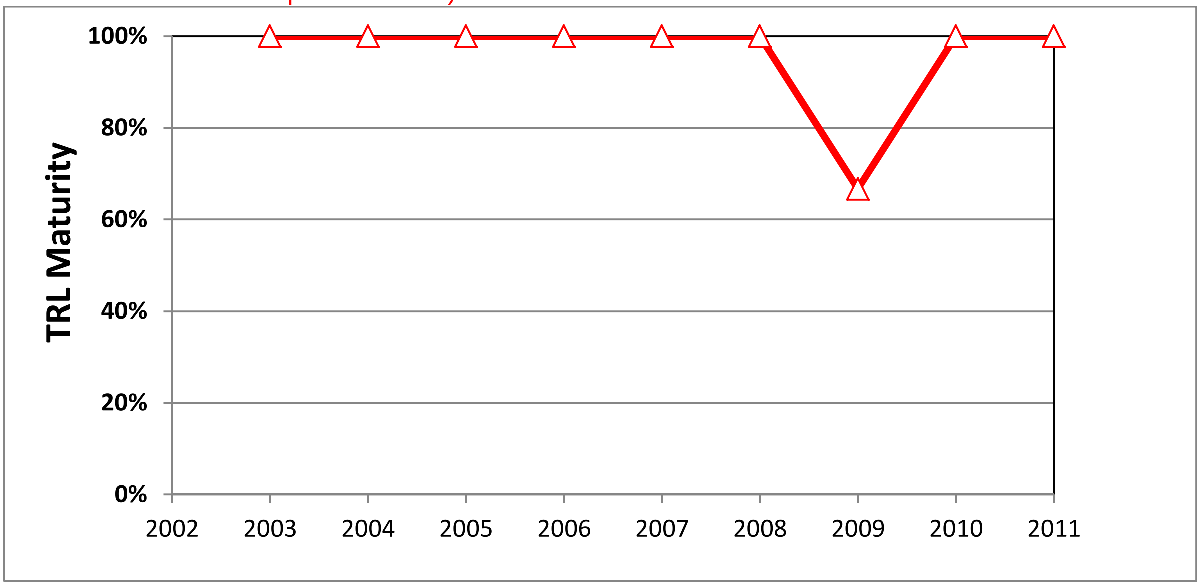

Figure 53. SBIRS: Technical Maturity

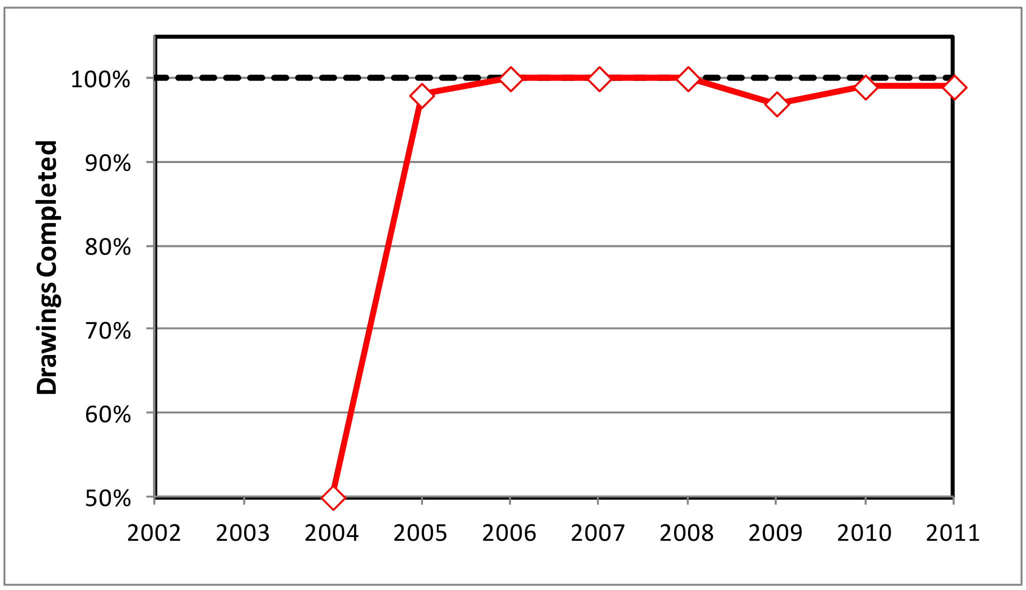

Figure 54. SBIRS Drawings Completed

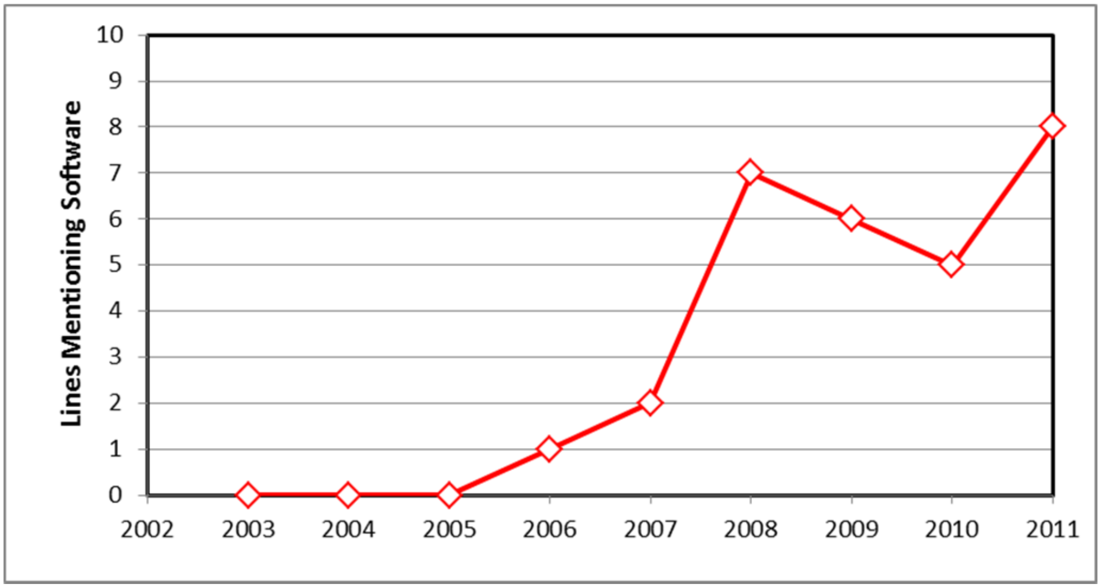

Figure 55. SBIRS: Lines in the GAO Reports That Mentioned Software

V. Summary and Recommendations

Risk management is one of the eight technical management processes in the overall systems engineering process. The process of risk management provides a framework for risks to be identified, analyzed, mitigated, and monitored. For example, defining stakeholder needs early in development reduces the chances of building the wrong system. Requirements analysis reduces the risk of a constantly changing functional baseline. Testing LRIP units as part of IOT&E reduces the risk of costly upgrades to full-rate production units. The list of mitigation activities is unbounded. It is not possible to examine every activity and its impact on risk reduction.

This research paper addresses risk mitigation activities that are considered *best practices* and that are documented in the yearly GAO "Assessments of Selected Weapon Programs" reports. The GAO has spent a considerable amount of time every year evaluating several dozen major weapon system programs. This research project is based on the prior work by the GAO office. Namely, this project has involved the analysis and evaluation of eight major weapon system programs over a nine-year period (2003–2011). Changes in cost, schedule, and performance have been tracked over time, which provides a unique perspective to understanding program execution.

