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BEST PRACTICES

Capturing Design and Manufacturing Knowledge Early Improves Acquisition Outcomes

G A O

Accountability ★ Integrity ★ Reliability

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July 15, 2002

The Honorable Daniel Akaka
Chairman
The Honorable James Inhofe
Ranking Minority Member
Subcommittee on Readiness and Management Support
Committee on Armed Services
United States Senate

As you requested, this report examines how best practices offer improvements to the way the Department of Defense develops new weapon systems, primarily the design and manufacturing aspects of the acquisition process. It examines the attainment of design and manufacturing knowledge and its use at critical junctures to make decisions about weapon systems' readiness to move forward in the acquisition process. We make recommendations to the Secretary of Defense for improvements to weapon system acquisition policy to better align design and manufacturing activities with best practices that have shown that the capture and use of key knowledge can result in better cost, schedule, and performance outcomes.

We are sending copies of this report to the Secretary of Defense; the Secretary of the Army; the Secretary of the Navy; the Secretary of the Air Force; the Director of the Office of Management and Budget; the Director, Missile Defense Agency; and interested congressional committees. We will also make copies available to others upon request. In addition, the report will be available at no charge on the GAO Web site at http://www.gao.gov.

If you have any questions regarding this report, please call me at (202) 512-4841. Other contacts are listed in appendix II.

Katherine V. Schinasi
Director
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Executive Summary

Purpose

Historically, the Department of Defense (DOD) has taken much longer and spent much more than originally planned to develop and acquire its weapon systems, significantly reducing the department's buying power over the years. Clearly, it is critical to find better ways of doing business and, in particular, to make sure that weapon systems are delivered on time and cost-effectively. This is especially true given the vast sums DOD is spending and is expected to spend on weapons acquisition—$100 billion alone in 2002 and an anticipated $700 billion over the next 5 years. DOD has recognized the nature of this problem and has taken steps to address it, including advocating the use of best practices for product development from commercial companies. Leading commercial companies have achieved more predictable outcomes from their product development processes because they identify and control design and manufacturing risks early and manage them effectively. While DOD has made some progress in recent years, GAO's recent weapon system reviews show that persistent problems continue to hinder acquisition cost, schedule, and performance outcomes. For this reason, GAO has continued a body of work to identify the lessons learned by best commercial companies to see if they apply to weapon system acquisitions.

This report addresses how DOD can manage its weapon system acquisition process to ensure important knowledge about a system's design, critical manufacturing processes, and reliability is captured and used to make informed and timely decisions before committing to substantial development and production investments. It identifies best practices to facilitate this decision making at two critical junctures—transition from system integration to system demonstration during product development and then transition into production. Ultimately, this should improve cost, schedule, and quality outcomes of DOD major weapon system acquisitions. In response to a request from the Chairman and the Ranking Minority Member, Subcommittee on Readiness and Management Support, Senate Committee on Armed Services, GAO (1) assessed the impact of design and manufacturing knowledge on DOD program outcomes, (2) compared best practices to those used in DOD programs, and (3) analyzed current weapon system acquisition guidance for applicability of best practices to obtain better program outcomes.

Background

In any new product development program there are three critical points that require the capture of specific knowledge to achieve successful outcomes. The first knowledge point occurs when the customer's requirements are clearly defined and resources—proven technology, design, time, and money—exist to satisfy them. Commercial companies insist that technology be mature at the outset of a product development program and, therefore, separate technology development from product development. The second knowledge point is achieved when the product's design is determined to be capable of meeting product requirements—the design is stable and ready to begin initial manufacturing of prototypes. The third knowledge point is achieved when a reliable product can be produced repeatedly within established cost, schedule, and quality targets. GAO's prior work on best practices covers achieving the first knowledge point.[1] This report examines best practices for achieving the second and third knowledge points.

Commercial companies understand the importance of capturing design and manufacturing knowledge early in product development, when costs to identify problems and make design changes to the product are significantly cheaper. In a knowledge-based process, the achievement of each successive knowledge point builds on the preceding one, giving decision makers the knowledge they need—when they need it—to make decisions about whether to invest significant additional funds to move forward with product development. Programs that follow a knowledge-based approach typically have a higher probability of successful cost and schedule outcomes. Problems occur in programs when knowledge builds more slowly than commitments to enter product development or production. The effects of this delay in capturing knowledge can be debilitating. If a decision is made to commit to develop and produce a design before the critical technology, design, or manufacturing knowledge is captured, problems will cascade and become magnified through the product development and production phases. Outcomes from these problems include increases in cost and schedule and degradations in performance and quality.

[1] U.S. General Accounting Office, *Best Practices: Better Matching of Needs and Resources Will Lead to Better Weapon System Outcomes*, GAO-01-288 (Washington, D.C.: Mar. 8, 2001) and *Best Practices: Better Management of Technology Development Can Improve Weapon System Outcomes*, GAO/NSIAD-99-162 (Washington, D.C.: July 30, 1999).

Results in Brief

The success of any effort to develop a new product hinges on having the right knowledge at the right time. Knowledge about a product's design and producibility facilitates informed decisions about whether to significantly increase investments and reduces the risk of costly design changes later in the program. Every program eventually achieves this knowledge; however, leading commercial companies GAO visited have found that there is a much better opportunity to meet predicted cost, schedule, and quality targets when it is captured early, in preparation for critical investment decisions. A product development process includes two phases followed by production—integration phase and demonstration phase. The commercial companies GAO visited achieved success in product development by first achieving a mature, stable design supported by completed engineering drawings during an integration phase and then by demonstrating that the product's design was reliable and critical manufacturing processes required to build it were in control before committing to full production. The more successful DOD programs GAO reviewed—the AIM-9X and the FA-18-E/F programs—had achieved similar knowledge as the commercial companies, resulting in good cost and schedule outcomes. In contrast, the DOD programs, which had completed about one-quarter of their drawings when they transitioned to the demonstration phase and had less than half of their manufacturing processes in control when entering production, experienced poor cost and schedule outcomes.

Leading commercial companies employed practices to capture design and manufacturing knowledge in time for making key decisions during product development. Two were most prominent. First, the companies kept the degree of the design challenge manageable before starting a new product development program by using an evolutionary approach to develop a product. This minimized the amount of new content and technologies on a product, making it easier to capture the requisite knowledge about a product's design before investing in manufacturing processes, tooling, and facilities. Second, the companies captured design and manufacturing knowledge before the two critical decision points in product development: when the design was demonstrated to be stable—the second knowledge point—and when the product was demonstrated to be producible at an affordable cost—the third knowledge point. A key measure of design stability was stakeholders' agreements that engineering drawings were complete and supported by testing and prototyping when necessary. A key measure of producibility was whether the companies' critical manufacturing processes were in control and product reliability was demonstrated. Most DOD programs GAO reviewed did not complete engineering drawings prior to entering the demonstration phase, nor did they bring critical manufacturing processes in control or demonstrate reliability prior to making a production decision.

DOD has made changes to its acquisition policy[2] in an attempt to improve its framework for developing weapon systems, but the policy does not require the capture of design or manufacturing knowledge or sufficient criteria to enter the system demonstration and production phases. In addition, it does not require a decision review to enter the demonstration phase of product development. Further, there is little incentive for DOD program managers to capture knowledge early in the development process. Instead, the acquisition environment emphasizes delaying knowledge capture and problem identification since these events can have a negative influence on obtaining annual program funding—a key to success for DOD managers. In contrast, commercial companies encourage their managers to capture product design and manufacturing knowledge to identify and resolve problems early in development, before making significant increases in their investment.

GAO is making recommendations to the Secretary of Defense on ways to improve DOD's acquisition process to achieve better outcomes by incorporating best practices to capture design and manufacturing knowledge and then use this knowledge as a basis for decisions to commit significant additional time and money as an acquisition program progresses through system demonstration and into production.

[2] DOD Directive 5000.1, The Defense Acquisition System (Oct. 23, 2000), DOD Instruction 5000.2, Operation of the Defense Acquisition System (Apr. 5, 2002), and DOD Regulation 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs (Apr. 5, 2002).

Principal Findings

Timely Design and Manufacturing Knowledge Is Critical to Program Success

Knowledge that a product's design is stable early in the program facilitates informed decisions about whether to significantly increase investments and reduces the risk of costly design changes that can result from unknowns after initial manufacturing begins. Likewise, later knowledge that the design can be manufactured affordably and with consistent high quality prior to making a production decision ensures that targets for cost and schedule during production will be met. Leading commercial companies do not make significant investments to continue a product development or its production until they have knowledge that the product's design works and it can be manufactured efficiently within cost and schedule expectations.

DOD programs that captured knowledge similar to commercial companies had more successful outcomes. For example, the AIM-9X and the F/A-18E/F captured design and manufacturing knowledge by key decision points and limited cost increases to 4 percent or less and schedule growth to 3 months or less. In fact, the AIM-9X had 95 percent of its drawings completed at its critical design review. The F/A-18E/F had 56 percent of its drawings completed and also had over 90 percent of its higher level interface drawings completed, adding confidence in the system design. Both took steps to ensure that manufacturing processes were capable of producing an affordable product by the time the programs made production decisions.

On the other hand, the F-22, PAC-3, and Advanced Threat Infrared Countermeasures/Common Missile Warning System (ATIRCM/CMWS) programs did not capture sufficient knowledge before significant investments to continue the programs and experienced cost growth that ranged from 23 to 182 percent and schedule delays that ranged from 18 months to over 3 years. None of these programs had completed more than 26 percent of their engineering drawings for their critical design reviews, and only the F-22 and PAC-3 programs attempted to track the capability of their critical manufacturing processes prior to production.

Best Practices Enable Timely Capture of Design and Manufacturing Knowledge

Leading commercial companies developed practices that enabled the timely capture of design and manufacturing knowledge. First, they used an evolutionary approach to product development by establishing time-phased plans to develop a new product in increments based on technologies and resources achievable now and later. This approach reduced the amount of risk in the development of each increment, facilitating greater success in meeting cost, schedule, and performance requirements. The commercial companies GAO visited used the evolutionary approach as their method for product development. Each company had a plan for eventually achieving a quantum leap in the performance of its products and had established an orderly, phased process for getting there, by undertaking continuous product improvements as resources became available. For the most part, DOD programs try to achieve the same leap in performance but in just one step, contributing to development times that can take over 15 years to deliver a new capability to the military user.

Second, each leading commercial company had a product development process that was prominent and central to its success. The process was championed by executive leadership and embraced by product managers and development teams as an effective way to do business. Critical to the product development process were activities that enabled the capture of specific design and manufacturing knowledge and decision reviews to determine if the knowledge captured would support the increased investment necessary to move to the next development phase or into production. These activities provided knowledge that the product design was stable at the decision point to start initial manufacturing (exiting the integration phase) as demonstrated by the completion of 90 percent of the engineering drawings. They also captured knowledge that a product was ready to begin production (exiting the demonstration phase) as demonstrated by proof that critical processes were in control and product reliability was achievable. The activities that enabled the capture and use of this knowledge to make decisions are listed in table 1.

Table 1: Activities That Enable the Capture of Design and Manufacturing Knowledge

Design is stable	Product can be produced
• Limit the design challenge.	• Identify key system characteristics and critical manufacturing processes.
• Demonstrate, through prototyping or other means, that product works.	• Determine that processes are in control and stable.
• Complete design reviews of system and subsystems.	• Analyze potential failure modes and their effects on performance.
• Obtain stakeholder concurrence that the design is complete and producible.	• Set reliability goals and growth plan and conduct reliability testing.

DOD programs that had more successful outcomes used key best practices to a greater degree than others. For example, the AIM-9X missile program completed 95 percent of its engineering drawings at the critical design review because it made extensive use of prototype testing to demonstrate the design met requirements coupled with design reviews that included program stakeholders. The F/A-18-E/F program eliminated over 40 percent of the parts used to build predecessor aircraft to make the design more robust for manufacturing and identified critical manufacturing processes, bringing them under control before the start of production. Both programs developed products that evolved from existing versions, making the design challenge more manageable.

On the other hand, DOD programs with less successful outcomes did not apply best practices to a great extent. At their initial manufacturing decision reviews, the F-22, PAC-3, and ATIRCM/CMWS had less than one-third of their engineering drawings, in part, because they did not use prototypes to demonstrate the design met requirements before starting initial manufacturing. On the F-22 program, it was almost 3 years after this review before 90 percent of the drawings needed to build the F-22 were completed. Likewise, at their production decision reviews, these programs did not capture manufacturing and product reliability knowledge consistent with best practices. For example, the PAC-3 missile program had less than 40 percent of its processes in control and, as a result, the missile seekers had to be built, tested, and reworked on average 4 times before they were acceptable. The F-22 entered production despite being substantially behind its plan to achieve reliability goals. As a result, the F-22 is requiring significantly more maintenance actions than planned.

A Better Match of Policy and Incentives Is Needed to Ensure Capture of Design and Manufacturing Knowledge

DOD's acquisition policy establishes a good framework for developing weapon systems; however, more specific criteria, disciplined adherence, and stronger acquisition incentives are needed to ensure the timely capture and use of knowledge and decision making. DOD recently changed its acquisition policy to emphasize evolutionary acquisition and establish separate integration and demonstration phases in the product development process. Its goal was to develop higher quality systems in less time and for less cost. While similar to the leading commercial companies' approach, the policy lacks detailed criteria for capturing and using design and manufacturing knowledge to facilitate better decisions and more successful acquisition program outcomes. It also lacks a decision review to proceed from the integration phase to the demonstration phase of product development.

While the right policy and criteria are necessary to ensure a disciplined, knowledge-based product development process, the incentives that influence the key players in the acquisition process will ultimately determine whether they will be used effectively. In DOD, current incentives are geared toward delaying knowledge so as not to jeopardize program funding. This undermines a knowledge-based process for making product development decisions. Instead, program managers and contractors push the capture of design and manufacturing knowledge to later in the development program to avoid the identification of problems that might stop or limit funding. They focus more on meeting schedules than capturing knowledge. On the other hand, commercial companies must develop high-quality products quickly or they may not survive in the marketplace. Because of this, they encourage their managers to capture product design and manufacturing knowledge to identify and resolve problems early in development, before making significant increases in their investment. Instead of a schedule-driven process, their process is driven by events that bring them knowledge: critical design reviews that are supported by completed engineering drawings and production decisions supported by reliability testing and statistical process control data. They do not move forward without the design and manufacturing knowledge needed to make informed decisions.

Recommendations for Executive Action

GAO recommends that the Secretary of Defense revise policy and guidance on the operation of the defense acquisition system to include (1) a requirement to capture specific design knowledge to be used as exit criteria for transitioning from system integration to system demonstration and (2) a requirement that the current optional interim progress review between system integration and demonstration be a mandatory decision review requiring the program manager to verify that design is stable and that this be reported in the program's Defense Acquisition Executive Summary and Selected Acquisition Report. The policy and guidance should also be revised to include (1) a requirement to capture and use specific manufacturing knowledge at the production commitment point as exit criteria to transition from system demonstration into production and (2) a requirement to structure major weapon system contracts to ensure the capture and use of knowledge for DOD to make investment decisions at critical junctures when transitioning from system integration to system demonstration and then into production.

