United States Government Accountability Office

Report to Congressional Committees

May 2023

F-35 JOINT STRIKE FIGHTER

More Actions Needed to Explain Cost Growth and Support Engine Modernization Decision

GAO-23-106047

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GAO Highlights

Highlights of GAO-23-106047, a report to congressional committees

Why GAO Did This Study

The F-35 Lightning II Joint Strike Fighter program is DOD's most expensive weapon system program. DOD estimates it will cost nearly $1.7 trillion to buy, operate, and sustain the aircraft and systems over its lifetime. DOD is also assessing options for modernizing its engine.

Congress included provisions in three statutes for GAO to review the F-35 program and a Senate report included another. This report (1) identifies the F-35's progress toward full-rate production, (2) assesses DOD's F-35 modernization effort (known as Block 4), and (3) assesses DOD's approach for modernizing its engine and thermal management system. GAO reviewed program, DOD, and contractor documentation on these topics and interviewed program, DOD, and contractor representatives. GAO assessed the program's progress against its own plans. GAO also applied its cost estimating and technology readiness leading practices, as appropriate.

What GAO Recommends

Congress should consider directing the F-35 program to manage the engine modernization as a separate program. GAO added this matter for Congress because DOD has not committed to a separate engine program consistent with GAO's recommendation. GAO made seven total recommendations to DOD, including that it improve its reporting on Block 4 cost growth and define engine requirements. Overall, DOD concurred with three, partially concurred with three, and did not concur with one recommendation. GAO believes all the recommendations are warranted.

View GAO-23-106047. For more information, contact Jon Ludwigson at (202) 512-4841 or ludwigsonj@gao.gov.

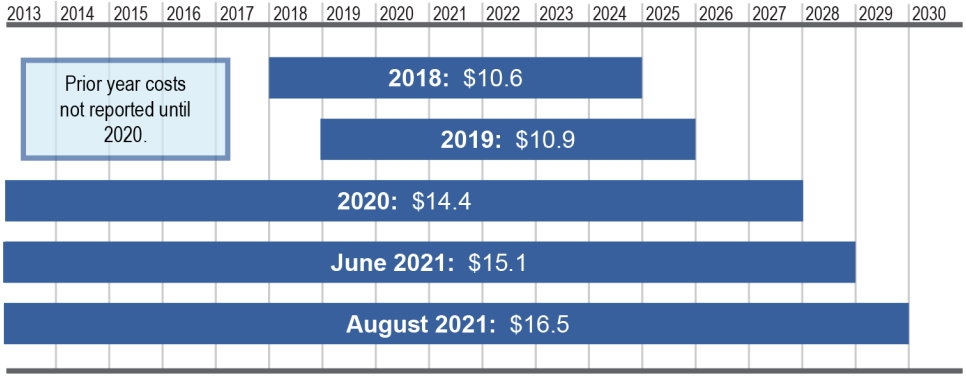
What GAO Found

The F-35 program continues to experience schedule delays, cost growth, and late deliveries. Program delays in completing the F-35 simulator continue to prevent the Department of Defense (DOD) from completing the testing required to demonstrate that the F-35 is ready for full manufacturing rates, even though the program is already producing over 125 aircraft per year.

The F-35 program's total procurement costs have increased by $13.4 billion since the last cost estimate in 2019. This is, in part, due to DOD spreading out aircraft purchases and adding years to its delivery schedule. Contractors also continue to have challenges with delivering aircraft and engines on time, but they are working to address these issues.

Further, DOD is 5 years into a development effort to modernize the F-35's capabilities. This effort, known as Block 4, is experiencing developmental delays for important technology updates. Block 4 costs also grew to $16.5 billion, an increase of more than $1 billion since GAO last reported.

F-35 Block 4 Modernization Cost Increases since 2018 (then-year dollars in billions)



Source: GAO analysis of Department of Defense data. | GAO-23-106047

The program's cost reporting mechanisms do not fully explain the reasons for cost growth. For example, DOD's reports to Congress on Block 4 cost growth do not distinguish higher-than-expected costs for previously planned Block 4 capabilities from growth due to adding new capabilities. Consequently, Congress does not have a complete picture of escalating F-35 modernization costs.

The program is exploring options for modernizing the F-35's engine and thermal management system that is used to cool aircraft subsystems that generate heat. The program plans to manage this multi-billion dollar effort under the existing program, which is scheduled to transition to sustainment soon and that would limit congressional oversight. The cooling system is overtasked, requiring the engine to operate beyond its design parameters. The extra heat is increasing the wear on the engine, reducing its life, and adding $38 billion in maintenance costs.

The program assessed some engine and cooling improvement options, but it has not fully defined the requirements for how much future cooling the aircraft will need. By obtaining this key information, DOD and the services would be more informed about the future performance, cost, and technical implications.

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Abbreviations

AETP	Adaptive Engine Transition Program
ALIS	Autonomic Logistics Information System
DOD	Department of Defense
DOT&E	Director of Operational Test and Evaluation
EAC	estimate-at-complete
ECU	Engine Core Upgrade
EVM	Earned Value Management
NDAA	National Defense Authorization Act
MDAP	major defense acquisition program
ODIN	Operational Data Integrated Network
PMB	performance measurement baseline
PTMS	power and thermal management system
R&M	reliability and maintainability
SRR	scrap, rework, and repair
TR-2	Technology Refresh 2
TR-3	Technology Refresh 3
TRA	technology readiness assessment
TRL	technology readiness level

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
441 G St. N.W.
Washington, DC 20548

May 30, 2023

Congressional Committees

The F-35 Lightning II Joint Strike Fighter is a family of fifth-generation strike fighter aircraft that integrates low-observable (stealth) technology with advanced sensors and computer networking capabilities. The Department of Defense (DOD) plans to procure 2,470 F-35s to replace several other aircraft used by the Air Force, Navy, and Marine Corps to perform a wide range of missions. The program has delivered over 900 aircraft to the U.S. military services, allied partners, and foreign military sales customers. However, it continues to identify new issues with the aircraft and has yet to demonstrate that the aircraft meets all the technical requirements established for it.

DOD is also now in the fifth year of a $16.5 billion modernization effort—known as Block 4—to upgrade the hardware and software systems of the F-35. DOD intends for Block 4 to help the aircraft address new threats that have emerged since DOD established the aircraft's original requirements in 2000. These Block 4 capabilities are requiring more power and cooling than anticipated, which has led the program to begin planning to modernize the already overworked F-35 engine.

The program completed development of the F-35's original capabilities in 2018 and is nearing the end of operational testing to evaluate whether or not the aircraft is operationally effective, suitable, and survivable. We have reported that DOD has experienced years-long delays to completing this testing and making a full-rate production decision, which would formally authorize DOD's transition to higher rates of production. Nonetheless, DOD is already acquiring over 125 aircraft annually and intends to do so each of the next several years for U.S. military services, partner nations, and foreign military sales customers, essentially at full production rates. Last year we testified that, at that rate, DOD would purchase about one-third of all planned F-35 aircraft purchases before achieving its final production milestone, which risks further cost increases.[1]

[1]If more performance issues are identified, fixing aircraft later will cost more than resolving issues before production. GAO, *F-35 Joint Strike Fighter: Cost Growth and Schedule Delays Continue*, GAO-22-105943 (Washington, D.C.: Apr. 27, 2022).

We have reviewed this program annually since 2001 and have reported on these and other program risks in the past and made recommendations for improvement. DOD has taken action to address some, but not all, of our recommendations. For a comprehensive list of our recommendations and a summary of DOD's actions in response, see appendix I.

Four mandates included provisions for us to review aspects of the F-35 program. First, the National Defense Authorization Act (NDAA) for Fiscal Year 2015 included a provision for us to review the F-35 program annually until the program reaches full-rate production.[2] Second, a Senate report accompanying the NDAA for Fiscal Year 2017 included a provision for us to assess and report on an Air Force report on the comparison testing and evaluation of its version of the F-35 and the A-10C—an aircraft designed for close air support.[3] Third, the NDAA for Fiscal Year 2020 included a provision for us to submit a report on the F-35 program's production and Block 4 progress within 30 days of the President's budget submission for fiscal years 2021 through 2025.[4] Lastly, the James M. Inhofe National Defense Authorization Act for Fiscal Year 2023 included a provision that we review DOD's efforts to modernize the propulsion, power, and thermal management systems of the F-35 aircraft.[5]

[2]Pub. L. No. 113-291, § 153(a) (2014).

[3]The NDAA for Fiscal Year 2017, as amended by the NDAA for Fiscal Year 2022, requires two reports to be submitted by the Department of Defense. One from the Director of Operational Test & Evaluation to the congressional defense committees that includes the results and findings of the initial operational test and evaluation of the F-35A and comparison tests and evaluations of the F–35A and A–10C in conducting close air support, combat search and rescue, and airborne forward air controller missions. Pub. L. No. 114-328, § 134 (e)(1)(A)(B), as amended by Pub. L. No.117-81, § 1046 (b)(1). The provision also requires submission by the Secretary of the Air Force to submit a report for addressing deficiencies and corrective actions identified in the report, and short- and long-term strategies for preserving the Air Force's capability to conduct the close air support, combat search and rescue, and airborne forward air controller missions. Pub. L. No. 114-328, § 134 (e)(1)(A)(B), as amended by Pub. L. No. 117-81, § 1046 (b)(2). GAO is to assess the conclusions and assertions contained in the Air Force's report. S. Report No. 114-255, at 50 (2016).

[4]Pub. L. No. 116-92, § 166(b)(1).

[5]Pub. L. No. 117-263, § 164(a). In July 2022, we reported on the F-35 engine sustainment strategy and challenges in ensuring the availability of operating engines for aircraft. We recommended DOD assess and make changes to the F-35 engine sustainment strategy while taking into consideration engine sustainment costs and modernization plans. DOD concurred with our recommendation and has begun to take actions to address it. GAO, *F-35 Aircraft: DOD Should Assess and Update Its Engine Sustainment Strategy to Support Desired Outcomes*, GAO-22-104678 (Washington, D.C.: July 19, 2022).

In this report, we (1) describe any remaining risks with completing the original development program, including production and manufacturing risks, as it progresses towards full-rate production; (2) assess DOD's progress in developing, testing, and delivering modernization capabilities and risks that remain; and (3) evaluate DOD's plans and assessment of the options for modernizing the F-35 engine and power thermal management system. For our assessment of DOD's efforts to compare the F-35A with the A-10C, see appendix II. In addition, a list of related GAO products is included at the end of the report.

To do this work, we interviewed officials and representatives from the F-35 program office; Office of the Director of Operational Test and Evaluation (DOT&E); Lockheed Martin (airframe contractor); Pratt & Whitney (engine contractor); and the Defense Contract Management Agency to discuss the original development program, modernization, the engine, and the thermal management system.

To describe any remaining risks with completing the original development program, we also collected and analyzed cost, schedule, and production data, such as on-time deliveries, labor hours, number of deficiencies, and technical risks, among others.

To assess DOD's progress in developing, testing, and delivering modernization capabilities and risks that remain, we analyzed cost, schedule, and performance documents for Block 4 modernization and compared them against the status we reported last year. We also evaluated the program's cost reporting mechanisms, including Block 4 cost estimates and Block 4 reports to Congress. We also analyzed the F-35 program's Earned Value Management (EVM) system. Specifically, we compared program and contractor documentation with EVM best practices as identified in GAO's *Cost Estimating and Assessment Guide*.[6] For a detailed description of our EVM analysis and findings, see appendix III.

To evaluate DOD's assessment of options for modernizing the F-35 engine and thermal management system, we reviewed Air Force and Navy reports, assessed detailed briefings on the contents of DOD's Business Case Analysis, and spoke with program officials about their plans. We found the assessment did not meet GAO's definition of a business case analysis and program officials stated that they did not follow specific DOD guidance for comparing acquisition options, such as

[6]GAO, *Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs,* GAO-09-3SP (Washington, D.C.: March 2009).

completing an analysis of alternatives. Therefore, we compared the analysis with general acquisition leading practices, such as those from GAO's *Cost Estimating and Assessment Guide* and *Technology Readiness Assessment Guide*.[7] At the time of this review, DOD had not finalized some analyses, so we could not assess some aspects of its plans, such as the cost estimates for each option.

To determine that the data we used were sufficiently reliable for the purposes of responding to our reporting objectives, we corroborated data collected from contractor representatives and program officials with other data sources or knowledgeable officials, such as the DOT&E. See appendix IV for a detailed description of our objectives, scope, and methodology.

