This report assesses the cost and policy implications of conducting Joint Strike Fighter (JSF) final assembly and checkout (FACO) at different potential locations and with different work splits, rather than doing all the work at a single location—which is Lockheed Martin’s current plan. The study was mandated by the U.S. Congress in the FY 2001 Appropriations Bill.¹

HISTORY OF THE JOINT STRIKE FIGHTER

The JSF emerged from technology and aircraft development efforts in the early 1990s as a joint aircraft designed to meet the long-term air-to-surface needs of the three services that operate strike aircraft. It originated from several advanced aircraft programs, including the Navy’s Advanced Attack/Fighter (A/F-X) meant to replace the canceled A-12 and a Defense Advanced Research Projects Agency (DARPA) project examining an advanced short takeoff and vertical landing capability. The JSF was designed to

- Replace U.S. Air Force F-16s and A-10s, and complement the F-22
- Augment carrier-based U.S. Navy F/A-18E/Fs
- Replace U.S. Marine Corps AV-8Bs and F/A-18 C/Ds
- Replace UK Harrier aircraft.

¹Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001; exact language can be found in Appendix A.
JSF Competition

The U.S. Department of Defense (DoD) Bottom-Up Review of 1993 made certain recommendations for aviation, including “continue the ongoing F-22 and F/A-18E/F programs, cancel the Multirole Fighter and the A/F-X programs, curtail F-16 and F/A-18C/D procurement and initiate the JAST Program.”2 (JAST, or Joint Advanced Strike Technology, was the name of the JSF’s predecessor.) This was done to create building blocks for affordable development of the next-generation strike fighter. Within the next year, more work was consolidated into the effort; “the JAST program had absorbed the DARPA Common Affordable Lightweight Fighter (CALF) program.”3

In December 1994, four companies—Boeing, Lockheed Martin, McDonnell Douglas, and Northrop Grumman—were awarded 15-month Concept Definition and Design Research contracts. Northrop Grumman and McDonnell Douglas/British Aerospace then agreed to work together. After various program reviews, Boeing and Lockheed Martin won Concept Demonstration Phase (CDP) prime contracts in November 1996. Boeing then merged with McDonnell Douglas, while Lockheed Martin began working with Northrop Grumman and British Aerospace (later, BAE Systems). By this time, the program had been renamed the JSF.

After five years of the CDP, on October 26, 2001, DoD awarded the System Development and Demonstration (SDD) contract of almost $19 billion to Lockheed Martin, as the final step in the winner-take-all competition.4

According to current plans, low-rate initial production (LRIP) is scheduled to begin in 2006. Full-rate production (FRP) of 206 aircraft per year will begin in 2012. The last U.S. aircraft will be ordered in 2026.

When completed, the JSF program will be one of the largest aircraft acquisition programs in U.S. history, worth some $300 billion (then-year dollars) over the next quarter-century. A total of 3,002 aircraft in

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2http://www.jsf.mil.
three configurations—a conventional takeoff and landing (CTOL) variant, a short takeoff/vertical landing (STOVL) variant, and a carrier variant (CV)—will be produced for DoD and for the UK Ministry of Defence (MOD). Figure 1.1 portrays the three variants of Lockheed Martin’s proposal aircraft.\(^5\)

Current acquisition plans call for the U.S. Air Force to buy 1,763 CTOL aircraft. The U.S. Navy will buy 480 of the CV aircraft, and the U.S. Marine Corps will purchase 609 STOVL aircraft. The MOD will procure 150 aircraft, most likely of the STOVL variety. It is estimated that other foreign customers could purchase an additional 3,000 aircraft. Indeed, a number of countries have already committed to participating in the program.

From the outset, affordability has been an important goal of the JSF program. In 1994, DoD established target prices for each variant. Table 1 presents these targets along with their value in FY 2002 dollars, which is the baseline used in this report.

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\(^5\)The design shown represents the proposal version of the JSF and does not necessarily reflect the final aircraft configuration.
### Table 1.1

<table>
<thead>
<tr>
<th>Variant</th>
<th>Original Program Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FY 1994</td>
</tr>
<tr>
<td>CTOL</td>
<td>28.0</td>
</tr>
<tr>
<td>STOVL</td>
<td>30.0–35.0</td>
</tr>
<tr>
<td>CV</td>
<td>31.0–38.0</td>
</tr>
</tbody>
</table>

**ORIGINS OF THIS STUDY**

Lockheed Martin’s current plan for the JSF is to perform all FACO work at its Fort Worth, Texas, plant. Congress has directed DoD to examine alternatives, including determining the different potential locations for JSF FACO and the implications of conducting JSF FACO at multiple locations, and to report on this within 180 days of contract award. The provisions of the FY 2001 Defense Authorization Act (see Appendix A), which mandated the study, stipulated that it accomplish the following:

- Examine JSF FACO at one, two, and multiple locations.
- Identify the potential locations for FACO.
- Estimate the costs of assembly and checkout at each location based on a reasonable annual procurement estimate.
- Compare costs across locations.