Agency Comments

DOD generally agreed with the report and its recommendations. A detailed discussion of DOD's comments appears in appendix I.

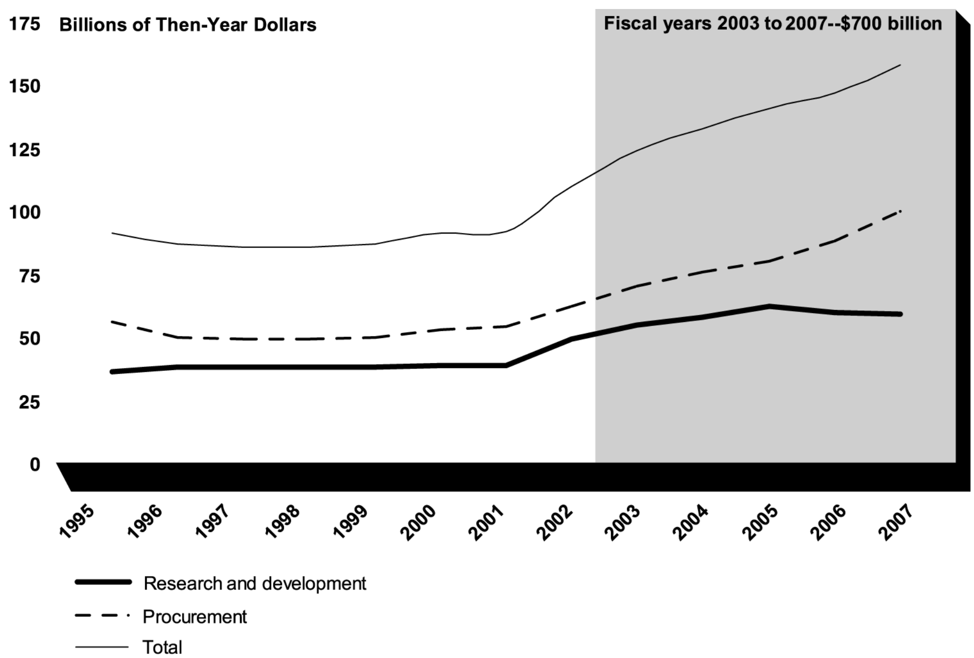
Introduction

The Department of Defense (DOD) spends close to $100 billion annually to research, develop, and acquire weapon systems, and this investment is expected to grow substantially. Over the next 5 years, starting in fiscal year 2003, DOD's request for weapon system development and acquisition funds is estimated to be $700 billion (see fig. 1).

How effectively DOD manages these funds will determine whether it receives a good return on its investment. Our reviews over the past 20 years have consistently found that DOD's weapon system acquisitions take much longer and cost much more than originally anticipated, causing disruptions to the department's overall investment strategy and significantly reducing its buying power. Because such disruptions can limit DOD's ability to effectively execute war-fighting operations, it is critical to find better ways of doing business.

In view of the importance of DOD's investment in weapon systems, we have undertaken an extensive body of work that examines DOD's acquisition issues from a different, more cross-cutting perspective—one that draws lessons learned from the best commercial product development efforts to see if they apply to weapon system acquisitions. This report looks at the core of the acquisition process, specifically product development and ways to successfully design and manufacture the product. Our previous reports looked at such issues as how companies matched customer needs and resources, tested products, assured quality, and managed suppliers and are listed in related GAO products at the end of the report.

Figure 1: Research, Development, Test and Evaluation, and Procurement Funding for Fiscal Years 1995 to 2007



Source: DOD.

Best Practices of Leading Commercial Companies

Leading commercial companies expect their program managers to deliver high-quality products on time and within budget. Doing otherwise could result in the customer walking away. Thus, the companies have created an environment and adopted practices that put their program managers in a good position to succeed in meeting these expectations. Collectively, these practices ensure that a high level of knowledge exists about critical facets of the product at key junctures during development. Such a knowledge-based process enables decision makers to be reasonably certain about critical facets of the product under development when they need this knowledge.

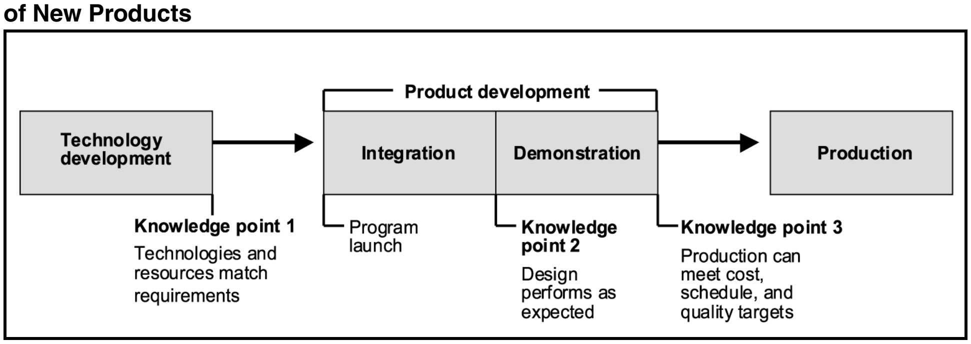
To ensure the right level of knowledge at each key decision point in product development, leading commercial companies separate technology from product development and take steps to ensure the product design is stabilized early so product performance and producibility can be demonstrated before production. The process followed by leading companies, illustrated in figure 2, can be broken down into the following three knowledge points.

- Knowledge point 1 occurs when a match is made between the customer's needs and the available resources—technology, design, time, and funding. To achieve this match, technologies needed to meet essential product requirements must be demonstrated to work in their intended environment. In addition, the product developer must complete a preliminary product design using systems engineering to balance customer desires with available resources.

- Knowledge point 2 occurs when the product's design demonstrates its ability to meet performance requirements. Program officials are confident that the design is stable and will perform acceptably when at least 90 percent of engineering drawings are complete. Engineering drawings reflect the results of testing and simulation and describe how the product should be built.

- Knowledge point 3 occurs when the product can be manufactured within cost, schedule, and quality targets and is reliable. An important indicator of this is when critical manufacturing processes are in control and consistently producing items within quality standards and tolerances. Another indicator is when a product's reliability is demonstrated through iterative testing that identifies and corrects design problems.

Figure 2: Knowledge-based Process for Applying Best Practices to the Development of New Products

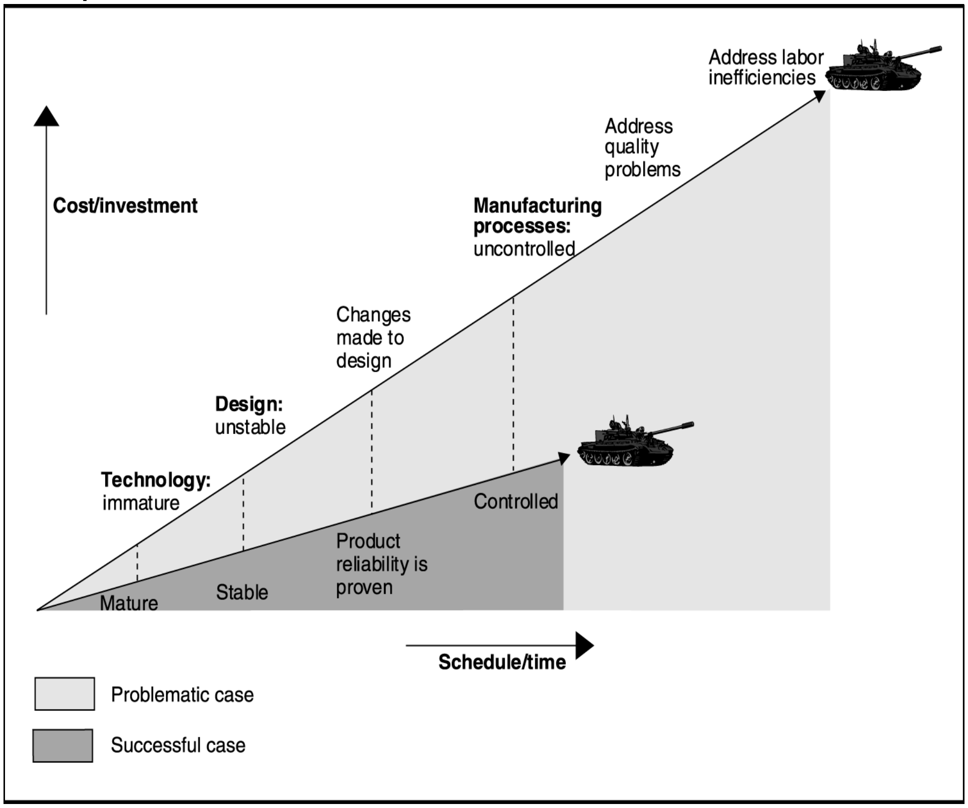


Source: GAO's analysis.

This report focuses on best practices for achieving knowledge points 2 and 3, particularly at how successful companies design and manufacture a product within established cost, schedule, and quality targets. The concepts discussed build on our previous reports, which looked at the earlier phases of an acquisition, including matching customer needs and available resources.

A key success factor evident in all our work is the ability to obtain the right knowledge at the right time and to build knowledge to the point that decision makers can make informed decisions about moving ahead to the next phase. Programs that do this typically have successful cost and schedule outcomes. Programs that do not typically encounter problems that eventually cascade and become magnified through the product development and production phases. As shown in figure 3, the effects of not following a knowledge-based process can be debilitating.

Figure 3: Notional Illustration Showing the Different Paths That a Product's Development Can Take

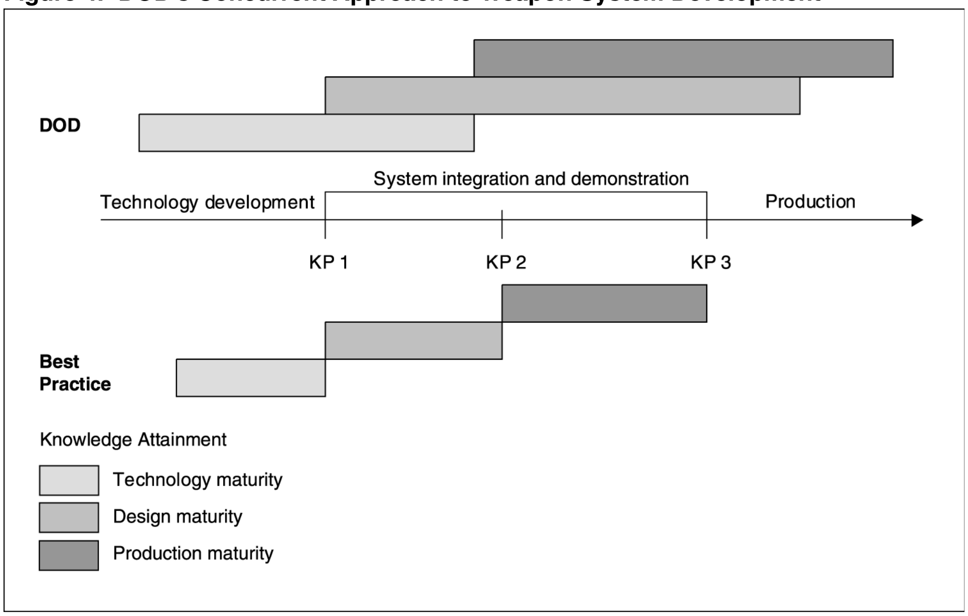


Source: GAO's analysis.

DOD's Traditional Approach to Product Development

DOD has historically developed new weapon systems in a highly concurrent environment that usually forces acquisition programs to manage technology, design, and manufacturing risk at the same time. This environment has made it difficult for either DOD or congressional decision makers to make informed decisions because appropriate knowledge has not been available at key decision points in product development. DOD's common practice for managing this environment has been to create aggressive risk reduction efforts in its programs. Cost reduction initiatives that typically arise after a program is experiencing problems are common tools used to manage these risks. Figure 4 shows the overlapping and concurrent approach that DOD uses to develop its weapon systems. This figure shows that DOD continues to capture technology, design, and manufacturing knowledge long after a program passes through each of the three knowledge points when this knowledge should have been available for program decisions.

Figure 4: DOD's Concurrent Approach to Weapon System Development



Source: GAO's analysis.

More important, the problems created by this concurrent approach on individual programs can profoundly affect DOD's overall modernization plans. It is difficult to prioritize and allocate limited budgets among needed requirements when acquisition programs' cost and schedule are always in question. Programs that are managed without the knowledge-based process are more likely to have surprises in the form of cost and schedule increases that are accommodated by disrupting the funding of other programs. Because of these disruptions, decision makers are not able to focus on a balanced investment strategy.

DOD's Adoption of Best Practices

DOD is taking steps to change the culture of the acquisition community with actions aimed at reducing product development cycle times and improving the predictability of cost and schedule outcomes. DOD recently made constructive changes to its acquisition policy that embrace best practices. These changes focused primarily on (1) ensuring technologies are demonstrated to a high level of maturity before beginning a weapon system program and (2) taking an evolutionary, or phased, approach to developing new weapon systems. Because these changes occurred in 2000 and 2001, it is too early to determine how effectively they will be put into practice. While these are good first steps, further use of best practices in product development would provide a greater opportunity to improve weapon system cost and schedule outcomes.

Objectives, Scope, and Methodology

Our overall objective was to determine whether best practices offer methods to improve the way DOD ensures that the design is stable early in the development process and whether having manufacturing processes in control before production results in better cost, schedule, and quality outcomes in DOD major acquisition programs. Specifically, we identified best practices that have led to more successful product development and production outcomes, compared the best practices to those used in DOD programs, and analyzed current weapon system acquisition guidance for applicability of best practices.

To determine the best practices for ensuring product design and manufacturing maturity from the commercial sector, we conducted general literature searches. On the basis of our literature searches and discussions with experts, we identified a number of commercial companies as having innovative development processes and practices that resulted in successful product development. We visited the following commercial companies:

- Caterpillar designs and manufactures construction and mining equipment, diesel and natural gas engines, and industrial gas turbines. In 2001, it reported sales and revenues totaling $20.45 billion. We visited its offices in Peoria, Illinois.

- Cummins Inc. (Engine Business group) designs and manufactures diesel and natural gas engines ranging in size from 60 to 3,500 horsepower for mining, construction, agriculture, rail, oil and gas, heavy and medium-duty trucks, buses, and motor homes. In 2001, the Engine Business Group reported sales of $3.1 billion. We visited its offices in Columbus, Indiana.

- General Electric Aircraft Engines designs and manufactures jet engines for civil and military aircraft and gas turbines, derived from its successful jet engine programs, for marine and industrial applications.

In 2001, it reported earnings totaling $11.4 billion. We visited its offices in Evendale, Ohio.

- Hewlett Packard designs and manufactures computing systems and imaging and printing systems for individual and business use. In 2001, it reported revenues totaling $45.2 billion. We visited its offices involved in the design and manufacturing of complex ink jet imaging equipment in Corvallis, Oregon.