This project has focused on some key systems engineering principles that are risk-mitigation activities. The best practices that have been evaluated in this research paper are the following:

- Use of technical readiness levels[24] to prevent immature technologies from being incorporated into new system designs since there is a high risk of cost overruns and schedule delays. This metric measures the maturity of technology being considered for use in a new weapon system.

[24] The GAO reports did not mention TRLs specifically, but they did identify the maturity of the critical technologies.

- “Design drawings completed” is an important entrance criterion to the Critical Design Review. This metric measures the maturity of a system’s design before prototypes are built and tested.
- Earned Value Management allows the government to monitor cost and schedule performance by the prime contractor. EVM provides an early and in-depth evaluation of progress by the prime contractor in the design of a new weapon system.
- Production maturity evaluates the effectiveness of production activities and the potential for cost increases and/or schedule delays.

One important best practice not directly addressed in the GAO reports is software development and test.

A. Technical Maturity

Technology Readiness Levels (TRLs) are a measure used by the United States Department of Defense, other government agencies, and many of the world's major companies to assess the maturity of evolving technologies (materials, components, devices, etc.) prior to incorporating that technology into a new system. Generally speaking, when a new technology is first invented or conceptualized, it is not suitable for immediate application. Instead, new technologies are usually subjected to experimentation, refinement, and increasingly realistic testing. Once the technology is sufficiently proven, it can be incorporated into a system/subsystem (“Technology Readiness Level,” 2012).

Unfortunately, based on this research project, TRLs are not a good indicator of program performance. Table 1 shows the number of technologies identified as mature versus the total number identified based on the yearly GAO reports. For example, “4/14” means that four of 14 technologies were identified as mature in the program write-ups. Except for JSF and JTRS, all of the other programs identified the technologies as mature, even though there were significant delays and cost overruns that occurred after the technologies were identified as mature. The cost increases in the program unit costs and the procurement unit costs are shown in Table 2.

For example, the EFV program reported that all critical technologies were mature in 2005. From 2005–2011, the program unit cost increased by 122% and the procurement unit cost increased by 106%. The Excalibur, C-5 RERP, and SBIRS programs saw large increases in unit costs. The Reaper and Global Hawk effectively had no increase in program unit costs and showed 17% and 13% increases in procurement unit costs, respectively. The Reaper had a large increase in units, which helped to keep the unit cost increases lower.

Table 1. Technical Maturity Levels for Eight Programs

Program	2004	2005	2006	2007	2008	2009	2010	2011
Excalibur	0 / 3	0 / 3	3 / 3	3 / 3	3 / 3	3 / 3	3 / 3	3 / 3
EFV	4 / 5	5 / 5	5 / 5	5 / 5	4 / 4	4 / 4	4 / 4	4 / 4
C-5 RERP	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1
JTRS Cluster 1	0 / 20	0 / 20	13 / 20	13 / 20	12 / 20	19 / 20	12 / 20	11 / 19
JSF	0 / 8	0 / 8	1 / 8	2 / 8	2 / 8	5 / 8	6 / 8	5 / 8
Reaper	3 / 4	3 / 4	3 / 4	3 / 4	4 / 4	4 / 4	4 / 4	
Global Hawk	4 / 14	5 / 14	6 / 13	10 / 10	10 / 10	10 / 10	10 / 10	10 / 10
SBIRS	3 / 3	3 / 3	3 / 3	3 / 3	3 / 3	2 / 3	3 / 3	3 / 3

Poor		Mostly Mature		All Mature

Table 2. **Program and Procurement Unit Cost Increases**

Program	Period	Program Unit Cost Increase	Procurement Unit Cost Increase
Excalibur	2006 to 2011	224%	136%
EFV	2005 to 2011	122%	106%
C-5 RERP	2004 to 2011	52%	38%
JTRS Cluster 1	Did not reach full maturity		
JSF	Did not reach full maturity		
Reaper	2008 to 2011	0%	17%
Global Hawk	2007 to 2011	-2%	13%
SBIRS	2004 to 2011	35%	167%