In carrying out these comparisons, the legislation directed the study to consider the following elements:

- State tax credits.
- State and local incentives.
- Skilled resident workforce.
- Supplier and technical support bases.
- Available stealth production facilities.
- Environmental standards.
RAND identified a number of other elements that differ among sites and included them in the cost analysis as well. These include indirect costs, taxes, transportation, and energy.

**FINAL ASSEMBLY AND CHECKOUT OF THE JOINT STRIKE FIGHTER**

As the name of the process implies, final assembly and checkout involves workers assembling major components and “checking out” the aircraft system performance. The process, which Lockheed Martin also calls “mate through delivery,” includes four major activities: structural mate, tail installation and systems mate, final assembly, and systems checkout and tests. Figure 1.2 shows the assembly process.

Structural mate joins the four primary aircraft components (the three portions of the fuselage to the wing) and includes the installation of the main landing gear. First, the wing is attached to the center fuselage, then the aft fuselage to the center fuselage, and finally the forward fuselage to the center fuselage. These aircraft components already contain most of the electronics and hydraulic subsystems. Edges may or may not be installed on the wing before final assembly. During tail installation/subsystems mate, the remaining aircraft systems are installed, and the vertical tails and horizontal stabilizers and the main landing gear access doors are also installed. The electrical, hydraulic, fuel, etc., systems are connected across the mate joints. Necessary checks are made to ensure proper function and connections. Other miscellaneous systems and structural parts are also installed.

Final assembly and final systems test involves installation and test of the cockpit seat, canopy, propulsion system, engine bay doors, weapons bay doors, radome, high-dollar components, and gun (CTOL variant only). All systems are to be checked out using either built-in-test or special test equipment. Final assembly and testing is complete at this point.

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6 Lockheed Martin plans to install certain expensive components, such as the lift fan, engine, and radar, during final assembly operations to save a few weeks of inventory costs on those items.
Figure 1.2—Final Assembly and Checkout

SOURCE: Lockheed Martin Aeronautics Company.
Final finish and verification work during FACO is not extensive because most of the paint and special coatings are applied at the module level. Remaining areas of the aircraft will be robotically coated. To verify the low-observable characteristics of the aircraft, it will be mounted on a turntable and its signature will be tested. In the fuel racks barn, the aircraft is fueled for the first time, any leaks are identified and repaired, and the fuel system is calibrated.

Finally, field operations include testing of certain components and performing a number of operations:

- fuel/wet system test indicators.
- engine feed checkout.
- fuselage transfer tank.
- fuel/wet systems test transfer.
- fuel level sense.
- remote input/outputs—fuel, hydraulics.
- fuel/ground refuel receptacle.
- fuel/aerial refuel receptacle fuel function.
- OBIGGS (on-board inert gas-generating system).
- escape system checkout.
- survival kit/seawars system checkout.
- green engine run (auxiliary power unit, environmental control systems, engine).
- engine starter/general checkout.
- bleed air/emergency power mode, integrated power package checkout.
- Environmental Control System ground test.
- cabin pressure checkout.
- on-board oxygen-generating system checkout.
- green engine run (preflight and mechanical).
The JSF will be the first fighter program that attempts to satisfy the needs of three different services using three highly common variants of a single design. The DoD program goal has been that each variant would have high commonality with the other two variants, on the order of 70–90 percent. This commonality is depicted in Figure 1.1. In theory, such commonality should make the JSF more affordable during production and throughout the service life of the aircraft. Because FACO activities for each variant of the JSF are highly common, it is reasonable to build the multiple variants on a single production line. Lockheed Martin has indicated that this would be its plan unless directed to do otherwise.

The total direct labor hours required for these tasks are divided into the categories of fuselage structural mate, subsystems mate, final assembly/test, flight operations, manloads/ITLs,9 and final finishes. Total support labor required for FACO is divided into the categories of manufacturing engineering, tool engineering, tool manufacturing, quality control, engineering, and material inventory. (Note that these categories are specific to Lockheed Martin.)