- Xerox Corporation designs and manufactures office equipment, including color and black and white printers, digital presses, multifunction devices, and digital copiers designed for offices and production-printing environments. In 2001, it reported revenues totaling $16.5 billion. We visited its offices in Rochester, New York.

At each of the five companies, we conducted structured interviews with representatives to gather uniform and consistent information about each company's new product development processes and best practices. During meetings with these representatives, we obtained a detailed description of the processes and practices they believed necessary and vital to mature a product design and get manufacturing processes under control. We met with design engineers, program managers, manufacturing and quality engineers, and developers of the knowledge-based processes and policies.

During the past 5 years, we have gathered information on product development practices from such companies as 3M, Boeing Commercial Airplane Group, Chrysler Corporation, Bombardier Aerospace, Ford Motor Company, Hughes Space and Communications, and Motorola Corporation. This information enabled us to develop an overall model to describe the general approach leading commercial companies take to develop new products.

Our report highlights several best practices in product development based on our fieldwork. As such, they are not intended to describe all practices or suggest that commercial companies are without flaws. Representatives from the commercial companies visited told us that the development of their best practices has evolved over many years and that the practices continue to be improved based on lessons learned and new ideas and information. They admit that the application and use of these have not always been consistent or without error. However, they strongly suggested that the probability of success in developing new products is greatly enhanced by the use of these practices. Further, because of the sensitivity to how data that would show the actual outcomes of new product development efforts might affect their competitive standing, we did not obtain specific cost, schedule, and performance data. Most examples provided by these companies were anecdotal. However, the continued success of these companies over time in a competitive marketplace indicated that their practices were important and key to their operations. Furthermore, based on our observations during meetings at these companies, it was apparent that because of the level of detailed process tools developed for their managers and executive leadership these best practices were a centerpiece of their operations.

Next, we compared and contrasted the best practices with product development practices used in five DOD major acquisition programs. Below is a brief description of each program we examined:

- The F-22 fighter aircraft program. This aircraft is designed with advanced features to allow it to be less detectable to adversaries, capable of high speeds for long ranges, and able to provide the pilot with improved awareness of the surrounding situation through the use of integrated avionics. The F-22 program began in 1986 and entered limited production in 2001. The Air Force expects to buy 341 at a total acquisition cost (development and procurement) estimated at $69.7 billion.

- The Patriot Advanced Capability (PAC-3) missile program. This program is intended to enhance the Patriot system, an air-defense, guided missile system. PAC-3 is designed to enhance the Patriot radar's ability to detect and identify targets, increase system computer capabilities, improve communications, increase the number of missiles in each launcher, and incorporate a new "hit-to-kill" missile. The "hit-to-kill" missile capabilities represent a major part of the development program, as these are not capabilities included in prior versions of the Patriot system. The missile program began in 1994 and entered limited production in 1999. The Army plans to buy 1,159 missiles at a total acquisition cost estimated at $8.5 billion.

- The Advanced Threat Infrared Countermeasures/Common Missile Warning System (ATIRCM/CMWS) program. ATIRCM/CMWS is a defensive countermeasure system for protection against infrared guided missiles. The common missile warning system detects missiles in flight, and the advanced threat infrared countermeasure defeats the missile with the use of a laser. The combined system is designed for helicopter aircraft. The common missile warning system is also designed for tactical aircraft such as fighters. The program began in 1995 and is expected to start limited production in 2002. The Army and the Special Operations Command plan to buy 1,078 systems at a total acquisition cost estimated at $2.9 billion.

- The AIM-9X missile program. AIM-9X is an infrared, short range, air-to-air missile carried by Navy and Air Force fighter aircraft. The AIM-9X is an extensive upgrade of the AIM-9M. The AIM-9X is planned to have increased resistance to countermeasures and improved target acquisition capability. A key feature is that it will have the ability to acquire, track, and fire on targets over a wider area than the AIM-9M. The AIM-9X program began in 1994 and entered limited production in 2000. DOD plans to buy 10,142 missiles at a total acquisition cost estimated at $3 billion.

- The F/A-18 E/F fighter aircraft program. This aircraft is intended to complement and eventually replace the current F/A-18 C/D aircraft and perform Navy fighter escort, strike, fleet air defense, and close air support missions. It is the second major model upgrade since the F/A-18 inception. The development program began in 1992. The program entered limited production in 1997 and full rate production in 2000. The Navy plans to buy 548 aircraft at a total acquisition cost estimated at $48.8 billion.

We selected these programs for review based on cost, schedule, and performance data presented in the Selected Acquisition Reports[3] for each program. We also selected these programs because we considered them to be in two basic categories—successful and unsuccessful cost and schedule performance outcomes. This basis for selection was to compare and contrast the development practices used on each with best practices used by the commercial companies. For each program, we interviewed key managers and design and manufacturing engineering representatives. In some cases, we discussed design and manufacturing issues with representatives of the primary contractor for the specific program to obtain information on the practices and procedures used by the program to ready

[3] The Selected Acquisition Report provides standard, comprehensive summary reporting of cost, schedule, and performance information for major defense acquisition programs to the Congress.

the product design for initial manufacturing and testing as well as for production. We also discussed the use and potential application of best practices that we identified. In addition to discussions, we analyzed significant amounts of data on engineering drawings, design changes, labor efficiencies, manufacturing processes, quality indicators, testing, and schedules. We did not verify the accuracy of the data but did correlate it to other program indicators for reasonableness. Our analysis of the data was used as a basis to develop indicators of each program's development efficiencies and detailed questions to discuss product design and manufacturing practices.

We conducted our review between May 2001 and April 2002 in accordance with generally accepted government auditing standards.

Timely Design and Manufacturing Knowledge Is Critical to Program Success

The success of any effort to develop a new product hinges on having the right knowledge at the right time. Every program eventually achieves this knowledge; however, leading commercial companies we visited have found that there is a much better opportunity to meet predicted cost, schedule, and quality targets when it is captured early, in preparation for critical decisions. Specifically, knowledge that a product's design is stable early in the program facilitates informed decisions about whether to significantly increase investments and reduces the risk of costly design changes that can result from unknowns after initial manufacturing begins. This knowledge comes in the form of completed engineering drawings before transitioning from the system integration phase to the system demonstration phase of product development. Best practices suggest that at least 90 percent of the drawings for a product's design be completed before a decision to commit additional resources is made. Likewise, later knowledge that the design can be manufactured affordably and with consistent high quality prior to making a production decision ensures that cost and schedule targets will be met. This knowledge comes in the form of evidence from data that shows manufacturing processes are in control and system reliability is achievable. Leading commercial companies rely on knowledge obtained about critical manufacturing processes and product reliability to make their production decisions.

The Department of Defense (DOD) programs we reviewed captured varying amounts of design and manufacturing knowledge in the form of completed engineering drawings and statistical process control data. We found a correlation between the amount of knowledge each captured and their cost and schedule outcomes. Programs that were able to complete more engineering drawings and control their critical manufacturing processes had more success in meeting cost and schedule targets established when they began.

DOD Programs Had Better Outcomes When Design and Manufacturing Knowledge Was Captured at Key Program Junctures

Conceptually, the product development process has two phases: a system integration phase to stabilize the product's design and a system demonstration phase to demonstrate the product can be manufactured affordably and work reliably. The system integration phase is used to stabilize the overall system design by integrating components and subsystems into a product and by showing that the design can meet product requirements. When this knowledge is captured, knowledge point 2 has been achieved. It should be demonstrated by the completion of at least 90 percent of engineering drawings, which both DOD and leading commercial companies consider to be the point when a product's design is essentially complete. In the DOD process, this knowledge point should happen by the critical design review, before system demonstration and the initial manufacturing of production representative products begins. The system demonstration phase is then used to demonstrate that the product will work as required and can be manufactured within targets. When this knowledge is captured, knowledge point 3 has been achieved. Critical manufacturing processes are in control and consistently producing items within quality standards and tolerances for the overall product. Also, product reliability has been demonstrated. In the DOD process, like with the commercial process, this knowledge point should happen by the production commitment milestone. Bypassing critical knowledge at either knowledge point will usually result in cost, schedule, and performance problems later in product development and production.

We found that the most successful programs had taken steps to gather knowledge that confirmed the product's design was stable before the design was released to manufacturing organizations to build products for demonstration. They had most of the detailed design complete, supported by the completion of a large percentage of engineering drawings to manufacturing. Again, engineering drawings are critical because they include details on the parts and work instructions needed to make the product and reflect the results of testing. These drawings allowed manufacturing personnel to effectively plan the fabrication process and efficiently build production representative prototypes in the factory so manufacturing processes and the product's performance could be validated before committing to production. The most successful DOD programs also captured the knowledge that manufacturing processes needed to build the product would consistently produce a reliable product by the end of system demonstration, before making a production decision. On these programs, the initial phase of production—sometimes known as low-rate initial production—was able to focus on building operational test articles and improving the production processes, instead of continuing the product's design and development.

Problematic programs moved forward into system demonstration without the same knowledge from engineering drawings that successful cases had captured. They increased investments in tooling, people, and materials before the design was stable. In these programs, only a small percentage of the drawings needed to make the products had been completed at the time the designs were released to manufacturing organizations for building production representative prototypes. In doing so, these programs undertook the difficult challenge of stabilizing the designs at the same time they were trying to build and test the products. This design immaturity caused costly design changes and parts shortages that, in turn, caused labor inefficiencies, schedule delays, and quality problems. Consequently, these programs required significant increases in resources—time and money—over what was estimated at the point each program began the system demonstration phase.

The most problematic programs also started production before design and manufacturing development work was concluded. In these cases, programs were producing items for the customers while making major product design and tooling changes, still establishing manufacturing processes, and conducting development testing. These programs encountered significant cost increases, schedule delays, and performance problems during production.

Table 2 shows the relationship between design stability and manufacturing knowledge at key junctures and the outcomes for the DOD programs we reviewed. To measure design stability at the start of the system demonstration phase, knowledge point 2, we determined the percentage of the product's engineering drawings that had been completed by the critical design review. In DOD programs, after the critical design review, the system design is released to manufacturing to begin building the production representative prototypes for the system demonstration phase. To measure producibility at the production decision, knowledge point 3, we determined whether the critical manufacturing processes were in statistical control at that time. We compared this information with best practices. The cost and schedule experiences of the program since the start of system demonstration are also shown.

Table 2: Attainment of Design and Manufacturing Knowledge in DOD Programs and the Program Outcomes

Weapon system	Percentage of drawings completed prior to manufacturing	Percentage of critical manufacturing processes in control at production	Program experience since system demonstration started
Best practice	At least 90 percent of drawings completed	All critical processes in statistical control	Meet cost and schedule targets
AIM-9X (air to air missile)	95 percent	Unknown[a]	4 percent unit cost increase, 1-month production delay
FA-18 E/F fighter	56 percent[b]	78 percent	No unit cost increase, 3-month production delay
F-22 fighter	26 percent	44 percent	23 percent unit cost increase, 18-month production delay
Patriot Advanced Capability (PAC-3) missile	21 percent	35 percent	159 percent unit cost increase, 39-month production delay
Advanced Threat Infrared Countermeasures/Common Missile Warning System (ATIRCM/CMWS)	21 percent	0	182 percent unit cost increase, 34-month production delay

[a]While AIM-9X used statistical process control on a limited basis, we believe other factors contributed to a successful production outcome to date. Other factors included early achievement of design stability, early identification of key characteristics and critical manufacturing processes, use of established manufacturing processes for components common to other weapon systems, design trade-offs to enhance manufacturing capability, and a product design less vulnerable to variations in manufacturing processes.

[b]F/A-18 E/F had 56 percent of drawings completed but also had completed most of the higher-level assembly drawings. The combination of these drawings with the fact the aircraft was a variant of previously fielded F-18 aircraft models provided the program a significant amount of knowledge that the design was stable at the start of system demonstration.

Source: DOD program offices and Selected Acquisition Reports.

As shown in the table, the AIM-9X and FA-18 E/F programs had captured a significant amount of design knowledge at the start of system demonstration and manufacturing knowledge by the start of production. In each of those programs, product developers had the advantage of prior versions of the systems. These programs came very close to meeting their original cost and schedule estimates for product development. The other three programs, F-22, PAC-3, and ATIRCM/CMWS, had less knowledge at each key junctures. Their development cost and schedule results significantly exceeded estimates. Specific details on the AIM-9X, F-22, and ATIRCM/CMWS program experiences follow.

AIM-9X Program Experience

The AIM-9X program began in 1994, continuing the long-term evolution of the AIM-9 series of short-range air-to-air missiles. In 1999, after developing and testing a number of engineering prototype missiles, the program held a critical design review to determine if the program was ready to begin initial manufacturing of a production representative prototype for system demonstration. At this review, about 95 percent of the eventual engineering drawings were completed—a stable design by best practices. Because AIM-9X was the next generation in this family of missiles, the program had significant knowledge on how to produce the missile. At the 1999 critical design review, the estimated development and production costs totaled $2.82 billion. As of December 2001, the estimate was $2.96 billion, less than a 5 percent increase.

F-22 Program Experience

The F-22 program began detailed design efforts in 1991 when it entered a planned 8-year product development phase. In 1995, about the expected midpoint of the phase, the program held its critical design review to determine if the design was stable and complete. Despite having only about a quarter of the eventual design drawings completed for the system, the program declared the design to be stable and ready to begin initial manufacturing. At that time, the program office had estimated the cost to complete the development program at $19.5 billion. However, the program did not complete 90 percent of its drawings for the aircraft until 1998, 3 years into the system demonstration phase. During the building of the initial aircraft, several design and manufacturing problems surfaced that affected the deliveries of major sections of the aircraft. Large sections were delivered incomplete to final assembly and had to be built out of the planned assembly sequence.

In 1997, an independent review team examined the program and determined the product development effort was underestimated. The team found that building the first three aircraft was taking substantially more labor hours than planned. Between 1995 and 1998, the development estimate for the F-22 increased by over $3.3 billion and the schedule slipped by a year. Achieving design stability late has contributed to further cost increases. As of December 2001, the estimated development cost was $26.1 billion, a 34 percent increase since the critical design review was held in 1995.

While the program attributes some production cost increases to a reduction in F-22 quantities, it has been significantly affected by design and manufacturing problems that started during development. The independent review team evaluated the cost impact on the production aircraft that would likely occur because of cost and schedule problems in development and found that production aircraft would have to begin later, at a slower pace, and cost more than expected. The team estimated that production costs could increase by as much as $13 billion if savings were not found. The Air Force subsequently increased the estimate to more than $19 billion in cost savings required to avoid cost increases. In 2001, when the F-22 limited production decision was made, the program had less knowledge about the aircraft's reliability and manufacturing processes than more successful cases. For example, at its limited production decision, it had only 44 percent of its critical manufacturing processes in control. In September 2001, the program reported that overall production cost would likely increase by more than $5.4 billion. This estimate was based on the effort needed so far to build the aircraft during product development.