B. Design Stability

Use of “design drawings completed” is an important entrance criterion to the Critical Design Review. This metric measures the maturity of system’s design before prototypes are built and tested. According to the DAG (Defense Acquisition University [DAU], 2012),

> The CDR should be conducted when the product baseline has been achieved, allowing fabrication of hardware and coding of software deliverables to proceed. A rule of thumb is that 75 percent to 90 percent of (manufacturing quality) product drawings … are complete. (p. 267)

Observations from the eight programs studied are as follows:

1. Some of the values are questionable because they are an exact multiple of 10%.
2. In many cases, the “percent of drawings completed” decreased after obtaining 98% or higher in a previous year. This suggests that a lot of redesign had taken place, that the measurement of the original value was poor, and/or that the original release of a drawing was before the design had stabilized.
3. The number of drawings released may be an early indicator of large cost over-runs and schedule delays. For example, for the C-5 RERP program, the percent of drawings released dropped in 2007, but it wasn’t until 2008 when the time to FRP changed.

Regarding the phrase "product drawings are complete," there are many different valid definitions. Ideally, documents "complete" should mean

1. the design and all supporting information have been completed,
2. the drawing has been developed,
3. the drawing has been reviewed and approved by the appropriate people,
4. the drawing has been made part of the physical baseline,
5. the drawing has been released to manufacturing,
6. a supplier and cost data have been identified, and
7. the prototype has or will be manufactured using the "completed drawing."

Another wrinkle into the use of "drawings complete" is when an engineering change proposal (ECP) occurs. How changes to existing drawings and the addition of new drawings are reported will impact the reported percentage of drawings completed.

Metrics that would aid in understanding the design maturity of a program include the following:

- drawings released,
- drawings modified and re-released (gross number and percentage of existing drawings),
- new drawings (number and percentage of existing drawings), and
- number of obsolete drawings.

It is also important to track the severity of any changes in a drawing. For example, fixing a typo in the notes section of a drawing is not as significant as changing the design of the part, material callouts, tolerances, and so forth. The best measure of this will be if there is a change in "fit, form or function." A way to easily measure that is the number of new part numbers.

An important additional metric that is not directly related to drawings is the number of modified or new requirements. New requirements could cause large re-design efforts, which could affect the number of released drawings.

C. Earned Value

Earned value management (EVM) is a project management technique for measuring project performance in an objective manner. EVM is able to provide accurate forecasts of project performance problems, which enables proactive project management.

Earned value will be required[25] on all of the programs in the reports because of the cost of the development or production. The requirement for EVM applies to cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements that meet the dollar thresholds prescribed in DoD Instruction 5000.02 (DoD, 2008, p.44).

There were only a few programs that mentioned EVM in the GAO reports.

2003 → no programs

2004 → no programs

2005 → one program

2006 → two programs

2007 → four programs

2008 → six programs

2009 → six programs

[25] The application thresholds (total contract value including planned options in then-year dollars) are as follows: $20 million but less than $50 million—EVM implementation compliant with the guidelines in ANSI/EIA-748 is required. No formal Earned Value Management System (EVMS) validation is required. If $50 million or greater, then EVM implementation compliant with the guidelines in ANSI/EIA-748 is required. An EVMS that has been formally validated and accepted by the responsible contracting officer is required.

2010 → one program

2011 → two programs

Even when mentioned, the data were often vague: for example, from the 2004 GAO report on major weapon systems (GAO-04-248, p. 66), "Contract performance data indicates that work is slightly behind schedule and over cost."