We conducted this performance audit from May 2022 to May 2023 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

DOD started the F-35 program in 2001 to develop a fifth-generation fighter aircraft intended to replace a range of aging aircraft in the U.S. military services' inventories and to provide enhanced capabilities that capitalized on technological innovations to warfighters. Among other capabilities, DOD intended the F-35 aircraft to be difficult to detect using radar and included sensors that can provide insights into potential targets and other warfighting information. Lockheed Martin is the prime contractor

[7]In January 2020, DOD reissued Department of Defense Instruction 5000.02, renaming it Operation of the Adaptive Acquisition Framework. In the updated guidance, DOD established the Adaptive Acquisition Framework, which includes six acquisition pathways. Each pathway has different requirements for milestones, cost and schedule goals, and reporting. The analysis of alternatives is normally conducted during the Materiel Solution Analysis phase for major defense acquisition programs, is a key input to the Capability Development Document, and supports the materiel solution decision at milestone A. An analysis of alternatives may be conducted at comparable points for other Adaptive Acquisition Framework pathways as appropriate. See Department of Defense, Office of Secretary of Defense, Cost Assessment and Program Evaluation, *Analysis of Alternatives Cost Guide*, (Jan. 12, 2022). GAO, *Cost Estimating and Assessment Guide: Best practices for Developing and Managing Program Costs*, GAO-20-195G (Washington, D.C.: March 2020); and *Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects* [Reissued with revisions on Feb. 11, 2020.], GAO-20-48G (Washington, D.C.: Jan. 7, 2020).

for the F-35 aircraft and is responsible for integrating the engine into the airframe. Pratt & Whitney is the contractor for the engine, also known as the F135.[8]

The program is producing and delivering three variants of the F-35 aircraft, as shown in figure 1.

Figure 1: F-35 Aircraft Variants

Source: GAO analysis of Department of Defense documents and interviews with officials. Photos (left to right): U.S. Air Force/ Staff Sgt. Andrew Lee, U.S. Navy/Petty Officer 1st Class Jeremy Starr, and U.S. Air Force/Defense Visual Information Distribution Service. | GAO-23-106047

Note: Initial operational capability is generally attained when some units and/or organizations in the force structure scheduled to receive a system have received it and have the ability to employ and maintain it.

The F-35 program operates under the Office of the Under Secretary of Defense for Acquisition and Sustainment, who provides program oversight. DOD leads the F-35 program, but it also involves several allied partner countries in its development.[9] Companies in these countries also

[8]The government acquires the engines directly from Pratt & Whitney and delivers them as government-furnished equipment to Lockheed Martin for integration into the airframes during production.

[9]Seven partner nations— Australia, Canada, Denmark, Italy, Netherlands, Norway, and United Kingdom—contribute to F-35 development, production, and sustainment. In addition, the program currently has nine foreign military sales customers: Belgium, Finland, Germany, Israel, Japan, Korea, Poland, Singapore, and Switzerland. According to program officials, multiple additional countries are at various stages of consideration for foreign military sales.

support aircraft production by producing certain parts of the airframe or engine, according to program office officials.

In July 2019, DOD, at the direction of the White House, removed Turkey from the program due to its government's decision to procure Russian-made radar systems. Consequently, the F-35 program office and the prime contractors have identified and contracted with alternative suppliers to produce the 1,005 parts made in Turkey. In 2022, we reported that the program had spent nearly $1.4 billion and had planned to spend $46.6 million more to finish the Turkish parts replacement effort for the airframe and engine.[10] Lockheed Martin representatives estimate that the change in suppliers will increase the cost per airframe by between $800,000 and $1 million, depending on the variant. In addition, Pratt & Whitney representatives estimate that the cost of the engine will increase by about $300,000.

Program Costs and Performance

As we previously reported in March 2005, DOD began development of the F-35 aircraft in 2001 without adequate knowledge of its critical technologies or a solid design.[11] Later, we reported that DOD's acquisition strategy called for high levels of concurrency between development and production—building aircraft while continuing to refine and test the designs of key components—which runs counter to leading practices we have identified for major defense acquisition programs (MDAP).[12] In our prior work, we reported on the F-35 program's lack of adequate knowledge and high levels of concurrency as major drivers of the program's eventual significant cost and schedule growth, among other performance shortfalls.[13]

Since 2001, DOD has significantly revised the cost and schedule goals for the program several times. For example, DOD revised these goals in March 2012 after the cost of each aircraft grew by an amount that

[10]GAO, *F-35 Joint Strike Fighter: Cost Growth and Schedule Delays Continue*, GAO-22-105128 (Washington, D.C.: Apr. 25, 2022).

[11]GAO, *Tactical Aircraft: Opportunity to Reduce Risks in the Joint Strike Fighter Program with Different Acquisition Strategy*, GAO-05-271 (Washington, D.C.: Mar. 15, 2005).

[12]GAO, *Joint Strike Fighter: DOD Actions Needed to Further Enhance Restructuring and Address Affordability Risks*, GAO-12-437 (Washington, D.C.: June 14, 2012); and *Best Practices: Capturing Design and Manufacturing Knowledge Early Improves Acquisition Outcomes*, GAO-02-701 (Washington, D.C.: July 15, 2002).

[13]GAO-05-271 and GAO-12-437.

exceeded critical thresholds established by statute—a condition known as a Nunn-McCurdy breach.[14] This 2012 revised baseline increased the program's cost estimate by $162.7 billion and extended delivery schedules 5 to 6 years into the future. Since 2012, the program has revised its baseline schedule four more times due to delays in development, among other things. As of December 2021, based on the most current estimate, the program estimates its acquisition costs at $416.2 billion, an increase of $20.5 billion since 2012, as shown in table 1.

Table 1: Total F-35 Acquisition Costs Are $20.5 Billion More Than 2012 Estimate

	October 2001 baseline	March 2012 baseline	Difference from 2001 to 2012	December 2021 estimate	Difference from 2012 to 2021
Development	34.4	55.2	20.8	76.3[a]	21.1
Procurement	196.6	335.7	139.1	335.9	0.2
Military construction	2	4.8	2.8	4.0	(0.8)
Total program acquisition	**233**	**395.7**	**162.7**	**416.2**	**20.5**

Source: GAO analysis of Department of Defense data. | GAO-23-106047

Note: Costs in the table are in then-year dollars in billions and reflects data from the December 2021 Selected Acquisition Report, the most recent available.

[a]The F-35 baseline development program costs includes Block 4 costs, if applicable.

In addition to the acquisition costs, the program office estimates that the costs to operate and sustain the F-35 fleet for its planned 77-year life cycle is at least $1.3 trillion, bringing the total cost of the F-35 program to

[14]DOD is required to notify Congress whenever a major acquisition program's unit cost experiences cost growth that exceeds certain thresholds, commonly referred to as a Nunn-McCurdy breach. Significant breaches occur when the program acquisition unit cost or procurement unit cost increases by at least 15 percent over the current baseline estimate or at least 30 percent over the original estimate. 10 U.S.C. § 4371(a)(1)-(3). For critical breaches, when these unit costs increase at least 25 percent over the current baseline estimate or at least 50 percent over the original, DOD is required to take additional steps, including conducting an in-depth review of the program. Programs with critical breaches must be terminated unless the Secretary of Defense certifies to certain facts related to the programs and takes other actions, including restructuring the programs. 10 U.S.C. § 4376(b).

nearly $1.7 trillion. We have reported on various sustainment issues, most recently in 2022.[15]

Block 4 Modernization Effort

In addition to the F-35 original development program, DOD is pursuing a $16.5 billion modernization effort, known as Block 4. Block 4 seeks to produce a large number of new capabilities, including significant software development to support them. To develop Block 4, DOD is using a different approach called continuous capability development and delivery, which is loosely based on the Agile software development process. With this approach, the program office plans to deliver capabilities incrementally to the warfighter, which it had hoped would result in a more timely release of capabilities. For example, rather than develop and deliver all the required capabilities to the warfighter at one time, which would take several years, the program office intends to have the contractor incrementally develop, test, and deliver small groups of capabilities as they are completed. Examples of these capabilities include radar enhancements and technology to avoid aircraft collisions.

To develop and deliver each set of capabilities, the prime contractor, Lockheed Martin, is expected to sequentially develop four software increments—which are referred to as software drops—that eventually lead up to each delivery to the warfighter. These software increments are intended to refine and further develop capabilities over time as each is tested first by operators in the developmental test fleet and later by operators in the operational test fleet. Over the last 3 years, however, we reported that the program has struggled with delivering capabilities on time using its Agile development approach. In March 2021, we made several recommendations intended to improve their process.[16] The program generally agreed with our recommendations and has taken actions to address them, which we discuss in more detail later in this report.

The projected $16.5 billion cost of the Block 4 effort exceeds the statutory and regulatory thresholds for what constitutes a major defense acquisition

[15]GAO, *F-35 Sustainment: DOD Faces Several Uncertainties and Has Not Met Key Objectives*, GAO-22-105995 (Washington, D.C.: Apr. 28, 2022).

[16]GAO-22-105128; *F-35 Joint Strike Fighter: DOD Needs to Update Modernization Schedule and Improve Data on Software Development*, GAO-21-226 (Washington, D.C.: Mar. 18, 2021); and *F-35 Joint Strike Fighter: Actions Needed to Address Manufacturing and Modernization Risks*, GAO-20-339 (Washington, D.C.: May 12, 2020).

program.[17] In 2016, we recommended that the Secretary of Defense manage it as a separate MDAP to provide better oversight of Block 4 activities.[18] Relatedly, in April 2019, we found that the F-35 program started Block 4 development without a complete business case identifying baseline cost and schedule estimates, which was inconsistent with leading acquisition practices.[19] Therefore, we recommended that the Secretary of Defense ensure that the F-35 program office complete its business case for the initial Block 4 capabilities under development before initiating additional development work. DOD did not concur with our recommendations, and it continues to manage Block 4 within the larger F-35 program.

Congress subsequently required DOD to submit a report containing certain elements of an acquisition program baseline—in essence, a full program business case—to include the cost, schedule, and performance information for Block 4.[20] The program has released its Block 4 report to Congress each year. The F-35 program has also completed nearly all of the documentation that is required of major defense acquisition programs, although it completed some of these documents after Block 4 development began. For example, the F-35 program office drafted, completed, or updated baseline documentation for key acquisition documents such as the Acquisition Strategy and a Test and Evaluation Master Plan after the Block 4 effort was already underway.

F135 Engine

The F-35 has a single engine (the F135 engine), which is built by Pratt & Whitney and then provided as government-furnished equipment to Lockheed Martin, which integrates it into the airframe during production.[21]

[17]MDAPs are those identified by DOD or that have a dollar value for all increments estimated to require eventual total expenditure for research, development, test, and evaluation of more than $525 million, or for procurement of more than $3.065 billion, in fiscal year 2020 constant dollars. DOD Instruction 5000.85, *Major Capability Acquisition* (Aug. 6, 2020) (Change 1, Nov. 4, 2021). See also 10 U.S.C. § 4201.

[18]GAO, *F-35 Joint Strike Fighter: Continued Oversight Needed as Program Plans to Begin Development of New Capabilities*, GAO-16-390 (Washington, D.C.: Apr. 14, 2016).

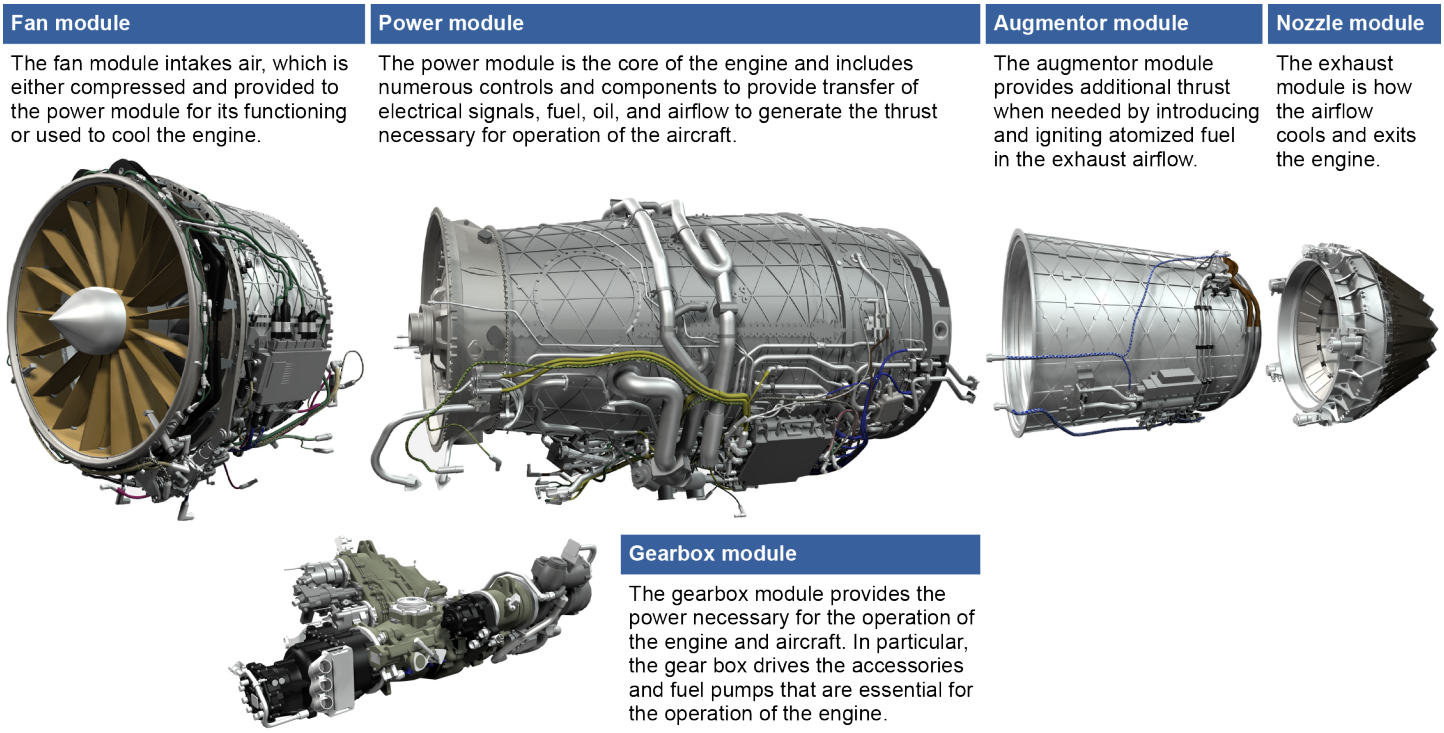
[19]GAO, *F-35 Joint Strike Fighter: Action Needed to Improve Reliability and Prepare for Modernization Efforts*, GAO-19-341 (Washington, D.C.: Apr. 29, 2019).