ATIRCM/CMWS Program Experience

Since it began in 1995, the ATIRCM/CMWS program has had significant cost growth and schedule delays during product development. The product developer held a major design review in 1997. Like the F-22, the review demanded less proof about the product's design in the form of engineering drawings before deciding to begin initial manufacturing. At that time, only 21 percent of the engineering drawings had been completed, and it was still unknown whether the design would meet the requirements. In fact, the program knew that a major redesign of a critical component was needed. Despite this, the program office deemed the risk acceptable for moving the program forward to begin manufacturing prototypes. Over the next 2 years, the program encountered numerous design and manufacturing problems. It was not until 1999, about 2 years after the critical design review, that program officials felt that the design had stabilized; however, by this time, the product development cost had increased 160 percent and production had been delayed by almost 3 years.

ATIRCM/CMWS is scheduled to begin limited production in early 2002, but without the same degree of assurance as the more successful programs that the product can be manufactured within cost, schedule, and quality targets. The program has not yet determined if manufacturing processes needed to build the product are in control. Many of the development units were built by hand, in different facilities, and with different processes and personnel. Program officials stated that because they did not stabilize the design until late in development, manufacturing issues were not adequately addressed. Since 1997, the estimated unit cost for the system has increased by 182 percent.

Best Practices Enable Timely Capture of Design and Manufacturing Knowledge

Leading commercial companies have been successful in achieving product development goals because they have found ways to enable the capture of design and manufacturing knowledge about the products they are developing in a timely way. We found two practices that allowed leading commercial companies to capture necessary knowledge for product development. First, they established a framework of evolutionary product development that limited the amount of design and manufacturing knowledge that had to be captured. This framework limited the design challenge for any one new product development by requiring risky technology, design, or manufacturing requirements to be deferred until a future generation of the product. Second, each company (1) employed a disciplined product development process that brought together and integrated all of the technologies, components, and subsystems required for the product to ensure the design was stable before entering product demonstration and (2) demonstrated the product was reliable and producible using proven manufacturing processes before entering production.

The product development process includes tools that both capture knowledge and tie this knowledge to decisions about the product's design and manufacturing processes before making commitments that would significantly affect company resources. For example, during system integration, each leading commercial company used various forms of prototypes and information from predecessor products to stabilize the product's design and identify critical processes, then used a decision review that required agreements from key stakeholders that the requisite design knowledge was captured in making a decision to move into system demonstration. During system demonstration, each company used statistical process control and reliability testing to ensure the product could be produced affordably and would be reliable, then used a similar decision review that required agreements from key stakeholders that the requisite knowledge was captured when deciding to move into production.

The Department of Defense (DOD) programs that we reviewed used some of these practices to varying degrees and experienced predictable outcomes. For example, the AIM-9X and F/A-18 E/F programs were evolutionary in nature, modifications of existing products with a manageable amount of new technological or design challenges. They also gathered design and manufacturing knowledge, although not to the extent we found at commercial companies. Finally, they held program reviews and ensured that the design and manufacturing knowledge was captured before moving forward. They had relatively successful outcomes. The other DOD programs—the F-22, ATIRCMS, and PAC-3—did not closely approximate best practices in capturing design or manufacturing knowledge during product development. They took on greater design challenges, had program reviews that were not supported by critical design and manufacturing knowledge, and made decisions to advance to the next phases of development without sufficient design and manufacturing knowledge.

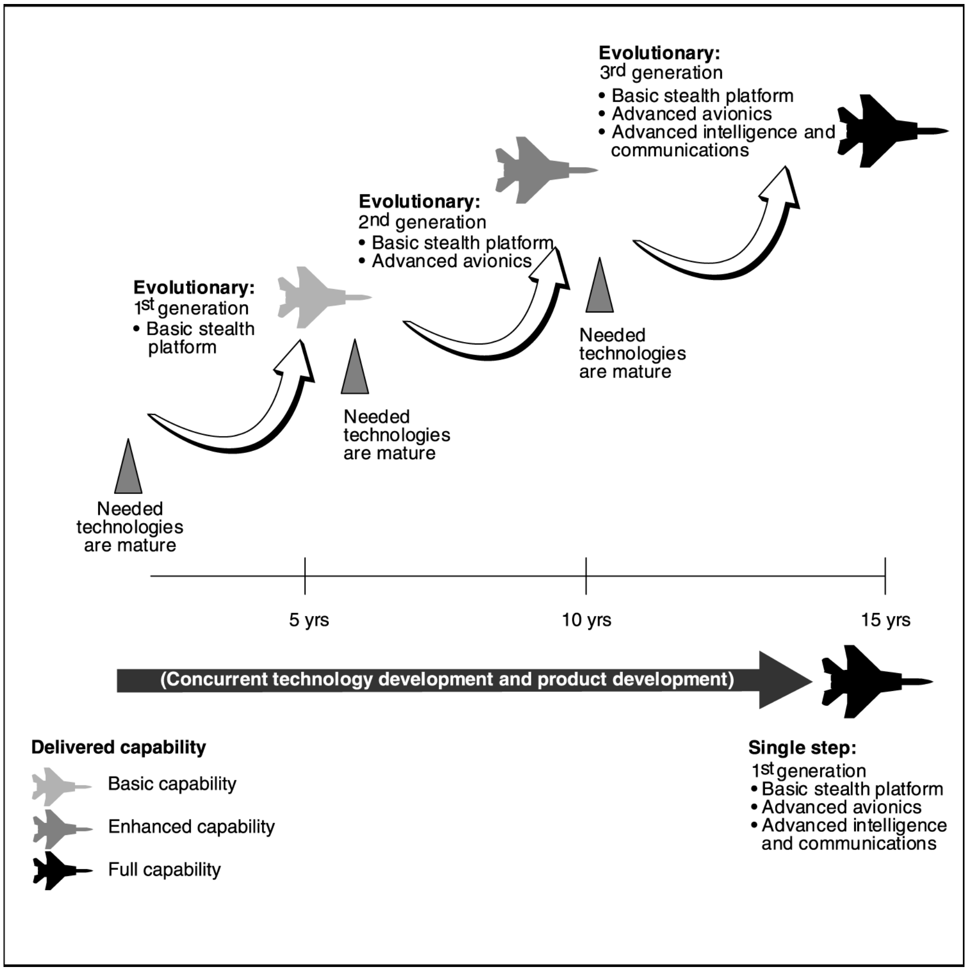
Leading Commercial Companies Use Evolutionary Product Development Framework to Reduce Development Risks

A key to the success of commercial companies was using an evolutionary approach to develop a product. This approach permitted companies to focus more on design and development with a limited array of new content and technologies in a program. It also ensured that each company had the requisite knowledge for a product's design before investing in the development of manufacturing processes and facilities. Companies have found that trying to capture the knowledge required to stabilize the design of a product that requires significant amounts of new content is an unmanageable task, especially if the goal is to reduce cycle times and get the product into the marketplace as quickly as possible. Design elements not achievable in the initial development were planned for subsequent development efforts in future generations of the product, but only when technologies were proven to be mature and other resources were available.

Commercial companies have implemented the evolutionary approach by establishing time-phased plans to develop new products in increments based on technologies and resources achievable now and later. This approach reduces the amount of risk in the development of each increment, facilitating greater success in meeting cost, schedule, and performance requirements. In effect, these companies evolve products, continuously improving their performance as new technologies and methods allow. These evolutionary improvements to products eventually result in the full desired capability, but in multiple steps, delivering a series of enhanced interim capabilities to the customer more quickly.

Historically, DOD's approach has been to develop new weapon systems that often attempt to satisfy the full requirement in a single step, regardless of the design challenge or the maturity of technologies necessary to achieve the full capability. Under this single-step approach, a war fighter can wait over 15 years to receive any improved capability. Figure 5 shows a notional comparison between the single-step and evolutionary approaches.

Figure 5: Notional Single-Step and Evolutionary Approaches to Developing New Products



Source: GAO's analysis and DOD acquisition guidance.

Each commercial company we visited used the evolutionary approach as the primary method of product development. General Electric builds on the basic capability of a fielded product by introducing proven improvements in capability from its advanced engineering development team. General Electric considers the introduction of immature technologies into fielded products or new engine development programs as a significant cost and schedule risk. Its new product development process is primarily focused on reducing and managing risk for design changes and product introductions. Cummins and Hewlett Packard managers indicated that, in the past, their companies learned the hard way by trying to make quantum leaps in product performance and by including immature technologies. Now, both companies have new product development processes that actively manage the amount of new content that can be placed on a new product development effort. Caterpillar also limits new content on its new products as a way to more successfully and cost-effectively develop new, but evolutionary, products. Even during the development of its 797 mining truck, which it considered a major design challenge, it did not require the truck to achieve capabilities—such as prognostics for better maintenance—that it could not demonstrate or validate in the design in a timely manner.

Of the five DOD programs we reviewed, two—the F/A-18-E/F and the AIM-9X—were variations of existing products—the F/A-18-C/D and the AIM-9M—and the programs made a commitment to use existing technologies and processes as much as possible. These two programs had relatively successful cost and schedule outcomes. They represented an exception to the usual practice in DOD. The overwhelming majority of DOD's major acquisitions today require major leaps in capability over their predecessors or any other competing weapon systems, with little knowledge about the resources that will be required to design and manufacture the systems. Decisions are continually made throughout product development without knowing the cost and schedule ramifications.

Leading Commercial Companies Use a Product Development Process to Capture Design and Manufacturing Knowledge for Decision Making

Leading commercial companies we visited had spent significant amounts of time and resources to develop and evolve new product development processes that ensured design and manufacturing knowledge was captured at the two critical decision points in product development: when the product's design was demonstrated to be stable—knowledge point 2—and when the product was demonstrated to be producible at an affordable cost—knowledge point 3. The process established a disciplined framework to capture specific design and manufacturing knowledge about new products. Companies then used that knowledge to make informed decisions about moving forward in a new product development program. Commercial companies tied this knowledge to decisions about the products' design and manufacturing processes before making commitments that would significantly impact company resources. Each commercial firm we visited had a new product development process that was prominent and central to the firm's successes. It included three aspects: (1) activities that led to the capture of specific design knowledge, (2) activities that led to the capture of specific manufacturing and product reliability knowledge, and (3) decision reviews to determine if the appropriate knowledge was captured to move to the next phase.

Design Knowledge Should Be Captured before Entering Product Demonstration

To ensure that the product's design was stable before deciding to commit additional resources to product demonstration, commercial companies demanded knowledge, either from existing product information or by building engineering prototypes. They also used a disciplined design review process to examine and verify the knowledge that had culminated at the end of product integration, This design review process required agreement from stakeholders that the product design could be produced and would satisfy the customer's requirements. Stakeholders included design engineers, manufacturing or production personnel, and key supplier representatives who used engineering drawings, supported by test results and engineering data, as a key indicator of the design's stability. Once the program achieved a stable design, the certainty of their cost and schedule estimates was substantially increased, allowing them to plan the balance of the product development program with high confidence. Table 3 shows the activities required to capture design knowledge that leads to executive decisions about whether to transition to the next phase of development.

Table 3: Activities to Capture Design Knowledge and Make Decisions

Knowledge: Design is stable and performs as expected (knowledge point 2) **Decision: Product is ready for initial manufacturing and system demonstration phase** **Key indicator: 90 percent of engineering drawings completed**
Activities to Achieve Stable Design Knowledge • **Limit design challenge** - The initial design challenge is limited to a product that can be developed and delivered quickly and provide the user with an improved capability. A time-phased plan is used to develop improved products—future generations—in increments as technologies and other resources become available. • **Demonstrate design meets requirements** -The product's design is demonstrated to meet the user's requirements. For a new product that is not based on an existing product, prototypes are built and tested. If the product is a variant of an existing product, companies often used modeling and simulation or prototypes at the component or subsystem level to demonstrate the new product's design. • **Complete critical design reviews** - Critical design reviews are used to assess whether a product's design meets requirements and is ready to start initial manufacturing. They are conducted for the system, subsystems, and components to assess design maturity and technical risk. • **Stakeholders agree drawings complete and producible** - The agreement by stakeholders (engineers, manufacturers, and other organizations) is used to signify confidence that the design will work and the product can be built. • **Executive level review to begin initial manufacturing** - Corporate stakeholders meet and review relevant product knowledge, including design stability, to determine whether a product is ready to initiate manufacturing of production representative prototypes used during system demonstrations. The decision is tied to the capture of knowledge.

Demonstrating the Design Helped Achieve Stability

A key tool used by each company to ensure that a product's design was stable by the end of the product integration phase was a demonstration that the design would meet requirements. The companies visited indicated that prototypes at various system levels were the best way to demonstrate that the product's design would work. If the product under development was an incremental improvement to existing products, such as the next generation of a printer or engine, these companies used virtual prototypes for any components that were being used for the first time. If the product included more new content or invention, fully integrated prototypes were frequently used to demonstrate that the design met requirements. Prototypes at this stage in development were typically not built in a manufacturing facility. This allowed demonstrations of the design before the companies made more costly investments in manufacturing equipment and tooling to build production representative prototypes for the demonstration phase. Table 4 shows an example of the types and purposes for various kinds of prototypes used by Cummins Inc. depending on the amount of knowledge it needed to capture and the point it was in the development process. Prototypes were used by commercial companies throughout the product development process and not just during product integration.

Table 4: Examples of Prototypes Used by Cummins Inc. at Various Stages of Product Development

	Product integration	Product demonstration	Production
Prototype	Engineering prototypes (virtual or physical)	Production representative prototypes	Initial products
Purpose	Demonstrate form, fit and function, and a stable design	Demonstrate the product is capable, reliable, and manufacturing processes in statistical control	Demonstrate ready for full rate production
Build environment	Engineering	Manufacturing (1st set of production tooling)	Production (all rate tooling)

Cummins, the world sales leader in diesel engines over 200 horsepower, effectively uses prototypes to ensure that a design is stable and believes in the value of prototyping throughout product development. A Cummins representative stated that not using prototypes becomes a matter of "pay me now or pay me later," meaning that it is far less costly to demonstrate a product's design early in development with prototypes, concepts, and analyses than to incur the cost of significant design changes after a product has entered production—a much more costly environment to make changes. Cummins built and tested 12 engineering concept prototype engines for its Signature 600 engine, a new concept, 600 horsepower, overhead cam diesel engine that represented a quantum leap in performance beyond Cummins' existing products. These prototypes were built using production-like tooling and methods using production workers. In addition to using engineering prototypes during the product integration phase of product development, Cummins and other companies we visited used other prototypes—such as production representative prototypes—in the remaining product development phases before production, as shown in table 4, to demonstrate product reliability and process control. Prior to reaching production for its Signature 600 engine, Cummins used many prototypes to complete hundreds of thousands of test hours, accumulating millions of test miles.

Caterpillar, a major manufacturer of heavy equipment, has a continuous product improvement philosophy. That is, it tries to develop new products that increase the capabilities of existing product lines, but it limits the amount of new content on any one product development because new content inherently increases design risk. In evolving its products this way, Caterpillar is able to use modeling and simulation prior to initial manufacturing because it has existing products to provide a baseline of knowledge and a good benchmark for assessing the simulated performance. In addition, with knowledge of existing components, it can focus attention on maturing the new content, the higher risk element of the new product. When Caterpillar developed the 797 mining truck, a new 360-ton payload truck design, it demonstrated design stability by identifying the critical components and building engineering prototypes of them for reliability testing and demonstration of the design before beginning initial manufacturing. This knowledge, coupled with vast experience in manufacturing trucks, ensured the stability of the 797-truck design before initial manufacturing started. Caterpillar was able to deliver this design in 18 months after the product development was started.