In some cases, the EVM system was broken: for example, in the 2007 GAO report on major weapon systems (GAO-07-406SP):

> In March 2006, the lead contractor lost its earned value management certification due to a recent compliance review that found lack of progress in addressing long-standing systemic deficiencies. Without certified earned value management data, the Army will not have timely information on the contractor's ability to perform work within estimated cost and schedule. According to the program office, the contractor did not make its first milestone detailed in the Defense Contract Management Agency's corrective action plans in efforts to obtain earned value compliance. Still, the contractor plans to be compliant by the end of August 2007, 3 months after ARH low-rate initial production is scheduled to begin. (p. 38)

D. Production Maturity

Statistical Process Control (SPC) tools are a best practice, but they work best in production, usually on quantities in the many hundreds or more. Prior to actual production, a Production Readiness Review (PRR) will be an early indicator of potential manufacturing problems. Manufacturing readiness levels are useful for quantifying the maturity level of the manufacturing processes.

There are many questions that are important for manufacturing a system:

- Can the system be built per cost target?
- Can it be built to the schedule?
- Is the supplier base in place and stable?
- What's the lead time?
- Does the contractor have a trained workforce?
- Does the contractor have the necessary facilities?
- What is the contractor's quality management system?

- Does the prime contractor have a management plan for managing subcontractors?

There is a good write-up on this topic in the *Defense Acquisition Guidebook* in Section 11.3.3.1 (DAU, 2012, p. 935):

> The quality management process begins early in the life cycle and continues throughout. The principal elements of the quality management process include:
>
> - Objectively evaluating performed processes, work products, product/process design and services against the applicable process descriptions, standards, procedures, policies, and documented expectations;
> - Understanding the full scope of customer requirements, assessing risks associated with meeting those requirements, and verifying that they are satisfied;
> - Identifying and documenting noncompliance issues, especially those affecting cost, schedule, productivity, and performance;
> - Using tools and techniques in a disciplined manner to determine root causes of noncompliance issues;
> - Addressing noncompliance issues by initiating and tracking corrective and preventative actions to assure the root cause(s) of the defect/deficiency has been identified and removed; and
> - Providing feedback to program managers, their staff, and corporate managers to identify lessons learned, improve process robustness for future projects, and evaluate trends.

So even if a contractor is not using SPC, they need to have some data about how well they're doing in the above activities. Something as simple as *%scrap* and *%rework* will give a lot of insight into the production effectiveness. If contractors can't quantify those, then it's impossible for them to accurately predict the cost of future production.

E. Software

There wasn't enough attention given to software in the GAO reports. Design maturity is not just the number of drawings released. That is only a measure of the physical hardware design. Software is usually very important and risky on large weapon programs. Here are some statistics from the DAU level III course on systems engineering [SYS 302] (DAU, 2011; a little dated but still relevant):

- 64% of DoD software projects did not meet time/budget goals;
- Half of projects overran cost estimates by 43%; and
- 15% of projects were canceled.

Additional information on software from the DAU's SYS-302 class is as follows:

- Software controls most of today's systems key functionalities;
- Software is usually on the critical path; and
- Software is a complex, conformable, changeable, and invisible product.

On average,[26] there were 2.1 sentences devoted to software in the GAO reports studied (i.e., eight programs over nine years). With the possible exception of the Excalibur program, software is a major component of the programs studied.

For example, the importance of software is clearly stated in the SBIRS write-up for 2008. Prior to 2008, there were only a total of three sentences devoted to software. However, there were seven sentences in 2008 and six sentences in 2009. (Write-ups were usually around 38 sentences long, not including the cost data).

One part of the SBIRS write-up in the 2009 GAO report on major weapon systems (GAO-09-326SP) summed it up as follows:

> Design is considered stable since about 97 percent of expected design drawings are releasable. However, the program has experienced design-related problems and more could emerge. For example, the flight software that controls the health and status of the space vehicle was found to be inadequate when it unexpectedly failed during testing in 2007. In April 2008, independent experts approved a new software design. DOD estimates the design changes will delay the first satellite launch at least 15 months to December 2009 and increase costs by about $414 million. Further cost increases and schedule delays are likely. (p. 136)

This says that the problems with software will cost $414 million or more. Clearly, the problems with software were hidden during the period 2003–2007 because only three sentences mentioned software in five years of reports.