[20]Pub. L. No. 114-328, § 224(d) and Pub. L. No. 116-92, § 166.

[21]Government-furnished equipment is provided to a contractor by the government, for performance of a contract, and includes tangible items that are functionally complete for its intended purpose, durable, nonexpendable, and needed for the performance of the contract. FAR 45.101.

The three F-35 variants have the same basic engine design with some variations. Specifically, the F-35A and F-35C have the same engine with four modules: fan, power, augmentor, and nozzle (see fig. 2). The gearbox module is included in the power module. The F-35B's engine also has four main engine modules, though the power, augmentor, and nozzle modules have F-35B specific parts and features that enable short takeoff and vertical landing operation, in addition to the F-35B unique lift system made by Rolls Royce.

Figure 2: Diagram of an F-35A/C Engine



Source: Pratt & Whitney. | GAO-23-106047

In 2022, we reported that the F-35 program was in the early stages of planning to modernize the F-35 engine.[22] According to program officials, the program will need to modernize the current engine to provide the additional power and thermal management capabilities that are necessary to support F-35 aircraft modernization.

[22]GAO-22-105128.

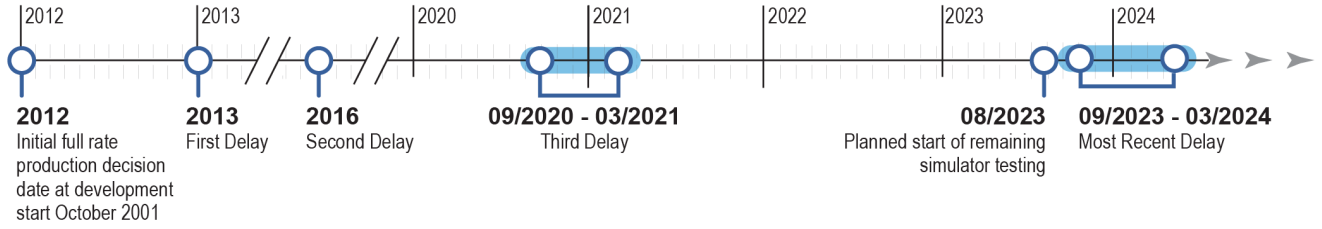
F-35 Program Continues to Experience Schedule Delays, Cost Growth, and Late Deliveries

We found that delays in completing the F-35 simulator continue to prevent DOD from completing the testing needed to achieve a full-rate production decision, now delayed to at least September 2023.[23] In addition, the F-35 program's total acquisition procurement costs have increased by $13.4 billion in its most recent cost estimate, in part, due to extending planned aircraft deliveries for 6 more years to 2052. Furthermore, the program's contractors continue to encounter challenges delivering airframes and engines on time.

Challenges in Completing the Simulator Continue to Delay Full-Rate Production Decision

Developmental challenges with the Joint Simulation Environment, which we refer to as the simulator, continue to delay initial operation testing and evaluation and therefore the program's schedule for a full-rate production decision.[24] Originally scheduled for March 2012, the most recently revised acquisition program baseline delayed a full-rate production decision to between September 2023 and March 2024, as shown in figure 3. Previously we reported that the program had not yet committed to the remaining simulator development schedule, in part, because it continued to find deficiencies with the simulator.[25] According to DOD officials, as part of these developmental challenges, the program is discovering deficiencies in the simulator while conducting the verification and validation process.

Figure 3: F-35 Full Rate Production Delays



Source: GAO analysis of Department of Defense data. | GAO-23-106047

[23]DOD conducts initial operational test and evaluation on production, or production representative articles, to determine whether systems are operationally effective and suitable to support a full-rate production decision.

[24]The simulator runs the F-35's mission systems software along with other software models (such as other weapons and modern threat systems) to provide complex test scenarios that the program cannot replicate in a real-world environment.

[25]GAO-22-105128.

The program has made progress, however, in addressing simulator deficiencies since we last reported. In April 2022, we reported that the simulator had 32 deficiencies that the program determined must be fixed before the system will meet its needs.[26] As of February 2023, six of these so-called must-fix simulator deficiencies remain and must be resolved before the program can conduct the final 64 operational trials (or tests).[27] Once the program fully addresses these deficiencies, the accreditation process can be completed, and DOT&E can determine that the simulator is ready to begin the 64 trials. Currently, the program expects these trials to take place in August 2023 and then, following the completion of DOT&E's beyond low-rate initial production report, the F-35 program can make a full-rate production decision.

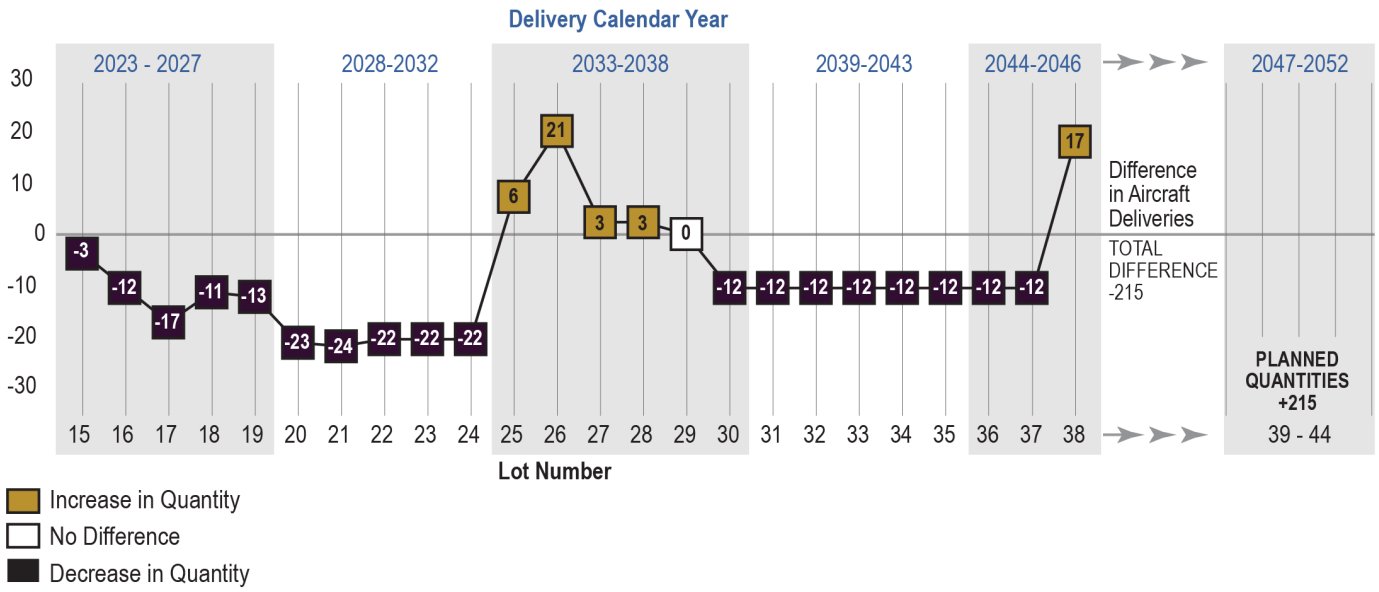
Procurement Costs Increased as the Program Is Adding Years to Its Production Schedule

We found that the program has extended its planned production, delaying deliveries of 215 F-35As and increasing the program's acquisition procurement cost by $13.4 billion. As of January 2023, the program's delivery schedule continues through 2052, 6 years beyond the 2046 completion date that it planned for in 2021, as shown in figure 4. The program attributes the increased procurement cost to additional years of costs related to airframe and engine production, along with support costs for equipment, technical data, and training. According to program officials, the program is deferring the delivery of these 215 aircraft to later years at the request of the Air Force. The total procurement amount of aircraft quantities remains the same with these changes to the delivery schedule.

[26]GAO-22-105128.

[27]An example of a must-fix deficiency failure is when a software model does not function properly for a required test. For example, the simulator display loses the tracks for specific surface-to-air missiles threats under certain conditions or only allows a limited set of capabilities to be tested.

Figure 4: F-35 Aircraft Delivery Schedule from 2023 through 2052



Source: GAO analysis of Department of Defense data | GAO-23-106047

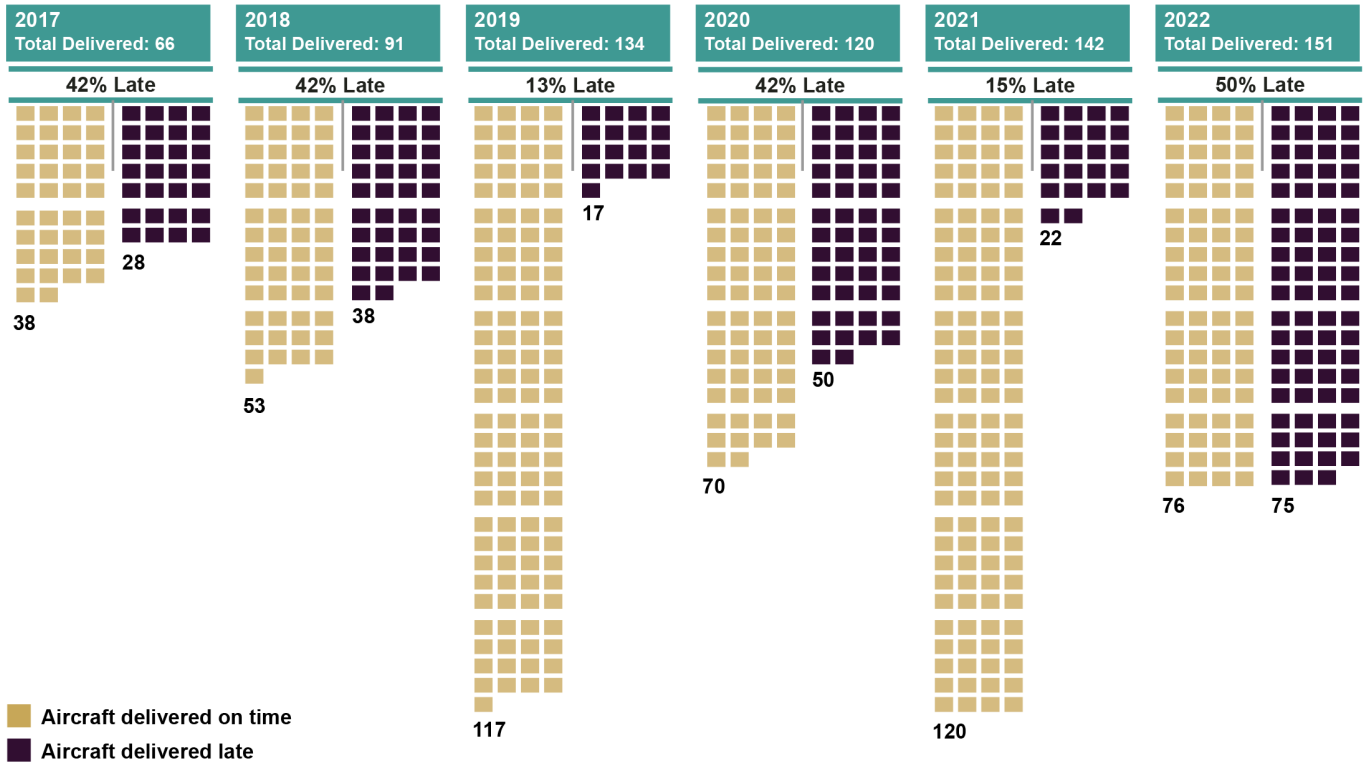
Note: DOD has not yet reported on the number of F-35As that will be delivered each year from 2047–2052, all of which will go to the U.S. Air Force.