Disciplined Reviews and Stakeholder Agreements Supported the Capture of Design Knowledge

The commercial companies we visited understood the importance of having disciplined design reviews and getting agreement from the stakeholders that the product's design had been demonstrated to meet requirements before beginning initial manufacturing. Each company had a design review process that began at the component level, continued through the subsystem level, and culminated with a critical design review of the integrated system to determine if the product was ready to progress to the next phase of development. In addition to design engineers, a cross-functional team of stakeholders in the process included key suppliers, manufacturing representatives, and service and maintenance representatives. From past experience, commercial companies have discovered that cross-functional teams provide a complete perspective of the product. While design engineers bring important skills and experience to creating a product design, they may not be aware of manufacturing issues, available technologies, or manufacturing processes, and they may design a product that the company cannot afford to produce or maintain.

The product's design is stable when all stakeholders agree that engineering drawings are complete and that the design will work and can be built. A commercial company considers engineering drawings[4] to be a good measure of the demonstrated stability of the product's design because they represent the language used by engineers to communicate to the manufacturers the details of a new product design—what it looks like, how its components interface, how it functions, how to build it, and what critical materials and processes are required to fabricate and test it. The engineering drawing package released to manufacturing includes items such as the schematic of the product's components, interface control documents, a listing of materials, notations of critical manufacturing processes, and testing requirements. It is this package that allows a manufacturer to build the product in the manufacturing facility.

In developing the Signature 600, Cummins used cross-functional design teams that included stakeholders from suppliers, machine tool manufacturers, foundry and pattern makers, purchasing, finance, manufacturing engineering, design engineering, and other technical disciplines. Signature 600 components were designed with the key suppliers co-located at the Cummins design facility. Likewise, Caterpillar said that early supplier and manufacturing involvement was critical to success and that engineering drawings were signed by design and manufacturing stakeholders. Caterpillar representatives said that signing the drawings was a certification that the design could be manufactured the next day, if necessary.

Executive Level Reviews Were Required to Begin Initial Manufacturing

Each commercial company, after capturing specific design knowledge, had an executive level review at the decision point to determine if the product design had sufficiently progressed to permit a transition from product integration to product demonstration. This decision point used the knowledge captured as exit criteria for moving to the next phase of development. For example, to demonstrate the product design was stable

[4] Engineering drawings can include the standard two-dimensional drawings or newer three-dimensional drawings that are the product of computer-aided design software systems.

and ready to move from integration to demonstration, the design had to be demonstrated, at least 90 percent of the engineering drawings had to be completed, design reviews had to be completed, and stakeholders had to agree the design was complete and producible. If the design team could not satisfy the exit criteria, then other options had to be considered. Options included canceling the development program, delaying the decision until all criteria were met, or moving ahead with a detailed plan to achieve criteria not met by a specific time when leadership would revisit the other options. One company emphasized that if a major milestone is delayed, an appropriate adjustment should be made to the end date of the program, thereby avoiding compressing the time allotted for the rest of product development and managing the risks that subsequent milestones will be missed.

This decision point coincides with the companies' need to increase investments in the product development and continue to the next phase. For this reason, the decision point was considered critical to achieving success in product development and could not be taken lightly. For example, transitioning from the integration to the demonstration phase requires a significant investment to start building and testing production representative prototypes in a manufacturing environment. This requires establishing a supplier base and purchasing materials. In addition, establishing tooling and manufacturing capability is also required. After a product passes this decision point and added investments are made, the cost of making changes to the product design also increases significantly. Therefore, commercial companies strive to firm the design as early in the process as possible when it is significantly cheaper to make changes.

Manufacturing and Product Reliability Knowledge Should Be Captured before Starting Production

We found that leading commercial companies used two tools to capture knowledge that a product's design was reliable and producible within cost, schedule, and quality targets before making a production decision. These tools are (1) a quality concept that uses statistical process control to bring critical manufacturing processes under control so they are repeatable, sustainable, and consistently producing parts within the quality tolerances and standards of the product and (2) product tests in operational conditions that ensure the system would meet reliability goals–the ability to work without failure or need of maintenance for predictable intervals. Company officials told us that these two tools enabled a smooth transition from product development to production, resulting in better program outcomes. Companies employed these tools on production representative prototypes, making the prototypes a key ingredient to successful outcomes. Table 5 shows the activities required to capture manufacturing knowledge that leads to executive decisions about whether to transition from product development into production.

Table 5: Activities to Capture Manufacturing Knowledge and Make Decisions

Knowledge: Product can be produced within cost, schedule, and quality targets (knowledge point 3) **Decision: Product is ready for production and will be reliable** **Key indicator: Critical processes in statistical control and product reliability demonstrated**
Activities to Achieve Manufacturing Knowledge • **Identify key system characteristics and critical manufacturing processes** – Key product characteristics and critical manufacturing processes are identified. Because there can be thousands of manufacturing processes required to build a product, companies focus on the critical processes—those that build parts that influence the product's key characteristics such as performance, service life, or manufacturability. • **Determine processes in control and capable** - Statistical process control is used to determine if the processes are consistently producing parts. Once control is established, an assessment is made to measure the process's ability to build a part within specification limits as well as how close the part is to that specification. A process is considered capable when it has a defect rate of less than 1 out of every 15,152 parts produced. • **Conduct failure modes and effects analysis** - Bottom-up analysis is done to identify potential failures for product reliability. It begins at the lowest level of the product design and continues to each higher tier of the product until the entire product has been analyzed. It allows early design changes to correct potential problems before fabricating hardware. • **Set reliability growth plan and goals** - A product's reliability is its ability to perform over an expected period of time without failure, degradation, or need of repair. A growth plan is developed to mature the product's reliability over time through reliability growth testing so that it has been demonstrated by the time production begins. • **Conduct reliability growth testing** –Reliability growth is the result of an iterative design, build, test, analyze, and fix process for a product's design with the aim of improving the product's reliability over time. Design flaws are uncovered and the design of the product is matured. • **Conduct executive level review to begin production** - Corporate stakeholders meet and review relevant product knowledge, including manufacturing and reliability knowledge, to determine whether a product is ready to begin production. The decision is tied to the capture of knowledge.

Statistical Process Control Is Important to Controlling Critical Manufacturing Processes

Commercial companies rely on statistical process control data to track, control, and improve critical manufacturing processes before production begins. Bringing processes under statistical control reduces variations in parts manufactured, thus reducing the potential for defects. Product variation has been called the "silent killer" on the manufacturing floor because it can result in defects that require additional resources to either rework or scrap the product. Products fielded with defects may have degraded performance, lower reliability, or increased support costs. Experience has taught commercial companies that it is less costly—in terms of time and money—to eliminate product variation by controlling manufacturing processes than to perform extensive inspection after a product is built. Because thousands of manufacturing processes can be required to build a product, companies focus on the critical processes—those that build parts that influence the product's performance, service life, or manufacturability. Therefore, when design engineers are designing the new product, they must identify its key characteristics so that manufacturing engineers can identify and control critical manufacturing processes. Key product characteristics and critical manufacturing processes are noted on the engineering drawings and work instructions that are released to manufacturing.

Once critical processes are identified, companies perform capability studies to ensure that a process will produce parts that meet specifications. These studies yield a process capability index (Cpk), a measure of the process's ability to build a part within specified limits. The index can be translated into an expected product defect rate. The industry standard is to have a Cpk of 1.33 or higher, which equates to a probability that 99.99 percent of the parts built on that process will be within the specified limits. Four of the five[5] companies we visited wanted their critical processes at a minimum of a 1.33 Cpk and many had goals of achieving higher Cpks. Table 6 shows various Cpk values and the defect rate associated with each value. The table also shows the higher the Cpk, the lower the defect rate.

Table 6: Cpk Index and Probability of a Defective Part

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

Cpk values also have an additive effect on various individual parts when each part is integrated into the final product. For example, a product composed of 25 parts, where each part is produced on a manufacturing process with a Cpk of 0.67, has a 95.5 percent probability that each part will be defect free. However, when all 25 parts are assembled into the final product, the probability that the final product will be defect free is only 32 percent. In comparison, if the same parts are produced with manufacturing processes at a Cpk of 1.33, the probability of each part being defect free is 99.99 percent. When these same 25 parts are assembled into the final product, the probability that the final product will be defect free is

[5] The fifth company wanted its critical manufacturing processes at a minimum of 1 Cpk.

99.8 percent. This comparison illustrates the impact that having manufacturing processes in control has on the amount of rework and repair that would be needed to correct defects and make the product meet its specifications.

Cummins uses statistical process control data to measure a product's readiness for production. In developing the new Signature 600 diesel engine, Cummins included manufacturing engineers and machine tool and fixture suppliers in the design decision process as the engine concept was first being defined. Cummins built production representative prototypes of its engines to demonstrate that the design and the engine hardware would perform to requirements. These prototypes represented the first attempt to build the product solely using manufacturing personnel, production tooling, and production processes. Cummins used the knowledge captured from these and subsequent prototypes to refine and eventually validate the manufacturing processes for the engine. This process of employing statistical process control techniques on prototype engines verified that the manufacturing processes were capable of manufacturing the product to high quality standards within established cost and schedule targets.

Other companies we visited emphasized the importance of controlling manufacturing processes before committing to production. For example, Xerox captures knowledge about the producibility of its product early in the design phase. By production, it strives to have all critical manufacturing processes for the product—including key suppliers' processes—in control with a Cpk index of at least 1.33. Xerox achieves this by building production representative prototypes and by requiring suppliers of key components and subassemblies to produce an adequate sample of parts to demonstrate the suppliers' processes can be controlled, usually before the parts are incorporated into the prototypes. General Electric Aircraft Engines has digitally captured, and made available to design engineers, Cpk data on almost all of its manufacturing processes and it strives to have critical processes in control to a point where they will yield no more than 1 defect in 500 million parts, a Cpk of 2.0. Other companies, such as Caterpillar and Hewlett Packard, told us that getting manufacturing processes in control prior to production is key to meeting cost, schedule, and quality targets. Each of the companies visited used this as an indicator of the product's readiness for production and emphasized the importance of having critical manufacturing processes under control by the start of production.

Demonstrating Product Reliability Indicates the Product Is Ready for Production

A product is reliable when it can perform over a specified period of time without failure, degradation, or need of repair. Reliability is a function of the specific elements of a product's design. Making design changes to achieve reliability requirements after production begins is inefficient and costly. Reliability growth testing provides visibility over how reliability is improving and uncovers design problems so fixes can be incorporated before production begins.

In general, reliability growth is the result of an iterative design, build, test, analyze, and fix process. Prototype hardware is key to testing for reliability growth. Initial prototypes for a complex product with major technological advances have inherent deficiencies. As the prototypes are tested, failures occur and, in fact, are desired so that the product's design can be made more reliable. Reliability improves over time with design changes or manufacturing process improvements. The earlier this takes place, the less impact it will have on the development and production program. Companies we visited matured a product's reliability through these tests and demanded proof that the product would meet the customer's reliability expectations prior to making a production decision.

Improvements in the reliability of a product's design can be measured by tracking a key reliability metric over time. This metric compares the product's actual reliability to a growth plan and ultimately to the overall reliability goal. Several commercial companies we visited began gathering this data very early in development and tracked it throughout development. The goal was to demonstrate the product would meet reliability requirements before starting full rate production.

Caterpillar establishes a plan to grow and demonstrate the product's reliability before fabrication of a production representative prototype begins. Before Caterpillar starts making parts, it estimates the product's reliability in its current stage of development based on knowledge captured from failure modes and effects analysis,[6] component prototype testing, and past product experience. This information marks the starting point for the product's reliability growth plan and is the basis for assessing whether the plan is achievable by production. If Caterpillar believes the risks are too

[6] Failure modes and effects analysis is a bottom-up approach to failure identification. It should begin at the lowest level of the product design. Through analysis potential failure modes are identified allowing early design change to correct potential problems before fabricating hardware—a more cost-effective time to identify and fix problems.

high and the goal cannot be achieved on time, decision makers assess trade-offs between new and existing components to reduce the risks to a more manageable level. Trade-offs might be made if the product's performance still fails to meet requirements. If trade-offs are not possible, decision makers may decide not to go forward with the development. Once Caterpillar has established this plan, it tracks demonstrated reliability against it as a management tool to measure progress. It sets an interim reliability milestone and expects to be at least halfway toward the expected goal by the time it begins to build production units. Caterpillar has learned from experience that it will achieve the full reliability goal by full production if it meets the interim goal by the time it produces pilot production units. If the reliability is not growing as expected, then decisions about changing or improving the design must be addressed.

Caterpillar improves the product's reliability during development by testing prototypes, uncovering failures, and incorporating design changes. According to Caterpillar officials, the production decision will be delayed if they are not on track to meeting their reliability goal. These officials told us that Caterpillar maintains the philosophy of first getting the design right, then producing it as quickly and efficiently as possible. They emphasized that demonstrating reliability before production minimized the potential for costly design changes once the product is fielded.

Executive Level Reviews Are Conducted to Begin Production

The commercial companies, after capturing specific manufacturing knowledge, had executive level reviews to determine if the product development had sufficiently progressed to permit a transition into production. Executives used the knowledge captured as exit criteria for the transition. For example, to demonstrate the product was ready for production, critical processes had to be in control and testing should have demonstrated the product reliability. If the design team could not satisfy the exit criteria, then other options had to be considered. The production decision led to increased investments for materials and resources such as additional tooling to build the product at a planned rate, facilities, people, training and support.

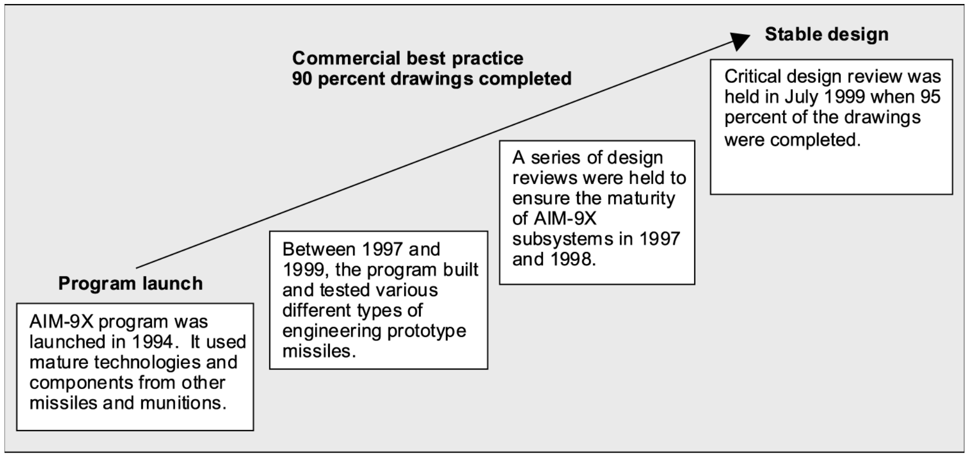
When DOD Programs More Closely Approximated Best Practices, Outcomes Were Better

Our analysis of DOD programs showed that those more closely approximating best practices had better outcomes. The F/A-18 E/F fighter and the AIM-9X missile were based extensively on predecessor programs and employed similar tools to capture design and manufacturing knowledge at critical program junctures. These programs had demonstrated a significantly higher degree of design stability prior to entering system demonstration and committing to initial manufacturing when compared to other DOD weapon programs in our review. They also gained control of most of their manufacturing processes and demonstrated that the products were reliable before entering production. The success of these programs is best demonstrated by the fact that they have been close to meeting cost, schedule, and performance objectives. On the other hand, the PAC-3 missile, F-22 fighter, and ATIRCM/CMWS programs did not use these best practices. These programs were not based on predecessor products or evolutionary in nature, and each product's full capability was expected in one step, with the first product off the production line. With this daunting task, these programs failed to demonstrate a stable design before committing to initial manufacturing, causing quality and labor problems. These programs also had much less knowledge about the manufacturability of their design when they entered production. As a result, they experienced significant increases in development costs and production delays usually at the expense of other DOD programs. Details on the five DOD programs follow.