[26] Excalibur was excluded from the average.

It should not be difficult to acquire software metrics. Any company that claims to be CMMI[27] (CMMI Institute, 2013) Level 2 or higher will be using metrics to manage their software projects. So theoretically, performance metrics should exist and should be reported. Some key software metrics include the following:

- requirement count,
- number of changes,
- coding size,[28]
- units tested, and
- defect count.

If the contractor is CMMI 2 or higher, then they should have identified metrics in their proposal and would be contractually obligated to generate and use the metrics.

F. Final Comments

There are various situations reported that deserve closer scrutiny, such as the following:

1. increases in procurement unit costs when quantities increase,
2. a drop in the percent of drawings completed,
3. "drawings completed" that stay the same even when R&D spending is high,
4. "drawings completed" that conveniently fall on a multiple of 10% (e.g., 80%),
5. lack of information on software development, and
6. lack of information on T&E activities and accomplishments.

[27] Capability Maturity Model Integration (CMMI) is a process improvement approach whose goal is to help organizations improve their performance.

[28] Lines of code is an easy way to measure the size of the software development, but it is not very relevant. Function points or configuration items are better measures.

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Appendix A. Technology Readiness Levels

Table A1. Technology Readiness Levels in the Department of Defense (DoD)
("Technology Readiness Level," 2012)

Technology Readiness Levels in the Department of Defense (DoD)		
Technology Readiness Level	**Description**	**Supporting Information**
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that out-line the application being considered and that provide analysis to support the concept.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
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 they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6. System/subsystem	Representative model or prototype	Results from laboratory testing of a

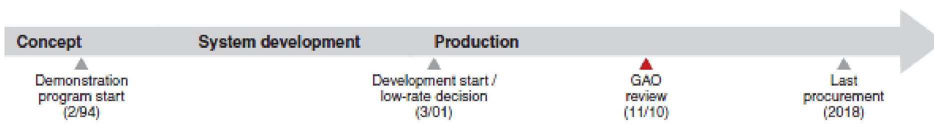
model or prototype demonstration in a relevant environment	system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	prototype system that is near the desired con-figuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an air-craft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8. Actual system completed and 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 (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9. Actual system 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 (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.

Appendix B. Example of a GAO Report on a Major Weapon System (GAO, 2011, p. 69)

Global Hawk (RQ-4A/B)

The Air Force's Global Hawk is a high-altitude, long-endurance unmanned aircraft with integrated sensors and ground stations providing intelligence, surveillance, and reconnaissance capabilities. The Global Hawk will replace the U-2. After a successful technology demonstration, the system entered development and limited production in March 2001. The program includes RQ-4A aircraft similar to the original demonstrators, as well as larger and more capable RQ-4Bs. We assessed the RQ-4B, which is being procured in three blocks.

Source: Northrop Grumman.



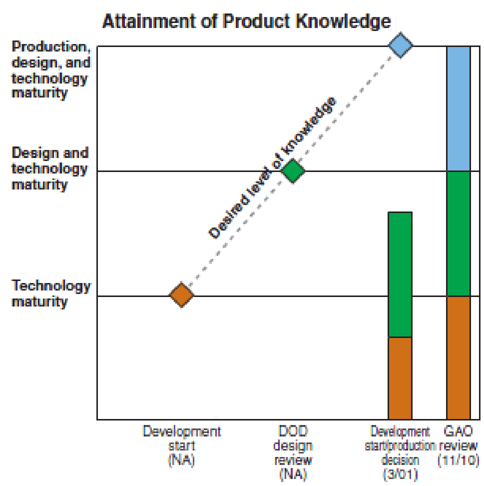
Program Essentials

Prime contractor: Northrop Grumman
Program office: Wright-Patterson AFB, OH
Funding needed to complete:
- R&D: $1,067.5 million
- Procurement: $5,339.1 million
- Total funding: $6,406.6 million
- Procurement quantity: 39