Airframe and Engines Continue to Deliver Late

Airframe

In 2022, Lockheed Martin delivered 50 percent of aircraft late, which represents the highest level of late deliveries over the past 6 years and three times worse than the percentage in 2021. According to program officials, these late deliveries were, in part, due to longstanding supply chain issues. We found in April 2022 that the program office modified the contracted delivery date for aircraft scheduled for delivery in 2020 through 2023. The program moved delivery dates for some of these aircraft to later dates to help Lockheed Martin and the production line recover from issues with ongoing supply chain challenges exacerbated by the COVID-19 pandemic. As a result, some aircraft initially considered late were determined to be on time. Regardless of this relief, Lockheed Martin is continuing to deliver aircraft late in part due to ongoing manufacturing issues and parts shortages, which were exacerbated by the COVID-19 pandemic, according to contractor representatives (see fig. 5).

Figure 5: F-35 Airframe Contractor Continues to Deliver Late Aircraft



Source: GAO analysis of Department of Defense data. | GAO-23-106047

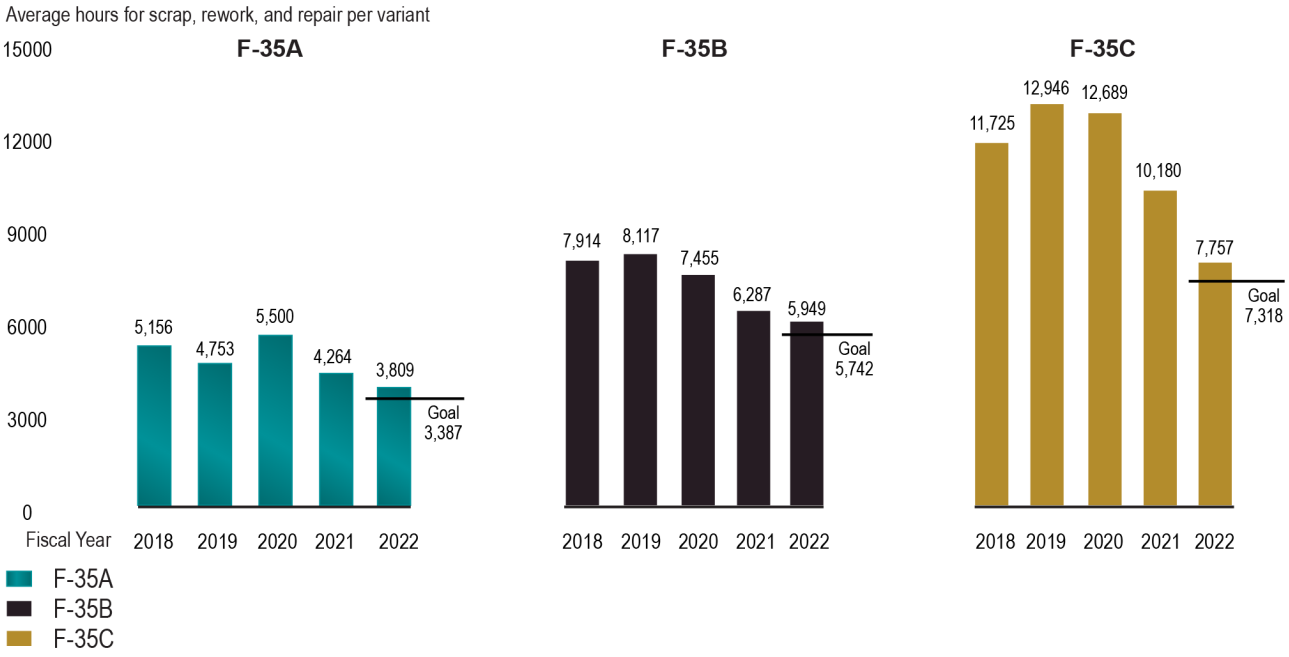
During each of the past 2 years, the contractor has generally taken more time to build the F-35A and F-35B variants than it has in the past. Prior to 2021, the contractor had made year-over-year progress reducing build time for the F-35A, the most common variant produced. In 2021, build times increased and remained high in 2022. While time to build the F-35C improved, it remains the longest to build of the three. Figure 6 illustrates the build times for each variant over the past several years.

Figure 6: F-35 Aircraft Are Generally Taking Longer to Build in Recent Years

Source: GAO analysis of Lockheed Martin data. | GAO-23-106047

Lockheed Martin's scrap, rework, and repair (SRR) hours continue to improve year to year; however, it continues to miss internal goals. SRR happens due to production defects, such as holes drilled incorrectly, that result in material scrapped or additional work performed to fix the defect. SRR hours along with parts shortages increase the amount of work conducted outside the planned station for that work, which hinders the contractor's ability to keep the production line on schedule. According to program officials, work conducted out of its planned station further increases the risk of mistakes during production. DOD officials attribute ongoing SRR issues to less experienced workers because of higher than usual turnover and increasing market competition for manufacturing skills. Figure 7 shows the number of SRR hours Lockheed Martin expended per variant over the past 5 years.

Figure 7: F-35 Airframe Contractor Scrap, Rework, and Repair Hours Improving but Still Not Meeting Goals



Source: GAO analysis of Lockheed Martin data. | GAO-23-106047

Parts shortages have increased significantly in 2022, and Lockheed Martin is taking steps to address late parts that affect the production line. As noted above, the program modified the contracted delivery dates for aircraft in 2020 through 2023 to help Lockheed Martin and the production line recover from issues with ongoing supply chain challenges. Initially this delivery modification reduced parts shortages to the production line by 79 percent in 2021. During the fall of 2021, the weekly average of parts shortages was down to 11 parts at its lowest.[28] However, as of December 2022, the weekly average of parts shortages increased to 169, the highest they have been since the contract modification.

DOD officials attribute recent parts shortage increases to staffing and quality issues throughout the supply chain. Lockheed Martin is evaluating the capacity of its suppliers and focusing on improving deliveries of late

[28]This only includes code 1 part shortages. Lockheed Martin classifies parts into three codes, 1, 2, and 3. A Code 1 part shortage is the most critical and could cause the production line to stop if a shortage continues.

parts that most affect production. For example, according to the program, shortages of center fuselages could cause about a 1-month delay to all aircraft deliveries for 2023 through 2025.[29] The center fuselage forms a significant portion of the aircraft's internal weapons bay and internal fuel capacity. To address this issue, Lockheed Martin and the program modified the aircraft delivery schedule to align with the number of center fuselages they expect to be available. According to program officials, since May 2022, production of center fuselages has successfully increased and the supplier has maintained a delivery rate that is supporting the F-35 production line needs.

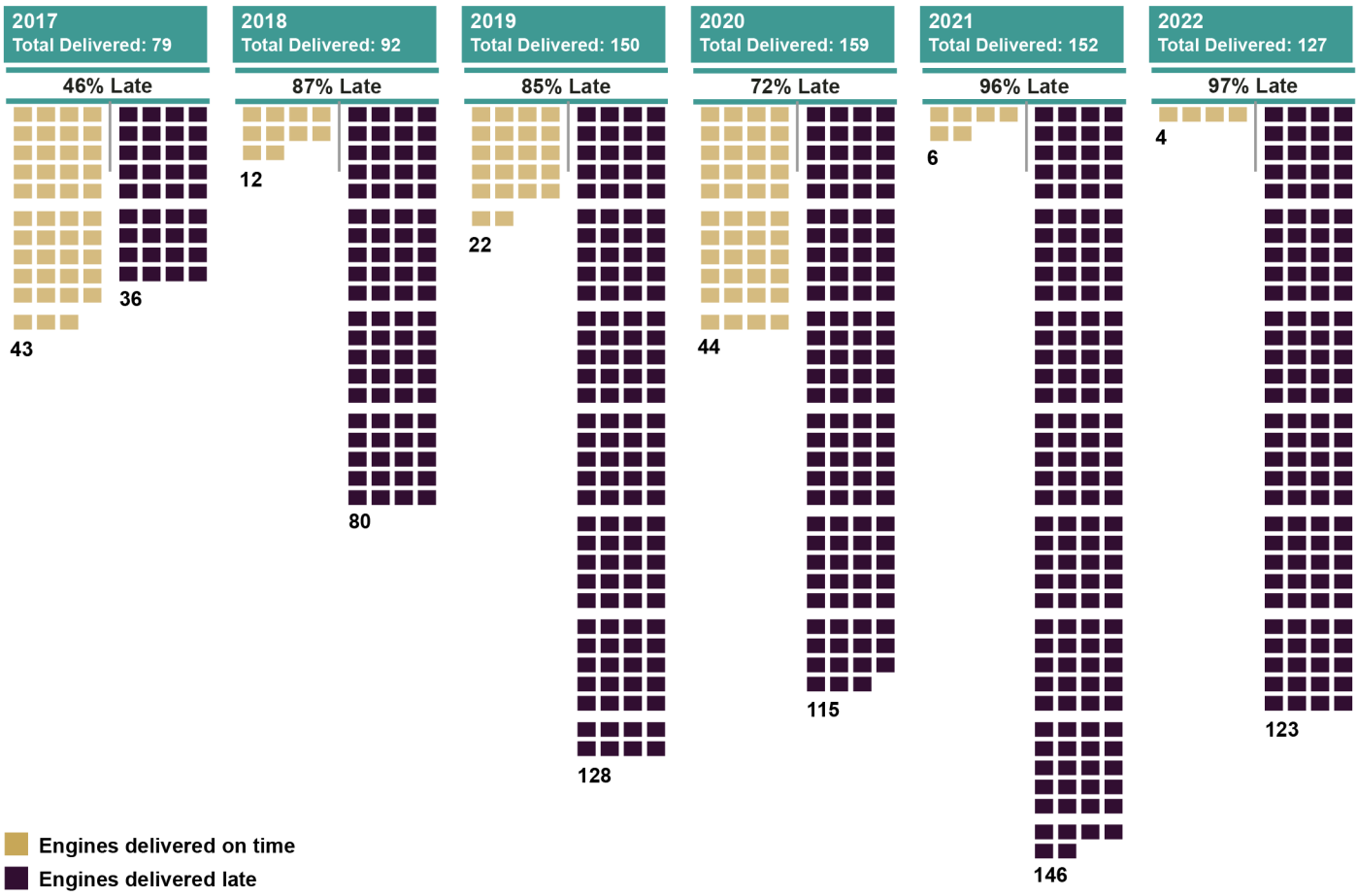
Engine

In 2022, the engine contractor—Pratt & Whitney—delivered four of 127 F135 engines on time even with multiyear efforts to address this long-standing issue. Since 2017, Pratt & Whitney has continually faced challenges delivering engines on time as shown in figure 8. Program officials attributed late engine deliveries over the past year to quality issues and contractor supply chain challenges, among other things. We previously reported that DOD requested that Pratt & Whitney address issues with late deliveries and quality control.[30] In response, the contractor submitted a corrective action plan and implemented steps to enhance delivery performance. DOD agreed and accepted the corrective action plan in September 2022, but late deliveries persist.

[29]The program experienced a shortage of center fuselages in part due to removing Turkey, which supplied some of the F-35 center fuselages, from the supply chain.

[30]GAO-22-105128.

Figure 8: Engine Contractor Continues to Deliver Nearly Every F-35 Engine Late in 2022



Source: GAO analysis of Pratt & Whitney data. | GAO-23-106047

Late engine deliveries are now affecting Lockheed Martin's aircraft production line. The program has been reliant on an engine buffer—a standing inventory of engines at government facilities—to mitigate the late deliveries in prior years. Specifically, program officials stated that Pratt & Whitney plans to deliver engines to DOD earlier than Lockheed Martin needs them for production. DOD holds the engines at a government-furnished warehouse until either Lockheed Martin needs them for production or the military services need them to replace engines for F-35s in the field.

As of February 2023, however, the program reported there is no longer a buffer, but officials are working on a recovery plan. Specifically, after an

F-35B crashed in December 2022, program officials stated that they implemented an engine delivery pause while DOD and the contractors could identify the root cause of the accident. Due to this pause in deliveries and the use of the engines that had remained in the buffer to support sustainment needs and the production line, there is no longer a buffer of engines. According to DOD officials, while engine deliveries resumed in mid-February 2023, program officials stated that they are still working through a recovery plan to restore the buffer and ensure Pratt & Whitney delivers engines on time.

Technology Issues and Reliability and Maintainability Concerns Remain

The program continues to identify and resolve issues with the aircraft and address aircraft reliability and maintainability. In 2022, the program discovered new deficiencies with the aircraft while resolving others. See appendix V for a full description of the status of F-35 deficiencies. Similarly, the program identified new technical risks in 2022, while others were resolved. See appendix VI for a description of selected technical risks.

Since August 2021, the program improved some reliability and maintainability metrics, but most stayed the same. Although the program is not meeting 11 of its 24 reliability and maintainability goals, measurable improvements can take time to manifest. See appendix VII for a summary of these metrics and the most recent performance towards meeting reliability and maintainability goals.

Modernization Program Provided Little Transparency into Its Continued Cost Growth

The F-35 program, now 5 years into its Block 4 modernization efforts, continued to experience developmental delays to important technology updates. The program office is implementing new software development initiatives to improve its Agile development practices. However, it is too soon to evaluate the effectiveness of these efforts because the program has not delivered the first software developed using its new Agile development practices. Furthermore, as Block 4 costs continue to grow, the program's cost reporting does not provide a full accounting of the sources of the increases.