AIM-9X Missile Program

The AIM-9X development practices closely paralleled best practices used by the commercial companies we visited. The program achieved design stability before moving into system demonstration by incorporating mature technologies and components from other missiles and munitions, using engineering prototypes to demonstrate the design, holding a series of design reviews prior to the system level critical design review, and completing and releasing 95 percent of the engineering drawings at that time. Figure 6 shows the building of knowledge required to achieve a stable design on the AIM-9X.

Figure 6: Achieving Stability on AIM-9X Missile Program by Knowledge Point 2



Source: GAO's analysis.

The AIM-9X program made extensive use of engineering prototypes to stabilize the missile's design before building production representative prototypes. Program officials stated that testing of engineering prototypes uncovered problems with missile design and manufacturing tooling early in the development, during system integration, allowing time to re-design and re-test in follow-on configurations. According to program officials, this not only helped stabilize the design before entering initial manufacturing but grew system reliability and reduced total ownership costs. The program also held design reviews for each of the major subsystems, allowing the program to achieve and demonstrate a stable design in July 1999, before beginning initial manufacturing of production representative prototypes.

While the AIM-9X used statistical process control only to a limited extent, other factors have allowed it to have a more successful production outcome to date. Program officials took steps to ensure that manufacturing aspects of the product were included in the design, including empowering a product leader with a manufacturing background, identifying the key characteristics and critical manufacturing processes early, making design trade-offs to enhance manufacturing capability, and demonstrating a robust design to make the product less vulnerable to variations in manufacturing process. In addition, the ability to achieve design stability at the critical design review allowed program officials to focus the system demonstration phase on maturing the manufacturing processes. Prior to committing to production, the program demonstrated that the product could be efficiently built using production processes, people, tools, and facilities to build prototypes. According to the former program manager, these steps gave the officials knowledge that a reliable product could be produced within cost and schedule targets prior to entering production. To date, the AIM-9X program has largely met its production targets.

F/A-18 E/F Program

The F/A-18 E/F aircraft development program was able to take advantage of knowledge captured in developing and manufacturing prior versions of the aircraft. This evolutionary approach significantly contributed to the cost and schedule successes of this program. Because the F/A-18 E/F was a variant of the older F/A-18 aircraft, the developer had prior knowledge of design and manufacturing problems. This knowledge, coupled with the use of modeling and computer-aided design software, helped create a design that was easier to manufacture. While the program did not fully use each of the best practices, it did embrace the concepts of capturing design and manufacturing knowledge early in the program.

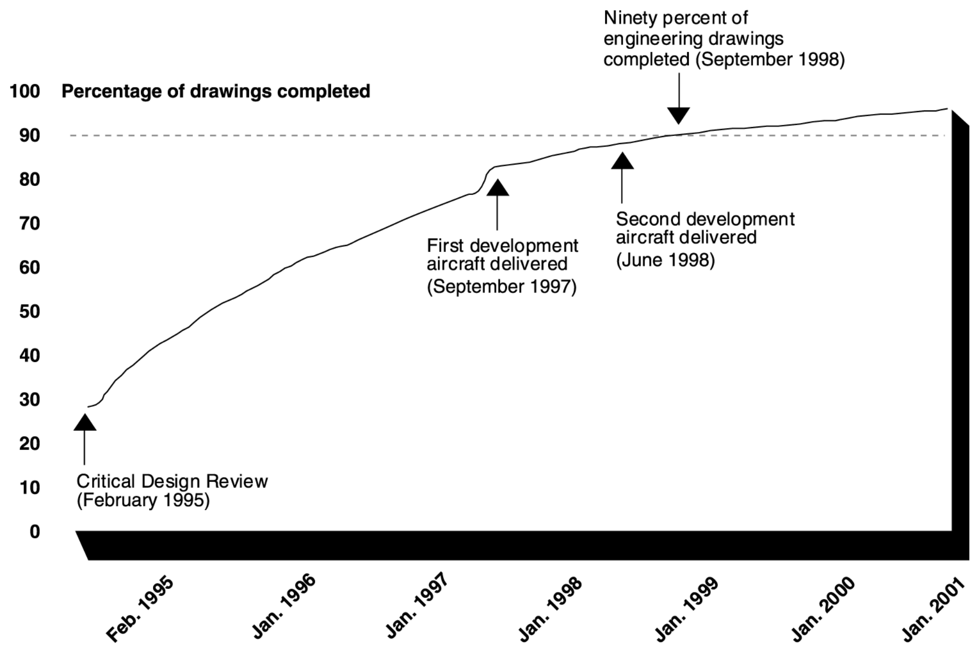
During the program's critical design review, about 56 percent of the drawings were completed and, while the program did not meet the best practice of 90 percent complete, it did have additional drawing data of the F/A-18 E/F assemblies available for review at the critical design review. The Navy used early versions of the F/A-18 aircraft to demonstrate new component designs and new materials. In addition, the aircraft was designed to have 42 percent fewer parts than its predecessor, making its design more robust. The program also identified the critical manufacturing processes and collected statistical process control data early in product development. At the start of production, 78 percent of these critical processes were in control. Unit costs for the F/A-18 E/F program have not grown since the critical design review and its schedule has been delayed by only 3 months.

F-22 Fighter Program

The F-22 program is structured to provide the product's full capability with the first product off the production line—an extreme design challenge. This required the product design to include many new and unproven technologies, designs, and manufacturing processes. It did not demonstrate design stability until about 3 years after it held its critical design review. The program completed 3,070 initial engineering drawings at its critical design review in 1995, about 26 percent of the eventual drawings needed. It did not complete 90 percent of the necessary engineering drawings until

1998, after the first two development aircraft were delivered. Figure 7 shows the drawing completion history for the program.

Figure 7: History of Drawing Completion for the F-22 Program



Source: GAO's analysis.

After its critical design review, the F-22 program encountered several design and manufacturing problems that resulted in design changes, labor inefficiencies, cost increases, and schedule delays. For example, delivery of the aft fuselage—the rear aircraft body section—was late for several of the test aircraft and two ground test articles because of late parts and difficulties with the welding process. According to the F-22 program office, design maturity and manufacturing problems caused a “rolling wave” effect throughout system integration and final assembly. Late engineering drawing releases to the factory floor resulted in parts shortages and work performed out of sequence. These events contributed to significant cost overruns and delays to aircraft deliveries to the flight test program.

The F-22 program initially had taken steps to use statistical process control data during development and gain control of critical manufacturing processes by the full rate production decision. In 1998,[7] we reported that the program had identified 926 critical manufacturing processes and had almost 40 percent in control 2 years before production was scheduled to begin. Although this did not match the standard set by commercial companies, it offered major improvements over what other DOD programs had attempted or achieved. Unfortunately, citing budgetary constraints and specific hardware quality problems that demanded attention, the program abandoned this best practices approach in 2000 with less than 50 percent of it critical manufacturing processes in control. Currently, the program is using post-assembly inspection to identify and fix defects rather than statistical process control techniques to prevent them. In March 2002,[8] we recommended that the F-22 program office monitor the status of critical manufacturing processes as the program proceeds toward high rate production. The program stated that it would assess the processes status as the program moves forward.

The program entered limited production despite being substantially behind its plan to achieve reliability goals. A key reliability requirement for the F-22 is mean time between maintenance, defined as the number of operating hours for the aircraft divided by the number of maintenance actions. The reliability goal for the F-22 is a 3-hour mean time between maintenance. The Air Force estimated that in late 2001, when the F-22 entered limited production, it should have been able to demonstrate almost 2 flying hours between maintenance actions. However, when it actually began limited production it could only fly an average of 0.44 hours between maintenance actions. In other words, the F-22 is requiring significantly more maintenance actions than planned. Additionally, the program has been slow to fix and correct problems that have affected reliability. To date, the program has identified about 260 different types of failures, such as main landing gear tires wearing out more quickly than planned, fasteners being damaged, and canopy delaminating. It has identified fixes for less than 50 percent of these failures. Ideally, the design fixes for the failures should be corrected prior to manufacturing production units.

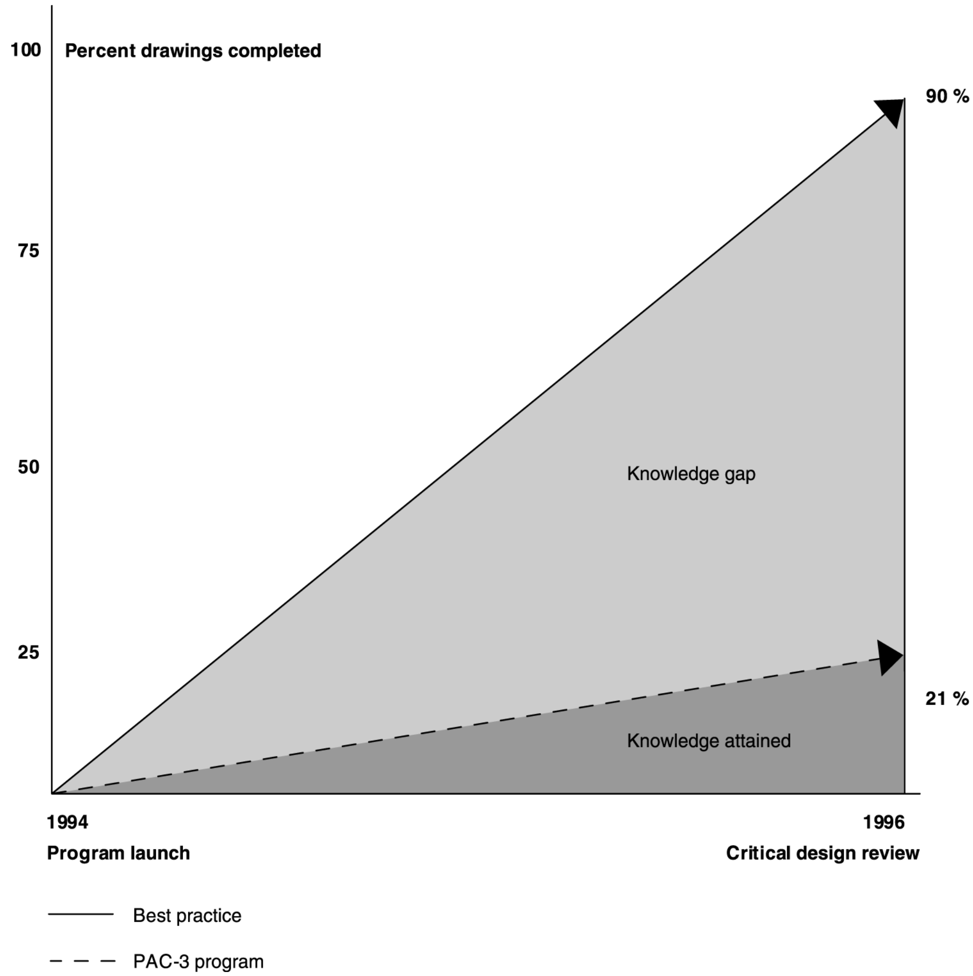
[7] U.S. General Accounting Office, B*est Practices: Successful Application to Weapon Acquisition Requires Changes in DOD's Environment* GAO/NSIAD-98-56 (Washington, D.C.: Feb. 24, 1998).

[8] U.S. General Accounting Office, T*actical Aircraft: F-22 Delays Indicate Initial Production Rates Should Be Lower to Reduce Risks* GAO-02-298 (Washington, D.C.: Mar. 5, 2002).

PAC-3 Missile Program

The PAC-3 missile did not achieve design stability until after the building of production representative prototypes for system demonstration began. At the program's critical design review, the PAC-3 program had completed 980 engineering drawings—21 percent of the eventual drawings needed for the missile. Since then, almost 3,700 more drawings have been completed. The total number of drawings expected to represent the completed design grew from about 2,900 at the critical design review to almost 4,700 as of July 2001. This uncertainty in the expected drawings not only indicates that the design was not stable when initial manufacturing began but also shows that there was a significant lack of knowledge about the design. Figure 8 shows the design knowledge at the critical design review, when the decision was made to commit to initial manufacturing of the missile.

Figure 8: PAC-3 Design Knowledge at Critical Design Review



Source: GAO's analysis.

Prototypes of the product design were not built before the critical design review or before initial manufacturing started to show that the design would work. Therefore, because of the immature design, initially manufactured development missiles were hand-made, took longer to build than planned, and suffered from poor quality. As a result, many design and manufacturing problems surfaced during system demonstration. Subsystems did not fit together properly, and many failed ground and environmental tests the first time. The contractor attributed $100 million of additional cost to first time manufacturing problems.

Prior to entering limited production in 1999, the program had less than 40 percent of the critical manufacturing processes in control for assembling the missile and the seeker. According to program officials, there was little emphasis during development or initial production on using statistical control on critical manufacturing processes. Most of the development missiles were built in specialty shops rather than in a manufacturing environment. The result was a lack of knowledge about whether the critical manufacturing processes could produce the product to established cost, schedule, and quality targets. This uncertainty is reflected in contractor estimates that more than 50 percent of the time charged to build the initial production missiles will be for engineering activities. Actual production labor is expected to account for about 30 percent of the charged time.

To further understand the problems on the PAC-3 program, we focused on its seeker subsystem, which is key to acquiring and tracking targets and represents a large percentage of the missile's cost. Currently, despite being in production, it is unclear whether the supplier of the seeker can produce it within cost, schedule, and quality targets. During development, the supplier had difficulty in designing and manufacturing this subsystem. It was not uncommon for seekers to be built, tested, and reworked seven or eight times before they were acceptable. The program entered production, despite these producibility issues. Now, even with 2 years of production experience, the supplier continues to have difficulty producing the seeker with acceptable quality. Data provided by the supplier in October 2001 showed that less than 25 percent of the seekers were being manufactured properly the first time and the rest had to be reworked, on average, four times.