The JSF takes advantage of recent advances in aircraft design tools and concepts, which should improve the quality and shorten the cycle time for the required FACO processes. These include advances in tooling concepts and improvements in computer-aided design/computer-aided manufacturing (CAD/CAM) including three-
dimensional solids modeling tools. The JSF design incorporates very few attachment points compared with legacy systems. The airframe mate of the major subassemblies will be accomplished through a numerically controlled laser alignment system. Electrical and hydraulic systems are joined using adapter plates. Given these technologies, which facilitate the assembly process and reduce the need for complex assembly tools, jigs, and fixtures, Lockheed Martin’s total expected time for mate through delivery is 40.8 workdays. The time can be broken out as shown in Table 1.2.

By way of comparison, Lockheed Martin’s planned FACO cycle time for the 257th JSF aircraft is expected to be half that of the F-16, a much less complex aircraft.

FACO activities make up a relatively small portion of the total aircraft cost. Lockheed Martin estimates that the JSF FACO cost is about 2 percent of fleet unit recurring flyaway (URF) costs. Other airframe work totals 35 percent of costs, propulsion totals 19 percent, and other non-airframe items total 44 percent of URF costs.

The 2-percent figure is a lower FACO percentage than other recent programs have experienced. Historically, FACO has been a larger portion of the total manufacturing labor because most of the electronics and subsystems were integrated into the airframe during this stage. Also, old design and manufacturing approaches led to part and subassembly variability problems. Often these problems were discovered during final assembly and resulted in considerable

<table>
<thead>
<tr>
<th>Activity</th>
<th>Days to Complete</th>
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<tbody>
<tr>
<td>Structural mate</td>
<td>2.4</td>
</tr>
<tr>
<td>Subsystems mate and tail installation</td>
<td>4.8</td>
</tr>
<tr>
<td>Final assembly and systems test</td>
<td>12.0</td>
</tr>
<tr>
<td>Final finishes</td>
<td>10.8</td>
</tr>
<tr>
<td>Field operations</td>
<td>10.8</td>
</tr>
<tr>
<td>Total Workdays</td>
<td>40.8</td>
</tr>
</tbody>
</table>
rereel. Thus, historically, the FACO percentage of the total labor has been higher than is projected for the JSF.

The FACO portion for the F-22 is 3.3 percent (not including engines and some support). Reports indicate that F/A-18E/F FACO percentage is higher still. The original F-22 production plan was to have all major assemblies arrive “fully stuffed” with all the components, subassemblies, avionics, and so forth, rather than have them installed during FACO. According to interviews with DoD personnel, there have been some difficulties during the initial production experience, with more work than expected taking place during FACO. Lockheed Martin managers have indicated that they are attempting to resolve associated issues. It is not uncommon to have to work through difficulties during initial production. In any case, advances in design technology and production and tooling approaches since the F-22 was originally designed may enable the JSF to meet its goals for FACO—but this is not guaranteed.

PURPOSE OF THE STUDY

The JSF Program Office and OSD asked RAND’s National Defense Research Institute to conduct the study mandated by Congress, and to assess fully and objectively different FACO strategies. This report responds to that request. It details the different FACO strategies that were examined, the different sites that were selected, and how the costs of doing different portions of the work at different sites were assessed.

FACO Strategies

One of the first steps of our research was to identify different FACO strategies. The congressional language makes it clear that the acquisition strategies to be examined include an examination of allocating all or portions of FACO to different potential locations. RAND has identified a number of ways this allocation can occur.

The baseline FACO strategy, for cost comparison purposes, is to have all activities at a single site. As described above, these activities include substructures mating and assembly work, systems checkout, final finishing, and field operations. All of these tasks would take
place at a single site for the entire life of the program, from SDD\textsuperscript{10} through LRIP, to FRP. Unless directed otherwise by the U.S. government, Lockheed Martin plans to perform FACO at its Fort Worth location, Air Force Plant (AFP) 4. Company officials cite their capabilities there as the reason for the choice of that site, and the cost efficiencies of performing all FACO at a single location as the reason they do not plan to split the work.

But there are other ways to accomplish FACO. It could be done at multiple sites: two, three, or even more FACO sites could, conceivably, be operated. This approach would spread work across different locations, but each additional site would potentially add cost because of extra facilities requirements, along with the costs stemming from the multiple learning curves.

Multiple site approaches can vary by how the different JSF variants are distributed among the sites. One option is to build all of the variants at every site. Another option is to split the variants among sites, for example, assembling each variant at a separate site. Alternatively, one variant could be built at one site, and the other two variants could be built at another site.