Modernization Capabilities Continue to Be Delivered Late

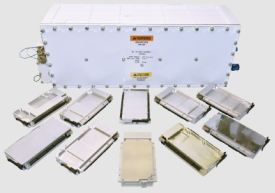
Technology Refresh 3 Delays

The program plans to install Technology Refresh 3 (TR-3), the $1.64 billion suite of upgraded hardware and software technologies that will enable many future Block 4 capabilities, on production aircraft in July 2023.[31] However, the program has experienced testing delays, which means there is less time to improve TR-3 software before delivery of the initial Lot 15 aircraft, the first jets equipped with TR-3.[32] The upgrades within TR-3 are set to provide improved processing capability and increased memory capacity compared to the current F-35 processor and memory system, known as TR-2, as shown in figure 9.

[31]This cost estimate is current as of March 2023.

[32]Aircraft are procured in groups, also known as lots. Lot 15 is a group of 93 aircraft that are scheduled to be delivered between 2023 and 2024.

Figure 9: F-35 Technology Refresh 3 (TR-3) Components and Improvements

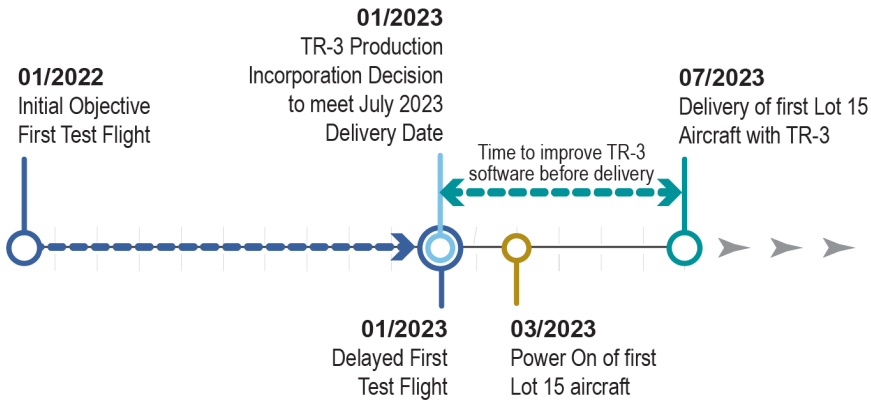
Component	Component Photo	Functionality	Improvement from TR-2
Integrated Core Processor		processes data for each mission Processing: Memory:	 16x 4.5x
Panoramic Cockpit Display		processes cockpit images Processing: Memory:	 8x 12x
Aircraft Memory System		stores aircraft memory	20x

Source: GAO analysis of Department of Defense data | GAO-23-106047

A 12-month testing delay compresses the time frame for final testing and resolving ongoing software issues prior to delivering the first TR-3 equipped aircraft. Program officials stated that the first TR-3 airworthiness flight test took place in January 2023, about a year later than planned. Program officials attributed the delay to software stability issues, which involved the software crashing at a rate that program officials said was not safe for flight. The first airworthiness flight test was an important milestone that signals the technology can safely support the aircraft in flight; however, the test uncovered some software issues that the contractor did not identify in software labs. The program expects to release additional software to address the issues and is evaluating options to improve TR-3 labs. Due to the delays noted above, however, the program will have less time to complete these additional tests and mitigate outstanding software issues than originally scheduled. This

means the program has about 6 months to resolve all TR-3 issues recently identified and conduct the additional testing before it delivers TR-3 with the first Lot 15 aircraft in July 2023, as shown in figure 10.

Figure 10: F-35 Technology Refresh 3 (TR-3) Testing Delay and Production Decision Schedule



Source: GAO Analysis of Department of Defense data. | GAO-23-106047

The program moved ahead with the decision to install TR-3 components in Lot 15 production aircraft to help TR-3 stay on schedule, even though it has less time to ensure TR-3 is ready for production. In January 2023, the program determined that TR-3 hardware had achieved the capability the program has determined it needs to move forward. According to program officials, the program installed the first TR-3 kit on a production line aircraft in February 2023. Although the program determined that TR-3 hardware was ready to be installed in a production line aircraft in February 2023, TR-3 software fixes are still ongoing. The program will have until the July 2023 scheduled aircraft delivery date to ensure TR-3 software is mature enough to be delivered to the military services.

Modernization Capability Delays

The program is continuing to experience late Block 4 capability deliveries due to software development delays and testing challenges, which creates risk for future delays. Late capability deliveries have been a problem throughout the Block 4 effort. For example, for the January 2022 software release, Lockheed Martin delivered two of the five planned Block 4 capabilities on time, with the other three capabilities delayed. Similarly,

of the six capabilities that were delayed in 2021, three have not been delivered as of March 2023, according to program officials.[33]

- **Software development delays.** These delays involve the contractor delivering software to flight testers late. The contractor is expected to deliver new capabilities in the first increment, allowing for later increments to resolve any issues identified with the capabilities during testing. According to flight testers, the contractor sometimes delivers new capabilities to DOD flight testers in later software increments within a software drop, resulting in less time for the testers to identify issues and less time for the contractor to resolve issues. This ultimately contributes to testing delays and late delivery of new capabilities to the fleet.
- **Limited testing capacity.** DOD flight testers' limited ability to test Block 4 capabilities in an operational environment also adds risk to the program's ability to deliver capabilities on time. For example, of the seven test fleet aircraft, four are currently devoted to TR-3 testing, leaving three TR-2-equipped jets able to test Block 4 capabilities.

  This limited availability of aircraft to test Block 4 software drops limits the program's testing capacity. Moreover, DOD officials noted that testing limitations could lead to future operational testing delays, which in turn would create risk of late capability deliveries. The program is aware of this testing limitation and plans to incorporate additional test aircraft by August 2023, for a total of 14 flight test aircraft for testing Block 4 capabilities in TR-2 and TR-3 configurations. However, test officials told us that schedule risk remains due to competing testing priorities and limited aircraft availability to test Block 4 capabilities, even with future aircraft additions to the test fleet.

Program Continues to Implement Software Development Improvement Initiatives

The program continues to take steps to improve the software development process, but it is too soon to assess the full effect of these steps. We have previously reported on capability development and

[33]Program officials stated that these three capabilities were delayed after a change in funding resulted in the program deciding to pause Block 4 development work. Development work restarted in fiscal year 2022, and the capabilities are now expected to be delivered in November 2023.

delivery delays due to software quality issues, which forced unplanned rework and additional software iterations for capabilities.[34]

Last year, we noted that the F-35 program and Lockheed Martin commissioned the Independent Review Team to improve the Block 4 software development process. In some cases, the findings of this review and its recommendations were similar to what we have reported, including that the program should reassess the Block 4 schedule.[35] The program has implemented several of the team's recommendations as discussed below.

- **Delivery cycle adjustment.** Based on an Independent Review Team recommendation, the program transitioned from 6- to 12-month software delivery cycles, with the goal of delivering incremental, partial capabilities over multiple software drops rather than delivering a full or more developed capability all at once. In March 2021, we recommended that the program office develop more achievable time frames for Block 4 modernization by updating its Block 4 schedule to reflect historical contractor performance. DOD concurred with this recommendation. The program's decision to adjust the delivery cycle involved increasing the number of software increments per delivery cycle from four to six, although DOD officials stated that the program will continue to release software increments until the software and capabilities are mature enough to proceed to testing. Program officials said that this adjustment's goal is to make on-time software deliveries more achievable.

  However, longer delivery cycle time frames is a departure from Agile software development best practices to release smaller increments of software at a faster pace. Program officials also said that a 12-month software delivery cycle will allow pilots more time to train on and become proficient with capabilities delivered in the previous delivery cycle. The contractor is currently scheduled to complete the first 12-month software delivery cycle in May 2023. Because the program has not completed this first 12-month software delivery cycle, it is too soon to fully assess the results of this delivery cycle adjustment and other related software development improvement initiatives.
- **Increased automated lab testing.** The team recommended and the program implemented increased automated lab testing to discover software issues earlier in the development process and deliver higher

[34]GAO-22-105128 and GAO-21-226.

[35]GAO-22-105128.

quality software to flight test. Previously, the program did not fully test new software through automated processes, which resulted in less frequent and less thorough reviews. This contributed to the program not discovering software defects until after it delivered the software to the test aircraft or fielded on to operational aircraft. Using automated lab testing, an Agile development best practice, should result in fewer defects discovered after the software is fielded if implemented effectively.

- **Metrics dashboard improvements.** The program and prime contractor also created and refined a metrics dashboard to improve the management of the Block 4 software development process, in response to another Independent Review Team recommendation. In our March 2021 report, we made a similar recommendation that the program office identify and implement automated tools to enable access to real-time data for software development metrics to inform program decisions and ensure the quality of data is reliable.[36] The dashboard allows the program to analyze development performance and software release quality, among other things, by having access to numerous metrics in near-real time. Program officials noted that access to this level of information allows them to better work with their Lockheed Martin counterparts to address software development issues as they arise. The program reported that since starting to use the dashboard, Lockheed Martin is identifying and resolving issues earlier in the software development process. Program officials said that there are 111 government employees with access to the dashboard and they are working to increase that number. When taken as a whole, the implementation of the dashboard and accessibility to real-time data generally meet the intent of our March 2021 recommendation.[37]

The program also plans to take more steps to increase Agile development practices and improve software quality. To continue the Independent Review Team's efforts to identify and implement opportunities to improve the software development process, the program initiated a new series of planned improvements. Some examples of these initiatives include:

- Implementing processes that will allow software development teams to use unclassified software development tools, such as automated

[36]GAO-21-226.

[37]GAO-21-226.

builds and testing, to identify defects earlier in classified development environments.

- Increasing automation for building and testing software. Automation allows these software development processes to run overnight, which increases the opportunities developers have to improve quality in the same amount of time.
- Running additional static analysis checks, which allow developers more opportunities to identify any issues that the new capability might create for the current aircraft software, which is known as legacy code.
- Creating more opportunities to test mission-based scenarios in a laboratory or virtual setting, which will allow developers to test weapons capability software, for example, in a high-intensity threat environment.

Evolving Content of the Modernization Program Obscures Reasons for Cost Growth

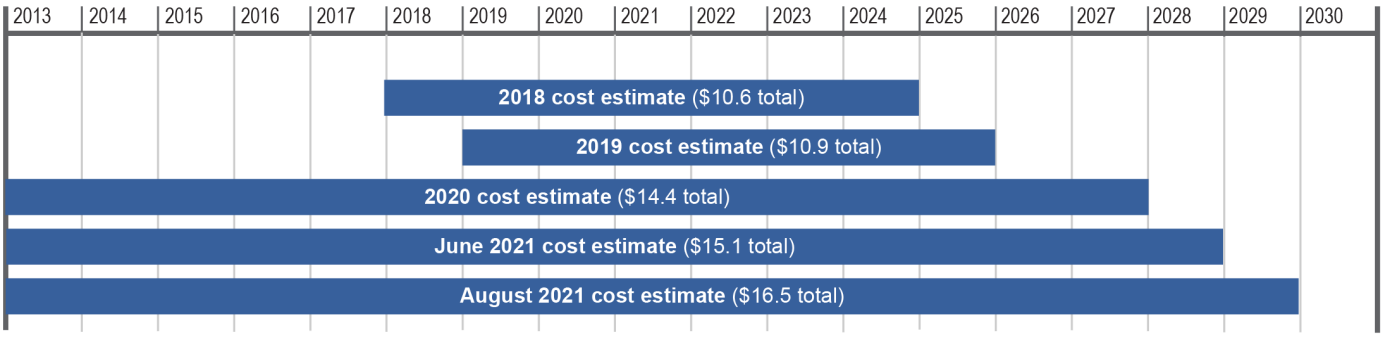
Cost Growth

Since we last reported in April 2022, Block 4 estimated development costs increased by $1.4 billion, from $15.1 billion to a new total of $16.5 billion, as shown in figure 11.[38] The total increase to date is 55 percent more than what the program originally reported it would cost in 2018. Program officials attribute $836 million in new cost growth to the inclusion of new capabilities into the content of Block 4 added since June 2021. Additionally, TR-3 costs grew by $30 million since August 2021. Other contributors to the cost increase include revising the cost estimate to reflect more realistic costs and the administrative costs of updating the Block 4 schedule.[39]

[38]GAO-22-105128. Our 2022 report reviewed the June 2021 Block 4 cost estimate. The August 2021 estimate was not provided in time for us to include it in our report.

[39]In previous cost estimates, the program underestimated costs for electronic warfare and foreign partners' weapons capabilities.

Figure 11: Change in Block 4 Cost Estimates from 2018 through 2021 (then-year dollars in billions)



Source: GAO Analysis of Department of Defense data. | GAO-23-106047

Note: The 2018 and 2019 estimates reflect a 6-year time frame as the Department of Defense (DOD) focused its estimates on the future year's defense program. The future year's defense program is the department's projected spending for the current budget year and at least the next 4 years. The 2020 and 2021 estimate includes costs for the entirety of the program, including all prior years' actual costs and the additional years' estimated-to-completion from the original 2018 estimate. Additionally, the most recent cost estimate is from August 2021 and includes Block 4 development through 2029.