ATIRCM/CMWS Program

According to program officials, ATIRCM/CMWS did not have a stable design until about 2 years after the critical design review. A contributing factor to this was a lack of understanding about the full requirements for the new system at the critical design review in 1997. This led to a major redesign of the common missile warning system's sensor. At the critical design review, only 21 percent of a product's engineering drawings had been completed. It did not complete 90 percent drawings—the best practice—until 1999. The immature design caused inefficiencies in manufacturing, rework, and delayed deliveries. In addition, between 1995 and 1999, the development contract target price increased by 165 percent.

The ATIRCM/CMWS program did not begin reliability growth testing until 4 years after its critical design review, leaving only 1 year to test the system prior to scheduled production. Program officials said that an immature design limited their ability to begin reliability testing earlier in development. About one-third of the way through the reliability growth test program, testing was halted because too many failures occurred in components such as the power supply, the high voltage electrical system, and the cooling system. According to a program official, the inability to demonstrate system reliability contributed to a production delay of about 1 year. The program plans to build, develop, and test six additional development units during 2002 and 2003 that will incorporate design changes to fix the system failures. ATIRCM/CMWS plans to enter limited production in the early part of 2002 with significantly less knowledge about the design's producibility than commercial companies. The contractor does not use statistical process control and has not identified critical manufacturing processes. A production readiness review identified the lack of statistical process control as a major weakness that needs to be corrected.

A Better Match of Policy and Incentives Is Needed to Ensure Capture of Design and Manufacturing Knowledge

The Department of Defense's (DOD) acquisition policy[9] establishes a good framework for developing weapon systems; however, disciplined adherence, more specific criteria, and stronger acquisition incentives are needed to ensure the timely capture and use of knowledge in decision making. DOD changed its acquisition policy to emphasize evolutionary acquisition and establish separate integration and demonstration phases in the product development process. Its goal was to develop higher quality systems in less time and for less cost. However, DOD's acquisition policy lacks detailed criteria for capturing and using design and manufacturing knowledge to facilitate better decisions and more successful acquisition program outcomes. As demonstrated by successful companies, using these criteria can help ensure that the right knowledge is collected at the right time and that it will provide the basis for key decisions to commit to significant increases in investment as product development moves forward.

While the right policy and criteria are necessary to ensure a disciplined, knowledge-based product development process, the incentives that influence the key players in the acquisition process will ultimately determine whether they will be used effectively. In DOD, current incentives are geared toward delaying knowledge so as not to jeopardize program funding. These incentives undermine a knowledge-based process for making product development decisions. Instead, program managers and contractors push the capture of design and manufacturing knowledge to later in the development program to avoid the identification of problems that might stop or limit its funding. They focus more on meeting schedules than capturing and having the knowledge necessary to make the right decisions at those milestones. Such an approach invariably leads to added costs because programs are forced to fix problems late in development.

By contrast, commercial companies must develop high-quality products quickly or they may not survive in the marketplace. Because of this, they encourage their managers to capture product design and manufacturing knowledge to identify and resolve problems early in development, before making significant increases in their investment. Instead of a schedule-driven process, their process is driven by events that bring them

[9] DOD Directive 5000.1, The Defense Acquisition System (Oct. 23, 2000), DOD Instruction 5000.2, Operation of the Defense Acquisition System (Apr. 5, 2002), and DOD Regulation 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs (Apr. 5, 2002).

knowledge: critical design reviews that are supported by completed engineering drawings and production decisions that are supported by reliability testing and statistical process control data. They do not move forward without the design and manufacturing knowledge needed to make informed decisions.

Acquisition Policy Lacks Specific Implementation Criteria

Greater emphasis on evolutionary acquisitions and structuring the product development process into two phases—system integration and system demonstration—were good first steps for DOD to achieve its goals of buying higher quality systems in less time and for lower costs. However, DOD policy still lacks criteria to be used to capture specific design and manufacturing knowledge and does not require the use of that knowledge as exit criteria at key decision points to transition from system integration to system demonstration and then into production. In three of the five DOD program examples in chapter 3, managers decided to move forward in development, even when developers had failed to capture design and manufacturing knowledge to support increased investments. As a result, these programs encountered significant increases in acquisition costs as well as delays in delivering capabilities to the war fighter.

Table 7 illustrates key criteria used by commercial companies that are currently lacking in DOD's policy. The table shows the design and manufacturing knowledge needed to make more informed decisions. The capture of some of the important manufacturing and reliability knowledge should begin in the integration phase in order to have the full knowledge needed to make decisions at the end of the demonstration phase for transitioning into production.

Table 7: Analysis of DOD Acquisition Policy for Inclusion of Best Practices for Knowledge-based Design and Manufacturing Decisions

Commercial criteria	Best practices to capture design knowledge by decision point to enter system demonstration phase	DOD criteria
X	Use of key indicator to show design stability (90 percent of drawings completed)	
X	Limit design challenge prior to entering system integration	X
X	Demonstrate the design meets requirements	X
X	Complete critical design reviews	
X	Obtain stakeholder agreements that drawings complete and producible	
X	Hold decision review to begin initial manufacturing	
	Best practices to capture product knowledge by decision point to enter production	
X	Use of key indicators to show the product is ready for production (processes in statistical control and product reliability demonstrated)	
X	Identify key system characteristics and manufacturing processes	
X	Determine critical processes are in control and capable	
X	Conduct failure modes and effects analysis	
X	Set reliability growth goals	
X	Conduct reliability growth testing	
X	Hold decision review to begin production	X

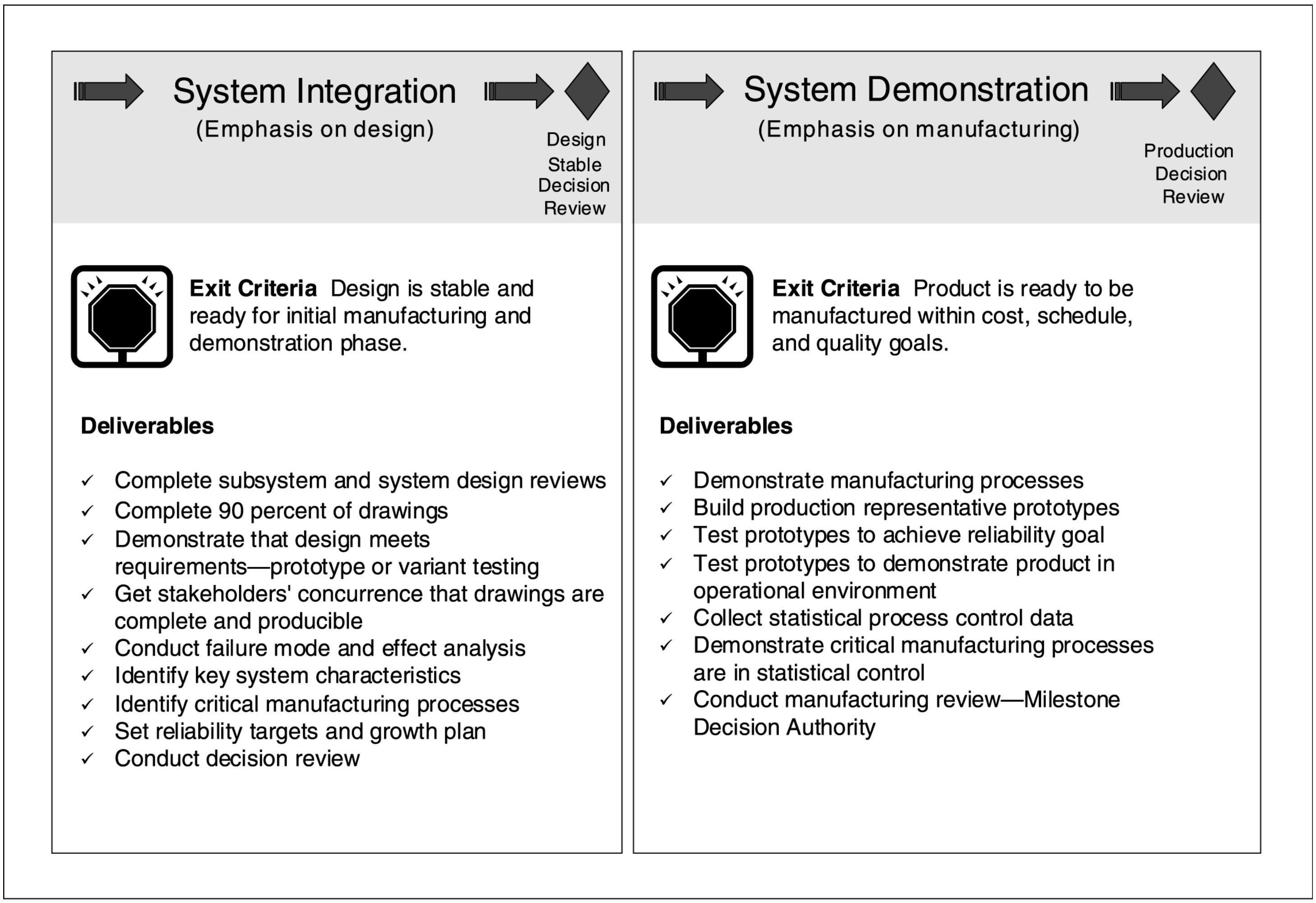
According to DOD's current acquisition policy, the system integration phase of an acquisition normally begins with the decision to launch a program. The policy states that, during this phase, a system's configuration should be documented and the system should be demonstrated using prototypes in a relevant environment. While these are noteworthy activities and resemble best practices, the policy does not provide criteria for what constitutes the level of knowledge required for completing this stage, nor does it require a decision—based on those criteria—as to whether a significant, additional investment should be made. Commercial companies demand knowledge from virtual or engineering prototypes, 90 percent of required engineering drawings for the product supported by test results, demonstration that the product meets customer requirements, a series of disciplined design reviews, and stakeholder agreement that the design is stable and ready for product demonstration before a commitment is made to move forward and invest in product demonstration. Under DOD's revised policy, it is still difficult to determine if a product should enter product demonstration with a stable design.

DOD's current acquisition policy also states that the system demonstration phase begins after prototypes have been built and demonstrated in a relevant environment during system integration. According to the policy, a system must be demonstrated before the department will commit to production. The low-rate initial production decision occurs after this phase of product development. Like the end of system integration, the policy fails to provide specific criteria for what constitutes the knowledge required to support the decision to move into production. For example, the policy states there should be "no significant manufacturing risks" but does not define what this means or how it is measured. Without criteria for building knowledge during the demonstration phase, the production decision is often based on insufficient knowledge, creating a higher probability of inconsistent results and cost and schedule problems. On the other hand, commercial companies demand proof that manufacturing processes are in control and product reliability goals are attained before committing to production. With more specific knowledge in hand at the end of development, decision makers can make a more informed decision to move into production with assurances that the product will achieve its cost, schedule, and quality outcomes.

Finally, while DOD's policy separates product development into a two-stage process—integration and demonstration—it does not require a decision milestone to move from one stage to the next. The policy states that an interim progress review should be held between the two stages, but the review has no established agenda and no required outputs of information unless specifically requested by the decision maker. Its purpose is to confirm that the program is progressing as planned. On the other hand, commercial companies consider this review a critical decision point in their product development process because it precedes a commitment to significantly increase their investment. Therefore, they use specific, knowledge-based standards and criteria to determine if the product is ready to enter the next phase and they hold decision makers accountable for their actions. These decision reviews are mandatory and are typically held at the executive level of the commercial firm.

Figure 9 illustrates the commercial model for knowledge to be captured and delivered during product integration and product demonstration and the possible application of that model to DOD's acquisition process. Without a similar decision review to bring accountability to the DOD process, acquisition programs can—and do—continue to advance into system demonstration without a stable design. As shown in our case studies, this provides for a high probability of cost growth and schedule delays to occur.

Figure 9: Illustration to Show How the Best Practice Model Would Apply to DOD's Acquisition Process



Source: GAO's analysis.

Incentives in the DOD Acquisition Environment Do Not Favor Capture of Design and Manufacturing Knowledge Early Enough

The incentives for program managers and product developers to gather knowledge and reduce risk are also critical to DOD's ability to adopt best practices for product development. In DOD, incentives are centered on obtaining scarce funding on an annual basis in a competitive environment to meet predetermined and typically optimistic program schedules. These incentives actually work against the timely capture of knowledge, pushing it off until late in the process to avoid problems that might keep a program from being funded. Because design and manufacturing knowledge is not captured, key decision points intended to measure and ensure that a weapon system has sufficiently matured to move forward in the process risk becoming unsupported by critical knowledge. In leading commercial companies, the opposite is true. Because companies know they have to deliver high-quality products quickly and affordably, they limit the challenge for their program managers and provide strong incentives to capture design and manufacturing knowledge early in the process. Program managers are empowered to make informed decisions before big investments in manufacturing capability are required.

DOD's current acquisition environment is driven by incentives to make decisions while significant unknowns about the system's design and manufacturability persist. This environment results in higher risks and a greater reliance on cost-reimbursement[10] contracts for longer periods of time during product development. Because events that should drive key decisions, such as critical design reviews, interim progress reviews, and production decision reviews, are based on inadequate design and manufacturing knowledge, they do not support decisions to invest more and move to the next phase of the acquisition process. Nevertheless, this approach has proven effective in securing funds year to year. For example, the F-22, PAC-3, and ATIRCMS/CMWS programs had less than one-third of their engineering drawings completed at their critical design review, but each obtained the funding necessary to move onto the initial manufacturing of production representative prototypes. That funding allowed a significant increase in investment to develop a manufacturing capability before critical

[10] Cost-reimbursement contracts provide for payment of allowable incurred costs, to the extent prescribed in the contracts. They are suitable for use only when uncertainties involved in contract performance, such as research and development work, do not permit costs to be estimated with sufficient accuracy. In contrast, fixed-priced contracts, except those subject to price adjustment, provide for a preestablished firm price, place maximum risk and full responsibility for all costs and resulting profit or loss on the contractor, and provide maximum incentive for the contractor to control costs and perform effectively.

knowledge had been captured. The incentive to capture funding for the program was greater than the incentive to wait, capture knowledge, and reduce the risk of moving forward. Each of these programs encountered significant cost increases and schedule delays.

The incentives are quite different for leading commercial companies. For them, the business case centers on the ability to produce a product that the customer will buy and that will provide an acceptable return on investment. If the firm has not made a sound business case, or has been unable to deliver on one or more of the business case factors, it faces a very real prospect of failure—the customer may walk away. Also, if one product development takes more time and money to complete than expected, it denies the firm opportunities to invest those resources in other products. For these reasons, commercial companies have strong incentives to capture product knowledge early in the process to assess the chances of making the business case and the need for further investments.

Production is a dominant concern in commercial companies throughout the product development process and forces discipline and trade-offs in the design process. This environment encourages realistic assessments of risks and costs since doing otherwise would threaten the business case and invite failure. For the same reasons, the environment places a high value on knowledge for making decisions. Program managers have good reasons to identify risks early, be intolerant of unknowns, and not rely on testing late in the process as the main vehicle for discovering the performance characteristics of the product. By adhering to the business case as the key to success, program managers in leading commercial companies are conservative in their estimates and aggressive in risk reduction. Ultimately, adherence to the business case strengthens the ability to say “no” to pressures to accept high risks and unknowns. Practices such as prototyping, early manufacturing and supplier involvement, completing 90 percent of engineering drawings by critical design review, demonstrating product reliability, and achieving statistical control of critical manufacturing processes by production are adopted because they help ensure success.