Program Performance (fiscal year 2011 dollars in millions)

	As of 03/2001	Latest 07/2010	Percent change
Research and development cost	$1,026.3	$3,948.7	284.8
Procurement cost	$4,255.0	$9,481.6	122.8
Total program cost	$5,312.4	$13,575.7	155.5
Program unit cost	$84.323	$176.307	109.1
Total quantities	63	77	22.2
Acquisition cycle time (months)	55	TBD	NA

The Global Hawk RQ-4B has mature critical technologies, a stable design, and proven production processes, but it remains at risk for late design changes and costly retrofits. The completion of operational tests for the aircraft that make up the largest part of the program has been delayed nearly 4 years by testing discoveries, concurrent testing, resource constraints, and weather problems. The program will have procured more than half of those aircraft by the time testing is complete in December 2010. The program also plans to procure more than half the aircraft with advanced radar before it completes operational testing in 2013. The Air Force is taking steps to address some of the testing delays. In fiscal year 2010, the Air Force increased the total number of aircraft to be procured from 54 to 77 and extended planned production through 2018.



Page 69 GAO-11-233SP Assessments of Selected Weapon Programs

Global Hawk Program

Technology Maturity

The critical technologies for the RQ-4B are mature. However, the program must still successfully test two key capabilities—the advanced signals intelligence payload and multiple platform radar—to ensure they perform as expected. The first flight of an RQ-4B equipped with the signals intelligence payload occurred in September 2008 and operational testing is scheduled to be completed in December 2010. After delays in its development, the first flight of an RQ-4B equipped with the multiple platform radar is expected to occur in April 2011. Development testing is underway.

Design Maturity

The RQ-4B basic airframe design is stable with all of its expected design drawings released; however, the program remains at risk for late design changes and costly retrofits if problems are discovered in testing. During the first year of production, frequent substantive engineering changes increased development and airframe costs and delayed deliveries and testing. Substantial commonality between the RQ-4A and RQ-4B had been expected, but as the designs were finalized and production geared up, the design differences were much more extensive and complex than anticipated.

Production Maturity

The manufacturing processes for the RQ-4B airframe are mature and in statistical control. In addition, the program reports that it is meeting its quality goal on the number of nonconforming parts. The RQ-4B aircraft is being produced in three configurations. Block 20 aircraft are equipped with an enhanced imagery intelligence payload; block 30 aircraft have both imagery and signals intelligence payloads; and block 40 aircraft will have an advanced radar surveillance capability. All six block 20 aircraft have been produced. Production continues on block 30 and block 40 aircraft. The first block 30 aircraft was delivered in November 2007 and the first block 40 aircraft was delivered without the sensor in November 2009.

Other Program Issues

The Global Hawk program expects to have procured all of its block 20 aircarft, and more than half of its block 30 and block 40 aircraft before operational testing is complete. As a result, if problems are found in operational testing, it could result in costly retrofits for large numbers of aircraft. The Global Hawk program has continued to experience delays in developmental and operational testing. The completion of operational tests for the block 20 and 30 aircraft has been delayed nearly 4 years to December 2010. The start of operational testing for block 40 aircraft has been delayed by more than 3 years to March 2013. According to the Global Hawk's December 2009 Selected Acquisition Report, several factors contributed to the most recent schedule slips, including developmental test discoveries; concurrent development and production testing; testing resource constraints; and weather problems. According to program officials, a shift in focus and resources required to address a Joint Urgent Operational Need, using two block 20 aircraft, has also contributed to block 40 operational test delays. The Air Force is taking steps to address some of the testing delays. For example, the program is now conducting aircraft acceptance tests at Beale Air Force Base in order to free up resources for operational testing at Edwards Air Force Base.