While Block 4 is complex and costly, DOD has managed it within the original F-35 program, which has made monitoring progress and oversight challenging. In April 2016, we recommended that the program manage Block 4 modernization as a separate MDAP from the main F-35 program, in part, to provide more visibility and to hold the program accountable for meeting cost, schedule, and performance goals.[40] DOD did not concur with our recommendation and continues to manage Block 4 as part of the original F-35 program, which DOD established decades ago. Because DOD has managed Block 4 within the broader F-35 program, some of the oversight tools that apply to MDAPs are not required for Block 4. For example, MDAPs that experience unit cost

[40]GAO-16-390. Major defense acquisition programs are those identified by DOD or that have a dollar value for all increments estimated to require eventual total expenditure for research, development, test, and evaluation of more than $525 million, or for procurement of more than $3.065 billion, in fiscal year 2020 constant dollars. DOD Instruction 5000.85, *Major Capability Acquisition* (Aug. 6, 2020) (Change 1, Nov. 4, 2021). See also 10 U.S.C. § 4201.

increases over certain thresholds trigger steps pursuant to the Nunn-McCurdy Act.[41]

The Nunn-McCurdy Act reporting provides Congress with greater visibility into MDAPs that experience cost growth, and encourages DOD to manage such growth. A critical Nunn-McCurdy breach—when unit costs increase at least 50 percent over the original estimate, among other things—triggers a DOD notification of the breach to Congress and requires the Secretary of Defense to submit a written certification to Congress for the program to avoid termination.[42] Since Block 4 is managed as part of the broader F-35 program, its increased unit costs that are now significantly higher than the program reported back in 2018 will not trigger a Nunn-McCurdy breach. Therefore, we still stand by our 2016 recommendation that this effort should have been managed as a separate program.

Modernization Program Content Growth

The program has continued to add planned capabilities to Block 4 after the effort began. In 2016, the program originally defined the Block 4 modernization effort as 66 capabilities scheduled for completion in fiscal year 2026. Since then, the program has added new capabilities into the content of Block 4 nearly every year, while removing others. For example, in 2020, the program expanded its definition of Block 4 by adding 13 capabilities. In 2021, the program added six capabilities and removed six others, bringing the total number of capabilities to 80, and extended the completion date through fiscal year 2029.[43]

In June 2022, the program described its efforts to reframe Block 4 modernization into a series of three capability increments as opposed to one large effort. Increment 1 involves 65 capabilities while increments 2

[41]DOD is required to notify Congress whenever a major defense acquisition program's unit cost experiences cost growth that exceeds certain thresholds, commonly referred to as a Nunn-McCurdy breach. See 10 U.S.C. § 4371(a).

[42]Critical breaches occur when the program acquisition unit cost or procurement unit cost increase 25 percent over the current baseline estimate or at least 50 percent over the original. See 10 U.S.C. § 4371(a)(1)-(3). In such cases, DOD is required to take additional steps, including conducting an in-depth review of the program. Programs with critical breaches must be terminated unless the Secretary of Defense certifies to certain facts related to the programs and takes other actions, such as restructuring the programs. See 10 U.S.C. 4376-4377.

[43]On nearly an annual basis through a formal review board process, the program reprioritizes Block 4 capabilities, while also adding capabilities and expanding schedule as necessary to address evolving threats and the needs of the services.

and 3 are planned to include 13 and 6 additional capabilities, respectively.[44] The program plans to introduce additional capability increments and continue modernization in the future.

Cost Reporting Shortfalls

As the content of Block 4 has grown beyond the original planned capabilities, the cost estimation reporting mechanisms used by the program have not provided visibility into relative modernization cost growth versus new capabilities. Program officials told us they attribute much of the Block 4 cost increases to its addition of new capabilities beyond the original Block 4 capabilities. We are unable to validate that view because the program's cost reporting does not provide information on cost increases that occur during capability development for those original Block 4 capabilities or new capabilities added since 2018. For example, while the program estimates what each capability will cost, challenges the program experiences with developing those capabilities, which have resulted in rework at times, can result in actual cost being higher than projected cost. Therefore, it is unclear how much the original Block 4 capabilities have cost to develop compared with the program's original estimate.

The program's three cost-reporting mechanisms for tracking Block 4 cost growth do not address GAO best practices for cost estimating because they do not explain cost variances experienced with developing capabilities. GAO cost estimating best practices state that variances between planned and actual costs should be documented, explained, and reviewed.[45] However, some of the program's cost-reporting mechanisms are focused on limited aspects of Block 4 program costs, and none fully explain modernization cost variances or how capability development costs changed over what was projected:

- **Block 4 cost estimate.** The Block 4 cost estimate does not document, explain, or review any variances between planned costs and actual costs. The Block 4 cost estimate provides a forward-looking perspective on what the program expects to spend in the current and next 6 fiscal years and only includes a single figure noting

[44]The number of capabilities currently included in each Capability Increment come from the program's most recent capability document, known as Decision Memorandum 153, a successor to the original Decision Memorandum 90, which identified Block 4 as 66 capabilities.

[45]The GAO *Cost Estimating and Assessment Guide* states that cost variance is the difference between actual costs and estimated costs. GAO-20-195G.

the program's past Block 4 expenditures. This limited information on the program's past Block 4 expenditures does not document, review, or explain any variances between projected and actual capability costs.[46] Therefore, the cost estimate does not provide visibility into any cost increases that are due to previously reported difficulties and delays with developing Block 4 capabilities.[47]

- **Block 4 report to Congress.** The program's annual report to Congress does not compare modernization costs against original estimates or document, explain, and review any variances between planned and actual capability costs. Statute requires the DOD to annually report on the cost, schedule, and performance progress against the Block 4 modernization original baseline.[48] Since 2018, the program has annually submitted this report on Block 4. The program's Block 4 reports to Congress have a specific section for reporting on progress to the baseline, but the section does not clearly describe current modernization costs compared with the original baseline.[49] These reports also do not document, explain, or review any variances between planned and actual costs for a defined set of capabilities, such as the original 66 capabilities planned in 2017. The Block 4 reports to Congress do provide some modernization cost information in the form of the most recent Block 4 cost estimate, which, as noted above, is limited.
- **Earned Value Management (EVM).** The program's frequent changes to the Block 4 baseline reduces the effectiveness of EVM, as a tool, for assessing Block 4 cost performance and does not document,

[46]In 2020, we recommended that the program report on all Block 4 costs rather than just near-term costs, and the program concurred (see GAO-20-339). However, the program's most recent modernization cost estimate includes Block 4 cost information through fiscal year 2027 but only limited cost information for fiscal years 2028 and 2029. According to program officials, the most recent Block 4 cost estimate only provides a cost window of 7 fiscal years as opposed to reporting all estimated Block 4 costs to provide a more accurate short-term cost estimate.

[47]We have previously reported on the program's Block 4 capability development difficulties and delivery delays. GAO-21-226.

[48]National Defense Authorization Act for Fiscal Year 2017, Pub. L. No. 114-328, § 224(d)(2017).

[49]The program's congressional requirement to report modernization costs, including reporting costs against the original 2018 Block 4 baseline, expires in March 2023. Pub. L. No. 114-328, § 224(d). We have previously suggested that Congress consider requiring this reporting throughout the life of F-35 modernization. Congress has not taken action on this recommendation. GAO-20-339.

review, or explain any variances between estimated and actual capability costs. The program uses EVM data—which measure the amount of work completed against the amount of planned work—to track Block 4 cost and schedule performance on contract.[50] Our analysis of the program's EVM system found that it generally followed best practices but had a significant limitation. Frequent baseline changes due to the inclusion of new scope make the program's EVM data difficult to interpret. This decreases the effectiveness of EVM because the program is measuring cost and schedule against a continuously changing target, instead of a static baseline. As a result, the program's Block 4 EVM data provide a less meaningful basis for documenting, reviewing, or explaining cost variances during Block 4 capability development. See appendix III for GAO's full analysis of the program's EVM practices.

Without adequate visibility into modernization cost growth over time in a program with regularly changing content, the amount of cost growth attributable to development of the original capabilities versus due to added capabilities is not clear. None of the program's cost estimating reporting tools assess and explain cost variances for a defined group of modernization capabilities. Program officials told us, however, that they are able to compare cost growth by capability from year to year and they, at times, have provided this information to DOD F-35 stakeholders. However, the program does not explain cost growth by capability in its annual reports to Congress and this information was not made available to us during the course of our work. Accordingly, it is not providing Congress with a complete picture of F-35 modernization cost growth and whether that growth is associated with adding new modernization content or the challenges we have documented with Block 4 development.

Engine and Thermal Management Modernization Effort Lacks Key Details

The F-35 program is exploring its options for modernizing the engine and thermal management system to reduce sustainment costs, improve engine life, and enable future F-35 capabilities. The program completed a comparative analysis of its modernization options. However, it has not fully defined the power and cooling requirements the engine and related components will need to support capabilities beyond those planned through 2035. Furthermore, the program office has not fully assessed the costs and some of the technical risks of the different engine and thermal management system upgrade options. Finally, the program plans to manage engine and thermal management upgrade options as part of the

[50]Earned value management is a project management tool that integrates the technical scope of work with schedule and cost elements for investment planning and control; it compares the value of work accomplished in a given period with the actual cost of work accomplished and the value of the work planned in that period.

overall F-35 program, which presents oversight and transparency risks similar to those we identified with Block 4.

Current Aircraft Cooling System Demands Exceed Its Original Design

The F-35 uses its power and thermal management system (PTMS) to cool the aircraft's subsystems that generate heat. The PTMS, a system designed by a Lockheed Martin subcontractor, among other things, uses air pressure from the engine to provide cooling to aircraft subsystems, such as the radar, to ensure they do not overheat and fail. The PTMS is a complex subsystem that also includes the equipment necessary to provide aircraft main engine start, emergency power, cockpit conditioning, equipment cooling, and some electrical power.

The PTMS, however, needs more air pressure from the engine to cool subsystems than originally anticipated, which is reducing the life of the engine. Program officials explained that Pratt & Whitney designed the engine to provide a certain amount of air pressure to the PTMS, which Lockheed Martin defined early in the development program. While Pratt & Whitney's F135 engine met those air pressure specifications, program officials stated that, in 2008, Lockheed Martin discovered that the PTMS would need more air pressure from the engine than originally anticipated to help cool aircraft subsystems. According to program officials, in 2013, Lockheed Martin requested to change the F135's design to provide more air pressure to the PTMS, but program officials determined that it was too late to redesign the engine given the cost and schedule effects of such a change at that stage of the overall program. Program officials decided to continue with the F135 engine's original design with the understanding that there would be increased wear and tear, more maintenance, and reduced life on the engine because it would need to provide more air pressure to the PTMS than its design intended.

These cooling problems will only get worse as the program adds new capabilities to the aircraft. Modernization capabilities—including Block 4 capabilities already installed and future ones planned for through 2035—require even more cooling capacity and air pressure than the PTMS and the engine can support, respectively. Program officials noted that Lockheed Martin did not anticipate needing more cooling from the PTMS when it proposed Block 4. However, the addition of Block 4 will require more cooling capacity. The program is planning additional future capabilities beyond Block 4, which will also need more cooling. Therefore, the program expects the engine will need to provide even more air pressure to PTMS to support future capabilities, which will further reduce engine life.

In total, the program has already added $38 billion to the program's life-cycle cost estimate because of these cooling challenges, largely due to the increased wear and tear on the engine. As we reported in March 2005, DOD began development of the F-35 aircraft in 2001 without adequate knowledge of its critical technologies or a solid design.[51] We reported that, as a result, the program has incurred additional costs as it has had to redesign and retrofit the aircraft. The misalignment of requirements with the engine and PTMS illustrates why it is important to fully understand the proposed designs at the beginning of an acquisition, prior to committing to development.

The program determined that it must upgrade the PTMS by 2029 to enable capabilities planned through 2035 and upgrade the engine to reduce life-cycle costs. The current design of the engine and PTMS, collectively, will not meet the cooling capacity needed to support future capabilities planned beyond 2029. If the program does not upgrade the PTMS by 2029, the program will not be able to support the new capabilities planned through 2035 or beyond. In contrast, program officials stated that the current engine could support capabilities planned through 2035, albeit with a significantly degraded engine lifespan. As a result, program officials stated that they would need to upgrade the engine to improve its lifespan and potentially avoid at least some of the $38 billion in increased life-cycle costs.

F-35 Program Did Not Fully Assess Modernization Risks, Costs, or Requirements

To address the need for additional cooling capacity, restore engine life, and reduce life-cycle costs, the F-35 program evaluated different options for modernizing, or upgrading, the PTMS and the engine. To support an informed acquisition decision, DOD requires programs following the major capability pathway to conduct planning activities to support the decision to move to different phases of the acquisition cycle.[52] For example,

[51]GAO-05-271.