In DOD’s current acquisition environment, the customer is willing to trade time and money for the highest performing weapon system possible. That willingness drives the business case. This creates strong incentives for the program office to take significant risks with technologies and designs to ensure it can offer the customer a weapon system that is a quantum leap above the competition. In addition, because funding is secured on an annual basis in DOD, strong incentives exist for the program office to make optimistic assumptions about development cost and schedule. Because the customer is willing to wait and funding is never certain, an environment exists where program managers have good reasons to avoid the capture of knowledge and delay testing. Since the business case in DOD places very little premium on meeting cost and schedule targets, but a very high premium on performance, programs succeed at the point where sunk costs make it difficult—if not prohibitive—for decision makers to cancel them.

The practices commercial companies use to capture knowledge are not currently used in this environment because the business case does not favor them. Instead, DOD's product development environment relies on cost-type contracting throughout the entire product development process. Once in production, programs will cut quantities to maintain funding or once fielded, they rely on the operations and maintenance budget to pay for reliability problems not solved in development.

Conclusions and Recommendations

Conclusions

The Department of Defense's (DOD) planned $700 billion investment in weapon systems over the next 5 years requires an approach that keeps cost, schedule, and performance risks to a minimum. This approach means adopting and implementing an evolutionary approach to developing new weapon systems, improving policy to more closely approximate a knowledge-based product development process, and creating incentives for capturing and using knowledge for decision making. Without an evolutionary approach as its foundation, the ability to capture design and manufacturing knowledge early in the development process is significantly reduced. Programs, in turn, take on too much new unproven content to meet their objectives and risks invariably increase. DOD has made improvements in its acquisition policy by incorporating guidance for evolutionary acquisition, creating guidelines for the development of a basic product that can be upgraded with additional capabilities as technologies present themselves. However, evolutionary acquisition has yet to be consistently implemented with success on individual weapon system acquisitions.

Regardless of whether DOD emphasized greater use of evolutionary acquisition, acquisition programs are not capturing sufficient design and manufacturing knowledge to make good decisions at key investment points. The current policy establishes a good framework to develop a product, but the policy still lacks specific criteria required to move a program forward and does not tie knowledge to decisions for increasing investments in the program as it moves from system integration to system demonstration. As a result, programs often pass through each development phase and into production with an unstable design and insufficient knowledge about critical manufacturing processes and product reliability. This results in greater likelihood for inconsistent and poor results and cost and schedule problems later in the program.

Additionally, DOD does not provide the proper incentives to encourage the use of best practices in capturing knowledge early in its development programs. Currently, managers are focused more on the annual exercise of obtaining funding needed to keep their programs viable and alive. The importance of capturing design and manufacturing knowledge early gives way to the pressures of maintaining funding, often resulting in the acceptance of greater risks. Raising problems on a program early because design and manufacturing knowledge is discovered can cause extra oversight and questions that threaten a system's survival. The prevailing culture is to accept greater risks upfront and then fix problems later in the development program.

We found that leading commercial companies over the years had found ways to overcome these problems and had identified best practices that resulted in the early capture of and use of design and manufacturing knowledge. This was done by a combination of four key elements. First, they established and used an evolutionary approach to develop products that made the capture of design and manufacturing knowledge a more manageable task. This framework limited the design challenge for any one new product development by allowing risky technology, design, or manufacturing requirements to be deferred until a future generation of the product. DOD's current policy addresses this; however, it has not had sufficient time to show how this will be implemented.

Second, each company we visited used the same basic product development process and criteria for bringing together and integrating all of the technologies, components, and subsystems required for the product to ensure the design was stable and then demonstrating that the product was producible and reliable using proven manufacturing processes. DOD's policy lacks the criteria to measure design stability and process controls. Third, successful companies used tools to capture design and manufacturing knowledge about the product and decide about whether to invest further based on that knowledge. Their new product development process included key, high-level decision points before moving into product demonstration, and again before making the production decision that required specific, knowledge-based exit criteria. DOD's policy does not require a decision to move from system integration to system demonstration. Finally, leading companies created an environment for their managers that emphasized capturing design and manufacturing knowledge early, before committing substantial investments in a product development that made cancellation a more difficult decision to make. DOD's environment encourages meeting schedule milestones instead of capturing design and manufacturing knowledge to make decisions.

Recommendations for Executive Action

DOD should take steps to close the gaps between its current acquisition environment and best practices. To do this, it should ensure that its acquisition process captures specific design and manufacturing knowledge, includes decisions at key junctures in the development program, and provides incentives to use a knowledge-based process. Such changes are necessary to obtain greater predictability in weapon system programs' cost and schedule, to improve the quality of weapon systems once fielded, and to deliver new capability to the war fighter faster. More specifically, we recommend that the Secretary of Defense:

- Require the capture of specific knowledge to be used as exit criteria for decision making at two key points—when transitioning from system integration to system demonstration and from system demonstration into production. The knowledge to be captured when moving from system integration into system demonstration should include the following:
  - Completed subsystem and system design reviews.
  - Ninety percent of drawings completed.
  - Demonstration that design meets requirements—prototype or variant testing.
  - Stakeholders' (cross functional design team that includes design engineers, manufacturing, key supplier) assurance that drawings are complete.
  - Completed failure modes and effects analysis.
  - Identification of key system characteristics.
  - Identification of critical manufacturing processes.
  - Set reliability targets and growth plan.

The knowledge to be captured when moving from system demonstration into production should include the following:

  - Demonstrated manufacturing processes.
  - Built production representative prototypes.
  - Tested prototypes to achieve reliability goal.
  - Tested prototypes to demonstrate product in operational environment.

- Collected statistical process control data.
- Demonstration that critical processes are capable and in control.

- Require that the interim progress review, currently identified in DOD's policy as that point in the process between system integration and system demonstration, be a mandatory decision review. At this point, the design should be demonstrated to be stable so that during the next phase of development attention can be focused on demonstrating manufacturing processes and product reliability. The program manager should have proof—based on the exit criteria for moving out of system integration in the above recommendation—that the product design is stable. The exit criteria should be demonstrated and verified by the program manager before the program can make the substantial investments needed to begin manufacturing production representative prototypes in the next phase of development—system demonstration. To ensure visibility of demonstrated exit criteria to decision makers, the criteria and the program's status in achieving them should be included in each program's Defense Acquisition Executive Summary and Selected Acquisition Reports. If the program does not meet the exit criteria, investments should be delayed until such time as the criteria are satisfied. To proceed without completing the required demonstrations should require approval by the decision authority.

- Expand exit criteria for the Milestone C decision to include the knowledge to be captured during the system demonstration phase as identified in recommendation one. This will require that the program office demonstrate that the critical manufacturing processes are under statistical control and that product reliability has been demonstrated before entering production of the new weapon system. These are best practices and indicate that the product design is mature and the program is ready to begin production of units for operational use that will meet the cost, schedule, and quality goals of the program.

- To ensure that contracts support a knowledge-based process, we further recommend that DOD structure its contracts for major weapon system acquisitions so that (a) the capture and use of knowledge described in recommendation one for beginning system demonstration is a basis for DOD's decision to invest in the manufacturing capability to build initial prototypes and (b) the capture and use of manufacturing and reliability knowledge discussed in recommendation one for moving from system demonstration to production is a basis for DOD's decision to invest in production.

Agency Comments and Our Evaluation

DOD concurred with a draft of this report and agreed with the benefits of using design and manufacturing knowledge to make informed decisions at key points in a system acquisition program. DOD had some comments with regard to the details contained in the recommendations, which are summarized below. DOD concurred with our recommendation to add exit criteria at two key points in the acquisition process—when transitioning from system integration to system demonstration and from system demonstration into production. DOD believes, however, that the milestone decision authority needs to retain flexibility in applying the knowledge requirement for drawings. Flexibility and judgment are management prerogatives that should exist in any decision process. We agree there may be circumstances, such as in the development of software, when it makes good sense to progress with less than the best practice standard for drawings, but the DOD policy should maintain the requirement to achieve 90 percent drawings by the completion of the system integration phase.

DOD also concurred that critical manufacturing processes must be demonstrated using statistical process control techniques before production, but believes that achieving this at Milestone C, the low rate production decision, is unlikely. It believes the criteria would be better applied to the full rate production decision or when low rate production quantities extend beyond 10 percent of the planned weapon system buy. This is a reasonable approach when processes are new or unique. However, not all critical processes will be new or unique to a specific weapon system. Some will have been used to manufacture parts or components for other systems or products. At a minimum, it should be possible to demonstrate these by Milestone C. For other critical processes that may require additional production experience to bring under statistical process control, a program manager should have a reasonable plan at the Milestone C decision review to bring those processes into control by the full rate production decision, but no later than completion of 10 percent of the planned buy.

Comments from the Department of Defense

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ACQUISITION,
TECHNOLOGY
AND LOGISTICS

19 JUN 2002

Ms. Katherine V. Schinasi
Director, Acquisition and Sourcing Management
U.S. General Accounting Office
441 G Street, N.W.
Washington, D.C. 20548

Dear Ms. Schinasi:

This is the Department of Defense (DOD) response to the GAO draft report, "BEST PRACTICES: Capturing Design and Manufacturing Knowledge Early Improves Acquisition Outcomes," dated May 15, 2002 (GAO Code 120054/GAO-02-701).

The Department concurs with the objectives of GAO's DRAFT report and we agree with the benefits of using important information about a system's design and critical manufacturing processes to make informed decisions. However, we have some comments with regard to the details contained in the recommendations.

In response to previous GAO reports, DoD has structured its acquisition process to make progress through the acquisition life-cycle dependent on the knowledge available at key decision points. This report adds robustness to our already disciplined process.

We look forward to discussing these issues with the GAO. Detailed comments are provided in the enclosure.

My action officer for this effort is Mr. Richard Sylvester, (703) 697-6399.

Sincerely,

Donna S. Richbourg

Donna S. Richbourg
Director, Acquisition Initiatives

Enclosure:
As stated

GAO DRAFT REPORT – DATED MAY 15, 2002
GAO CODE 120054/GAO-02-701

"BEST PRACTICES: Capturing Design and Manufacturing Knowledge Early Improves Acquisition Outcomes"

DEPARTMENT OF DEFENSE COMMENTS TO THE RECOMMENDATIONS

RECOMMENDATION 1: The GAO recommended that the Secretary of Defense require the capture of specific knowledge to be used as exit criteria for decision making at two key points - when transitioning from system integration to system demonstration and from system demonstration into production. The knowledge to be captured when moving from system integration into system demonstration should include the following:

- Completed subsystem and system design reviews
- 90% of drawings completed
- Demonstration that design meets requirements - prototype or variant testing
- Stakeholders' (cross functional design team that includes design engineers, manufacturing, key supplier) assurance that drawings are complete
- Completed failure modes and effects analysis
- Identification of key system characteristics
- Identification of critical manufacturing processes
- Set reliability targets and growth plan

The knowledge to be captured when moving from system demonstration into production should include the following:

- Demonstrated manufacturing processes
- Built production representative prototypes
- Tested prototypes to achieve reliability goal
- Tested prototypes to demonstrate product in operational environment
- Collected statistical process control data
- Demonstration that critical processes are capable and in control

(pgs. 69-70/GAO Draft Report)

DOD RESPONSE: Concur. DoD agrees with the benefits of identifying specific design and manufacturing information to support decision making at key decision points. However, we believe that the milestone decision authority needs to retain the flexibility to determine application of the knowledge requirement for drawings (e.g., software systems will not have drawings, 85% of completed drawings may be enough when measured against urgency of requirement, etc.). However, in no case should a system proceed without a substantial percentage of the drawings completed. We believe the specific measures should be set by the MDA at MS B and that the MDA should have the option to add specific criteria to reflect specific systems.

RECOMMENDATION 2: The GAO recommended that the Secretary of Defense require that the interim progress review, currently identified in DoD policy as that point in the process between system integration and system demonstration, be a mandatory decision review. At this point, the design should be demonstrated to be stable so that during the next phase of development attention can be focused on demonstrating manufacturing processes and product reliability. The program manager should have proof - based on the exit criteria for moving out of system integration in the above recommendation - that the product design is stable. The exit criteria should be demonstrated and verified by the program manager before the program can make the substantial investments needed to begin manufacturing production representative prototypes in the next phase of development - system demonstration. To ensure visibility of demonstrated exit criteria to decision makers, the criteria and the program's status in achieving it should be included in each program's Defense Acquisition Executive Summary and Selected Acquisition Reports. If the program does not meet the exit criteria, investments should be delayed until such time as the criteria is satisfied. To proceed without completing the required demonstrations should require approval by the decision authority. (p. 70/GAO Draft Report)

DOD RESPONSE: Concur. DOD agrees with the requirement to demonstrate design stability at a point between system integration and system demonstration and to satisfy criteria reflecting that stability established by the MDA at MS B. The PM should be able to demonstrate exit criteria satisfaction by providing a report to the Milestone Decision Authority. That data can then be considered in the context of other key indications of program progress. A mandatory review would only be considered if the exit criteria are not satisfied.

RECOMMENDATION 3: The GAO recommended that the Secretary of Defense expand exit criteria for the Milestone C decision to include the knowledge to be captured during the system demonstration phase as identified in recommendation 1. This will require that the program office demonstrate that the critical manufacturing processes are under statistical control and that product reliability has been demonstrated before entering production of the new weapon system. These are best practices, and indicate that the product design is mature and the program is ready to begin production of units for operational use that will meet the cost, schedule and quality goals of the program. (p. 70/GAO Draft Report)

DOD RESPONSE: Concur. DoD agrees that demonstration of critical manufacturing processes must occur prior to rate production. However, it is unlikely that the criteria suggested by the GAO could be satisfied at MS C. MS C authorizes the program to proceed to Low Rate Initial Production in support of Operational Test. That decision precedes the Full Rate Production Decision where approval is given for production in support of operational use. The criteria suggested by the GAO would be better applied to the Full Rate Production Decision or when LRIP extends beyond 10 percent of the total planned buy..

RECOMMENDATION 4: To ensure that contracts support a knowledge-based process, the GAO recommended that DoD structure its contracts for major weapon system acquisitions so that (a) the capture and use of knowledge described in Recommendation 1 for beginning system demonstration is a basis for DoD's decision to invest in the manufacturing capability to build initial prototypes, and (b) the capture and use of manufacturing and reliability knowledge discussed in Recommendation 1 for moving from system demonstration into production is a basis for DoD's decision to invest in production. (pgs. 70-71/GAO Draft Report)

DOD RESPONSE: Concur. See additional comments in response to recommendations 1 and 3. DoD agrees with the benefits of applying both design and manufacturing criteria at key points in the acquisition process and with capturing those criteria in program contracts. The specific criteria would be most effective if tied to established breaks (such as contract line items) designed into the contract structure.

GAO Staff Acknowledgments

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Related GAO Products

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