Program Office Comments

In commenting on a draft of this assessment, the Air Force emphasized that the Global Hawk program has improved program execution while reducing program risk. The Air Force noted that older RQ-4A Global Hawk aircraft—which we did not assess—have been successfully used by the warfighters and other government agencies to carry out various missions. The service also noted that each of the variants of its larger RQ-4B aircraft is now either in operations or testing. Flight operations of deployed aircraft and flight testing of the advanced radar payload are expected to begin in 2011. The Air Force noted that current challenges facing the program include initial system deployments and normalization of operations and sustainment. In addition to commenting on this assessment, the Air Force provided technical comments, which we incorporated where appropriate.

2003 - 2012 Sponsored Research Topics

Acquisition Management

- Acquiring Combat Capability via Public-Private Partnerships (PPPs)
- BCA: Contractor vs. Organic Growth
- Defense Industry Consolidation
- EU-US Defense Industrial Relationships
- Knowledge Value Added (KVA) + Real Options (RO) Applied to Shipyard Planning Processes
- Managing the Services Supply Chain
- MOSA Contracting Implications
- Portfolio Optimization via KVA + RO
- Private Military Sector
- Software Requirements for OA
- Spiral Development
- Strategy for Defense Acquisition Research
- The Software, Hardware Asset Reuse Enterprise (SHARE) repository

Contract Management

- Commodity Sourcing Strategies
- Contracting Government Procurement Functions
- Contractors in 21st-century Combat Zone
- Joint Contingency Contracting
- Model for Optimizing Contingency Contracting, Planning and Execution
- Navy Contract Writing Guide
- Past Performance in Source Selection
- Strategic Contingency Contracting
- Transforming DoD Contract Closeout
- USAF Energy Savings Performance Contracts
- USAF IT Commodity Council
- USMC Contingency Contracting

Financial Management

- Acquisitions via Leasing: MPS case
- Budget Scoring
- Budgeting for Capabilities-based Planning
- Capital Budgeting for the DoD
- Energy Saving Contracts/DoD Mobile Assets
- Financing DoD Budget via PPPs
- Lessons from Private Sector Capital Budgeting for DoD Acquisition Budgeting Reform
- PPPs and Government Financing
- ROI of Information Warfare Systems
- Special Termination Liability in MDAPs
- Strategic Sourcing
- Transaction Cost Economics (TCE) to Improve Cost Estimates

Human Resources

- Indefinite Reenlistment
- Individual Augmentation
- Learning Management Systems
- Moral Conduct Waivers and First-term Attrition
- Retention
- The Navy's Selective Reenlistment Bonus (SRB) Management System
- Tuition Assistance

Logistics Management

- Analysis of LAV Depot Maintenance
- Army LOG MOD
- ASDS Product Support Analysis
- Cold-chain Logistics
- Contractors Supporting Military Operations
- Diffusion/Variability on Vendor Performance Evaluation
- Evolutionary Acquisition
- Lean Six Sigma to Reduce Costs and Improve Readiness

- Naval Aviation Maintenance and Process Improvement (2)
- Optimizing CIWS Lifecycle Support (LCS)
- Outsourcing the Pearl Harbor MK-48 Intermediate Maintenance Activity
- Pallet Management System
- PBL (4)
- Privatization-NOSL/NAWCI
- RFID (6)
- Risk Analysis for Performance-based Logistics
- R-TOC AEGIS Microwave Power Tubes
- Sense-and-Respond Logistics Network
- Strategic Sourcing

Program Management

- Building Collaborative Capacity
- Business Process Reengineering (BPR) for LCS Mission Module Acquisition
- Collaborative IT Tools Leveraging Competence
- Contractor vs. Organic Support
- Knowledge, Responsibilities and Decision Rights in MDAPs
- KVA Applied to AEGIS and SSDS
- Managing the Service Supply Chain
- Measuring Uncertainty in Earned Value
- Organizational Modeling and Simulation
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- Terminating Your Own Program
- Utilizing Collaborative and Three-dimensional Imaging Technology

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