[52]DOD Instruction 5000.85, *Major Capability Acquisition* (Aug. 6, 2020) (incorporating change 1, Nov. 4, 2021). Released in August 2020 and updated in November 2021, this instruction established the policy and prescribed procedures that guide acquisition programs using the major capability acquisition pathway. Within this pathway, programs generally proceed through a number of phases.

programs usually conduct an analysis of alternatives to identify and assess a range of possibilities to meet requirements.[53]

In lieu of completing planning activities such as an analysis of alternatives, the program office completed what it refers to as the Business Case Analysis in March 2023.[54] According to program officials, they intended for the analysis to provide the services with information to help them make engine and PTMS modernization decisions. The analysis evaluated preselected options for improving power and cooling by upgrading the PTMS as well as modernizing or replacing the engine. It also compared some development risks associated with each option. Program officials acknowledged that the analysis did not follow any particular DOD guidance related to business case analysis or analysis of alternatives, though the analysis was intended to inform the military services' selection of a modernization option.

We found the program's analysis does not address key aspects of how we define a business case analysis.[55] For example, the analysis did not include an approved acquisition strategy for engine modernization or an independent cost estimate.[56] Therefore, we consider it a comparative analysis.

[53]DOD Instruction 5000.85, *Major Capability Acquisition* (Aug. 6, 2020) (incorporating change 1, Nov. 4, 2021); Department of Defense, Office of Secretary of Defense, Cost Assessment and Program Evaluation, *Analysis of Alternatives Cost Estimating Handbook* (Jan. 12, 2022).

[54]The analysis and findings of the F-35 program's engine and thermal management comparative analysis were complete at the time of our review, but the program did not release it until March 2023.

[55]In our prior work, we identified five key elements of a business case. They include: approved requirements, an approved acquisition strategy, a completed technical risk assessment, a completed schedule risk assessment, and a cost estimate based on an independent assessment. GAO, *Defense Acquisitions Annual Assessment: Drive to Deliver Capabilities Faster Increases Importance of Program Knowledge and Consistent Data for Oversight*, GAO-20-439 (Washington, D.C.: June 3, 2020).

[56]According to program officials, they planned to finalize the acquisition strategy in spring 2023. According to DOD officials, an Independent Cost Estimate was completed and in the process of being finalized by spring 2023. These documents were completed after the Business Case Analysis was complete, so they were not included in the analysis. Further, the completed Independent Cost Estimate did not address PTMS costs or the unknown costs the program is still analyzing.

The program provided the results of its assessment to the military services—the Air Force, Navy, and Marine Corps—to inform their modernization decisions. Program officials explained that the services will each define their own performance requirements based on their needs and each of the services will be able to select its own PTMS and engine modernization path. This means the services could select different modernization options, which would affect the commonality of the F-35s, potentially resulting in increased sustainment costs if multiple engines needed to be supported. Program officials said they provided the comparative analysis to the services for their consideration.

In the comparative analysis, the program evaluated three modernization categories.[57] These include:

- the current F135 with an upgraded PTMS,
- an upgraded F135 engine with an upgraded PTMS, and
- a fully redesigned engine with an upgraded PTMS.

For each category above, the program also evaluated different upgrades to the PTMS. Two of the PTMS upgrade options enhance the existing PTMS to varying degrees and one option is a totally redesigned PTMS. Each engine and PTMS combination presents different trade-offs based on levels of commonality, cooling capacity, costs, schedules, and other factors (see table 2 for some of these trade-offs and how the program assessed the options against these factors). Officials explained that some future capabilities will also place increased demands on other systems, such as the electrical power system, and may require an upgrade to the fuel thermal management system, another system that fuels the engine and removes excess heat from subsystems, as shown in table 2.[58]

[57]The analysis compared 20 engine and PTMS combinations. However, not all were feasible options due to the modernization timelines.

[58]According to program officials, if the fuel is too hot, it will not be used effectively to cool engine components.

Table 2: U.S. F-35 Engine and Thermal Management Modernization Options Comparison in Selected Areas

Factor	F135 with upgraded PTMS 1	F135 with upgraded PTMS 2	F135 with new PTMS	Engine upgrade with upgraded PTMS 1	Engine upgrade with upgraded PTMS 2	Engine upgrade with new PTMS	New engine with upgraded PTMS 1	New engine with upgraded PTMS 2	New engine with new PTMS
Common solution for all F-35 variants	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Cooling capacity	Increase	Increase	Increase	Increase	Increase	Increase	Increase [b]	Increase [b]	Increase [b]
Engine life[a]	Decrease[b]	Decrease[b]	Increase[b]	Return to Original Specification	Return to Original Specification	Return to Original Specification	Return to Original Specification[c]	Return to Original Specification[c]	Return to Original Specification[c]
Weight	No change	Increase	Increase	Increase	Increase	Increase	Increase [c]	Increase [c]	Increase [c]
Upgrade to electrical power system	Possibly	Highly Likely	Highly Likely	Less Likely	Highly Likely	Highly Likely	Less Likely	Highly Likely	Highly Likely
Major upgrade to fuel thermal management system	Possibly	Highly Likely	Highly Likely	Possibly	Highly Likely	Highly Likely	Less Likely	Less Likely	Less Likely

Source: GAO representation of Department of Defense data. | GAO-23-106047

[a]The original engine life specification was 2,000 hours for the F-35A/F-35C and 1,500 for the F-35B.

[b]Data on engine life for this option only includes data from the A and C variants. Data for the B variant were not available.

[c]Data on the new engine only assessed effects on the F-35A.

The three engine modernization categories are:

- **F135 with upgraded PTMS.** The first option is to keep the current F135 engine and upgrade the PTMS. This option would likely provide enough cooling to meet known capabilities through 2035. Based on the PTMS option selected, the program expects that it could begin installing a new PTMS between 2030 and 2032, with the simplest version completed earlier while the total redesign would come later. However, this option would not improve some of the existing issues, such as engine lifespan and the additional cost of maintaining the

engine. This option may also require costly modifications to the gearbox—which provides power to the generator that supplies electrical power to the aircraft—which the program has not assessed. This option also does not address increased weight from Block 4, which would put increased strain on all variants, but could be particularly challenging for the F-35B's vertical lift capability.

- **Engine upgrade and upgraded PTMS.** The second option is to upgrade the F135 and the PTMS. The proposed engine change would be to upgrade the F135, including the engine's core and power module, which the program refers to as the engine core upgrade.[59] The program reported that airframe integration risks for the engine core upgrade are low because it is similar to the existing F135 engine. Officials added this engine is the only viable option to address the decreased vertical lift for the F-35B caused by the weight increase of the aircraft. According to the program office, any F135 engine can incorporate the engine core upgrade, meaning it should be easier to support during sustainment. For example, program officials stated that maintainers would complete the upgrade during scheduled maintenance at the engine depots. Program officials estimate that F-35s with the engine core upgrade would be available in 2032, about 3 years after the program office estimates delivery of several key Block 4 modernization capabilities that require additional engine and PTMS capabilities. Between fiscal years 2022 and 2023, the program office received $195 million to mature the F135 engine core upgrade and move it through preliminary design review, currently planned for December 2023.
- **New engine and upgraded PTMS.** The third option is to use an Air Force technology development program's engine designed to be compatible with the F-35 and upgrade the PTMS. Specifically, the program office is considering using new engine technologies developed by the Air Force through its Adaptive Engine Transition Program (AETP).[60] The AETP is developing the first-ever completed, flight-weight prototypes of adaptive engines, specifically sized for the F-35. Program officials said that these prototype engines have matured adaptive engine technology and have demonstrated improved fuel efficiency, thrust, and cooling through testing. Other

[59]The engine core includes numerous controls and components to provide transfer or electrical signals, fuel, oil, and airflow to generate the thrust needed to operate the aircraft.

[60]An adaptive cycle engine is designed to easily switch between high-thrust and high-efficiency modes, which allows it to adapt while in the air. It can also provide additional cooled air to the engine, which can provide increase thrust and fuel efficiency.

benefits of an adaptive engine include improved range and acceleration. AETP has two contractors—General Electric and Pratt & Whitney—that are developing engine prototypes compatible with the F-35.[61]

According to the F-35 program's analysis, AETP engines deliver the greatest performance improvement of the engine modernization options, but they face challenges integrating into all three F-35 variants. Both contractors' AETP engines are compatible with both the F-35A and F-35C variants but not the F-35B variant.[62] The extent of redesign needed for the B variant would result in a loss of engine commonality across all variants, which will negatively affect life-cycle costs and affordability. According to a Navy report on engine modernization, selection of a propulsion system compatible with the F-35B is vital to reduce program costs and maximize commonality between all three F-35 variants.

Because we found the assessment did not meet GAO's definition of a business case analysis and the program did not follow specific DOD guidance for comparing acquisition options, such as completing an analysis of alternatives, we compared the analysis with general acquisition leading practices, such as those from the GAO's *Cost Estimating and Assessment Guide* and *Technology Readiness Assessment Guide*.[63]

In doing so, we found that analytical gaps in the program's comparative analysis—in areas such as unaddressed technical risks and cost estimating—mean that the military services' decisions are not fully informed by this key information. Program officials acknowledged that they are moving forward, although there are many unknowns. However, they noted that they have accelerated the process for the military services to select a modernization option because of the need to upgrade the PTMS by 2029.

[61]General Electric Aviation's AETP engine is referred to as XA100, and Pratt & Whitney's is referred to as XA101.

[62]The current F135 engine has two variants, one for the F-35A and F-35C, and one for the F-35B. The F-35B is the only aircraft variant with vertical lift capability, which is why it has a different engine variant.

[63]GAO-20-195G and GAO-20-48G.

- **Technical risks.** The program has not fully assessed the technical risks associated with the modernization of the engine, fuel thermal management system, and other related systems. Additionally, in conducting the comparative analysis, the program determined that it needs to assess other aspects of the aircraft affected but has not yet done so. For example:
  - The program discovered limitations to the electrical power system. The program will need to conduct a study to understand the technical risk, and cost and schedule effects of those limitations.
  - The fuel thermal management system is another system responsible for providing fuel to the engine and transferring heat away from the PTMS and other subsystems. Program officials reported that the fuel thermal management system will likely need costly modifications, for which there is no cost estimate yet.
  - The program will need to assess how long the F135 engine gearbox can continue before needing a replacement, if only the PTMS is upgraded. The gearbox is a key element of the F-35 that enables electrical power to be generated in the aircraft.

  Technology readiness assessments (TRA) evaluate the technical maturity of a technology at a specific point in time for inclusion into a larger system. They serve as the basis for realistic discussions on how to address potential risks as programs move from early research and technology development to system development and beyond. We have found that the readiness of critical technologies at the start of technology development affects the schedule and cost of developing a product.[64] Therefore, a TRA performed before development begins provides important information for both the technology developer and program manager responsible for the daily management of developing a product, and the governance bodies charged with the oversight of an acquisition program.

  The program's comparative analysis did not include an assessment of the technology readiness for the various engine and thermal management modernization options. Officials explained that, while the program has not completed a formal TRA for each engine and PTMS option, it has assessed some aspects of technology maturity. For example, program officials stated that they assessed technology maturity for each of the critical technologies associated with the engine options.

[64]GAO-20-48G.

Program officials stated, however, that they have not assessed the maturity of critical technologies for each of the PTMS options or for the combined engine and PTMS options as a system. Furthermore, the program has not completed TRAs for the other components that it has not fully studied, such as the gearbox, electrical system, and the fuel thermal management system. Officials stated that they expect to conduct a formal TRA later during the development process but did not define when. Without a formal TRA that evaluates all technologies related to the engine and PTMS, the program may identify technology risks later in the development phase that it did not anticipate, which could lead to cost and schedule growth.

Furthermore, officials said that some of the technologies within the modernization options were immature. Government agencies, including DOD, use technology readiness levels (TRL) to measure a technology's maturity and readiness for product development. There are nine levels, with TRL 1 being studies of a basic concept and TRL 9 being a technology that has proven itself in successful mission operations. According to GAO's *Technology Readiness Assessment Guide*, critical technologies should be at least a TRL 7—where a fully functional prototype has been demonstrated in an operational environment—prior to product development.[65] Statute requires that technology for MDAPs is demonstrated in a relevant environment (TRL 6) prior to the same milestone.[66] We have found that if a technology is under a TRL 7, the program does not have a solid technical basis of its design and the program could put itself at risk of approving a design that is less likely to remain stable. We also previously found that incorporating immature technologies less than a TRL 6 into products increases the likelihood of cost overruns and delays in product development.[67]

According to program officials, there is a detailed understanding of the TRL of each engine option, but not for all modernization aspects such as the PTMS. Program officials told us that some subcomponents of engine modernization are a TRL 4 and 5, but most others are a TRL 6. Further, officials stated that the engine upgrade options are at a sufficient level of maturity that the services could make an informed decision to choose one now, even though some aspects may be immature, which contradicts leading practices. Officials further stated

[65]GAO-20-48G.

[66]10 U.S.C. §4252(a)(2).