Another option is to divide FACO activities among sites. For example, assembly could occur at one location and system checkout at another. Lockheed Martin has argued convincingly against separating these functions, citing, for example the cost and risk of shipping the aircraft at any period before flight-test. Because of the obvious and strong disadvantages of this strategy, it has not been analyzed further in this report.

A final set of alternatives in the division of FACO activities concerns the timing of adding new sites. One option is that all sites start up at the same time—at LRIP. Alternatively, second and third sites could be added at later dates in the program (for example, at the beginning of FRP).

To provide a range of possibilities across these alternatives, we present the results from an analysis of a sample of the possible universe.

\textsuperscript{10}Terminology for the acquisition phases, as found in the DoD 5000 series of acquisition regulations, changed in 2001. SDD refers to what was previously known as Engineering and Manufacturing Development.
While these alternatives do not include all possibilities, we feel that the following represent the most reasonable:

1. 100 percent of FACO at Lockheed Martin–Fort Worth (baseline case).
2. 100 percent of FACO at Lockheed Martin–Palmdale (Calif.), at the beginning of LRIP.
3. 100 percent of FACO at Lockheed Martin–Marietta (Ga.), at the beginning of LRIP.
4. 100 percent of FACO at Northrop Grumman–Palmdale, at the beginning of LRIP.
5. 50 percent of FACO at Lockheed Martin–Fort Worth and 50 percent at Lockheed Martin–Palmdale, production starting in Fort Worth, then splitting at FRP.
6. 50 percent of FACO at Lockheed Martin–Fort Worth and 50 percent at Northrop Grumman–Palmdale, production starting in Fort Worth, then splitting at FRP.
7. 50 percent of FACO at Lockheed Martin–Fort Worth and 50 percent at Lockheed Martin–Marietta, production starting in Fort Worth, then splitting at FRP.
8. All CTOL at Lockheed Martin–Fort Worth and all CV and STOVL at Lockheed Martin–Marietta, variant production splitting at LRIP.
9. One-third of all production at each of the three Lockheed Martin sites, production starting in Fort Worth, then splitting at FRP.

We also provide results from analyses designed to test the sensitivity of these findings to different conditions, including different levels of transfer of learning across sites, different start dates for alternative sites, and the use of discounted net present value (NPV) instead of FY 2002 dollars.

**Methodology**

This research began approximately six months before the contract for SDD was awarded to Lockheed Martin on October 26, 2001.
During the months leading up to the SDD award, RAND collected general data on the specific issue areas called out by Congress, on other costs that would vary by location (e.g., energy), and on facilities, along with corporate data that were not source selection–sensitive. RAND began work on a cost model to estimate different costs of performing FACO at different sets of locations. The model can assess the costs of the different FACO strategies discussed above.

After the prime contractor selection, RAND engaged in a second round of data collection to populate the model with JSF program and other data. This period of the study was relatively compressed, with much data only becoming available in the remaining six weeks before this report was due. We identified a set of final potential FACO sites to be analyzed in the study, and collected specific costs pertaining to these locations. The cost model calculates FACO costs at different facilities, given the different FACO strategies. RAND also engaged the assistance of the Defense Contract Management Agency (DCMA) to conduct a site survey used to collect data specific to the different sites. This survey is provided in Appendix B.

Where specific cost information could not be collected, a description will be provided and the implications assessed. For example, one environmental issue is noise from acceptance flights. There is a risk that community activists could protest and create limitations on the times of day when aircraft can be flown. While this does not have a specific cost calculated for it, the potential implications are discussed.

**HOW THIS REPORT IS ORGANIZED**

This report is organized in 10 substantive chapters. Following this introduction, Chapter Two lays out the policy issues of alternate FACO strategies. It includes a brief history of programs with split production, and assesses rationales for splitting JSF FACO. Chapter Three describes facilities requirements for FACO and the approach we took to the selection of potential FACO sites. Chapters Four through Eight describe and assess the cost elements that vary for each site. Chapter Nine introduces the model used to evaluate the costs of performing FACO at different sites. Chapter Ten presents the results of the study; it also provides total cost estimates for a variety of FACO strategies and discusses the sensitivities of the
results to key parameters. Finally, conclusions are presented in
Chapter Eleven. In addition, Appendix A contains the language from
the appropriations law directing this study; Appendix B includes the
DCMA site survey; Appendix C contains a comparison of wages
across potential FACO sites; and Appendix D describes some of the
environmental legislation that affects the costs of establishing addi-
tional FACO sites.