[67]GAO-20-48G.

that they plan to mature the remaining engine subsystems to a TRL 6 by the time that engine option reaches its respective preliminary design review. Officials noted, however, that the PTMS modifications are less mature, with many around a TRL 3. A TRL 3 means development and analysis of separate elements of the technology have begun, but these elements are not yet integrated. If these technologies are not matured to a TRL 7 by the start of development, the program risks moving forward with an unstable design that can cause cost increases and schedule delays.

- **Life-cycle cost estimating**. The program's analysis did not capture all costs of each modernization pathway. While program officials said that they consider the cost estimates for the engine upgrade options to be complete, multiple related modernization efforts lack complete cost estimates.[68] For example, the program has not developed cost estimates for the PTMS upgrade options, so the respective development, production, support, or operation and sustainment costs are unknown. Additionally, while the program's cost estimates include the costs to integrate each engine option onto the aircraft, the additional integration costs associated with increasing the cooling capacity of the PTMS were not considered. We have previously found that, when integration costs and risks are not understood, programs risk incurring additional costs.[69]

  Similarly, the program's cost estimates do not include the costs to upgrade other components for all modernization options, such as the gearbox, electrical system, and the fuel thermal management system, that the program determined might need an upgrade.[70] Program officials explained that they were unable to develop cost estimates for these other components, in part, because they learned about these risks late in the process of completing their comparative analysis. In another case, officials said that the program is still validating cost information so it has not yet conducted a full cost analysis for each PTMS option and is currently relying on contractor estimates.

  The lack of key cost information is counter to GAO's *Cost Estimating and Assessment Guide*, which states a life-cycle cost estimate entails

[68]The comparative analysis had the following cost categories: development, production, retrofit, support, and operating and support with and without fuel consumption.

[69]GAO-20-48G.

[70]According to program officials, the cost of the gearbox upgrades is included in the cost estimates for ECU and AETP, but not for the F135 option.

identifying and estimating all costs that pertain to the program from initial concept through the end of the program.[71] As a result, the military services do not have complete cost information needed to make an informed choice of a modernization option. Without evaluating and including all costs for each component of a modernization option, the current life-cycle cost estimates in the comparative analysis are incomplete, and, therefore, do not provide an accurate and complete view of the costs of each option. Absent a full accounting of life-cycle costs, decision makers will not have a comprehensive picture of the costs for each alternative in the comparative analysis. Further, decision makers will have difficulty accurately comparing the alternatives because comparisons will not be based on complete and correct information.

- **Independent cost estimates.** According to program officials, they requested that the Office of the Secretary of Defense for Cost Assessment and Program Evaluation conduct an independent cost estimate that is due in the spring of 2023, but the F-35 program office has not finished assessing all costs to inform this estimate. As mentioned previously, the program does not have cost estimates for numerous aspects of thermal management modernization, including breakdowns of the PTMS upgrade options. One of GAO's *Cost Estimating and Assessment Guide's* best practices is for an outside group to conduct an independent cost estimate to determine if other cost estimators generate similar results.[72] Without an independent cost estimate encompassing all engine and related systems' modernization costs, decision makers lack insight into the true potential costs.

By completing additional work to fill in the elements missing from the business case analysis—identifying technical risks, full life-cycle costs, and completing an independent cost estimate—key leaders in the services and in Congress would have a more complete basis to make decisions.

Finally, while the program must take steps to upgrade the engine to maintain engine life and upgrade the PTMS to increase cooling capacity, the military services have not established requirements for engine and thermal management modernization. According to program officials, the military services will define their own requirements, or the future capabilities needed from the aircraft, which will dictate the amount of

[71]GAO-20-195G.

[72]GAO-20-195G.

power and cooling the engine and PTMS, respectively, will need to support. Program officials also stated that their comparative analysis was intended to help the military services make their decisions on what PTMS and engine options to select.

While the program generally knows the cooling capacity it will need to support known capabilities through 2035, program officials stated that the military services have not validated those capabilities as performance requirements, so they are notional. In addition, the program has not defined any capabilities after 2035, which means that it will face a period of unknown requirements within several years that the engine modernization options are available for insertion onto the aircraft. Each of the engine and PTMS options the program analyzed provide certain power and cooling capacity, with the AETP engine providing the most. The program, however, has stated that it cannot fully determine how much power and cooling the aircraft will need to support until the military services define their requirements.[73] Until they do so, the program is limited in determining what additional power and cooling are needed to support capabilities through 2035. Furthermore, it is unclear how far into the future any PTMS and engine upgrades will be able to support the F-35, which the program expects to operate well into the 2070s.

With clearly defined requirements from the military services, the program would reduce risks of poor program outcomes, such as not meeting future power and cooling needs as well as cost and schedule growth. Our previous work found that key enablers of a good business case include firm, feasible requirements that are clearly defined, affordable, and clearly informed.[74] Our work has consistently found that the approval of programs with business cases that contain inadequate knowledge about requirements and the resources needed to execute them is a key cause of poor program outcomes.[75] Additionally, pursuing poorly defined requirements results in overly optimistic cost and schedule estimates that are sometimes unachievable—leading to cost and schedule growth as programs encounter increased technical challenges necessary to achieve

[73]Additionally, the aircraft will likely need more electrical power to support future capabilities, but these needs have not been defined.

[74]GAO, *Defense Acquisitions: Joint Action Needed by DOD and Congress to Improve Outcomes*, GAO-16-187T (Washington, D.C.: Oct. 27, 2015).

[75]GAO, *Defense Acquisition Process: Military Service Chiefs' Concerns Reflect Need to Better Define Requirements before Programs Start,* GAO-15-469 (Washington, D.C.: June 11, 2015).

operational requirements. Until the military services define their requirements for engine and thermal management modernization, they risk selecting modernization options without understanding the future cost, schedule, and technical effects.

Furthermore, without defined PTMS and engine modernization requirements, the F-35 program is at greater risk of repeating prior missteps. By proceeding with planning and development of future capabilities without considering the demands on the PTMS and engine, the program endorsed capabilities that neither could support. The program risks repeating a similar mismatch between PTMS and engine capability and future modernization needs if the military services select an option without first defining future requirements. Without more clearly defined engine and PTMS modernization requirements, key decision makers in DOD and Congress will lack information to make informed decisions regarding this large investment and could leave warfighters without the tools they need, when they need them, and leave taxpayers bearing the consequences of greater than expected costs.

In March 2023, near the end of our review, DOD officials announced that they would pursue the engine core upgrade option but did not identify what upgrades they intend to make to the PTMS. Specifically, on March 29, 2023, senior Air Force, Navy, and Marine Corps officials testified before the House Committee on Armed Services, Subcommittee on Tactical Air and Land Forces and stated that they intend to support the engine core upgrade option. During the hearing, the Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics testified that the F-35 program's engine upgrade business case analysis provided the information the department needed to make an engine upgrade decision. However, the Assistant Secretary recognized the Air Force will complete more analysis to address the risks we identified above. As part of the President's budget for fiscal year 2024, the Air Force also requested about $255 million for engine core upgrade development and design contracts, but it did not indicate what the total upgrade effort would cost. During the hearing on March 29, 2023, the F-35 Program Executive Officer also testified that the program is in the process of developing an acquisition strategy to support the award of the engine core upgrade contracts and intends to address all development, test, production, and sustainment risks.

Engine and Cooling System Modernization Management Poses Transparency and Oversight Challenges

F-35 program officials told us that they intend to manage engine and thermal management modernization under the existing acquisition program. Officials explained that, because the military services have close partnerships to coordinate on the F-35's needs, it would be too disruptive to move engine and PTMS modernization out of the F-35 program. However, the F-35 program plans to upgrade at least two major components, the engine and thermal management system, and is at risk of needing to upgrade other aircraft components, such as the electrical power system, gearbox, and fuel thermal management system. Collectively, the program expects these upgrades to cost billions of dollars.

Managing the engine and thermal management modernization efforts as part of the existing F-35 program could limit opportunities for oversight of the effort. Certain DOD weapon programs are required to establish distinct program baselines that depict the current condition of the program, and establish threshold and objective values for the cost, schedule, and performance requirements for the program.[76] We reported in March 2009 that baselines represent starting points against which actual progress can be measured and provide indications of when a program is deviating from the agreed-upon plan and not meeting goals.[77] Congress has established a number of tools to aid in assessing such progress and for holding major defense acquisition programs accountable

[76]For example, programs following the major capability acquisition pathway, as well as major subprograms, are generally required to establish a cost, schedule, and performance baseline. Major capability acquisitions include MDAPs; other programs categorized as acquisition category I; major systems, usually categorized as acquisition category II; automated information systems (not managed by other acquisition pathways); and other capabilities developed via the major capability acquisition pathway. 10 U.S.C. 4214 ("The Secretary of a military department shall establish a baseline description for each major defense acquisition program and for each designated major subprogram under the program"), DOD Instruction 5000.85, *Major Capability Acquisition* (Aug. 6, 2020) (Change 1, Effective Nov. 4, 2021). See also, e.g., the Air Force's Supplemental Instruction DOD Instruction 5000.80_DAFI163-146, *Operation of the Middle Tier of Acquisition* (May 7, 2021). If the engine and thermal management modernization efforts were developed pursuant to any of these options, baselines would likely be established.

[77]GAO, *Defense Acquisitions: Production and Fielding of Missile Defense Components Continue with Less Testing and Validation Than Planned*, GAO-09-338 (Washington, D.C.: Mar. 13, 2009).

for meeting their baseline goals.[78] If the engine and thermal management modernization upgrades are not managed as separate efforts, for example by using the major capability acquisition pathway followed by MDAPs, or as major subprograms, separate baselines would not be required for these efforts. Without such baselines, decision makers will lack a key tool to monitor acquisition progress against established goals. Furthermore, by managing engine and thermal management modernization efforts under the existing program, DOD risks repeating choices that lead to oversight challenges with Block 4, as we previously discussed.[79]

Conclusions

The F-35 remains critical to DOD's defense strategy and to its warfighters. However, the program has yet to complete the acquisition effort and faces challenges, old and new, to its efforts to modernize the aircraft to face modern threats and incorporate new technologies.

As Block 4 continues to grow in cost, schedule, and content, it is important that Congress have a clear understanding of the causes of the increases. To date, the program describes Block 4 as an evolving, and ever increasing, set of new capabilities with a rising overall cost for completing them. Without providing insight into Block 4 cost growth that distinguishes what the program estimated it would cost to develop previously planned capabilities from the estimated cost of newly added ones, the program's cost reporting is inadequate for useful oversight. Further, without the program formally tracking the estimated cost of each capability to the actual cost of developing each and sharing that information, Congress lacks critical information for overseeing the broader Block 4 effort and holding the program and contractor accountable.

With engine and thermal management modernization on the horizon, DOD, the military services, and Congress are at a critical juncture. While

[78]As we noted previously in this report, unit cost reporting referred to as Nunn-McCurdy reporting provides greater visibility into MDAPs that experience significant or critical unit cost growth and encourages DOD to manage such growth. DOD is required to notify Congress whenever a MDAP's unit cost experiences cost growth that exceeds certain thresholds, commonly referred to as a Nunn-McCurdy breach. See 10 U.S.C. § 4371(a).

[79]We have made multiple recommendations to DOD and matters to Congress to address oversight and cost transparency issues with Block 4. DOD implementing one of these recommendations and Congress implementing the matters have helped provide more transparency into the Block 4 acquisition. For more on our recommendations and matters to Congress on Block 4 management and oversight, see GAO-16-390; *F-35 Joint Strike Fighter: Development Is Nearly Complete, but Deficiencies Found in Testing Need to Be Resolved*, GAO-18-321 (Washington, D.C.: June 5, 2018); and GAO-20-339.

the DOD has proposed moving forward with the engine core upgrade, it has not determined what PTMS option it will select and the other power and cooling related components that will it will need to modernize. DOD and the services want to move fast and deliver additional cooling capacity to enable capabilities planned by 2029 and beyond. The services have proposed moving forward with the engine core upgrade in the President's budget submission for 2024. However, DOD has not developed the full complement of information to support these acquisition decisions. Completing the additional analysis typically included in business case analyses would provide DOD, service leaders, and Congress with better information as they continue to make decisions related to engine and thermal management modernization. Without this type of information on technical risk, technology maturity, and costs, the military services may risk warfighters receiving less capability than anticipated while taking more time and resources than the military services can afford.

Absent a life-cycle cost estimate that includes all aspects for each option and an independent cost estimate, DOD risks underestimating the total cost for implementing this modernization effort. DOD is already funding technology maturation efforts for each of the engine modernization options it is considering. DOD and the military services are best served by allowing those maturation efforts to continue to drive down risk, allowing for more informed decisions. Additionally, without having defining power and cooling requirements, there is a risk of repeating a mismatch in engine and thermal management capability versus future modernization needs, similar to what happened with Block 4.

Furthermore, the program stands poised to pursue engine and thermal management modernization in a manner that risks less critical oversight. Pursuing poorly defined engine and thermal management modernization options—a costly and complex endeavor—within the F-35 program, which will soon be in sustainment, instead of as a separate acquisition program will limit opportunities for oversight of the effort. DOD is choosing to follow the path of the Block 4 effort—standing up a large, complex acquisition effort within an already large acquisition program—despite the evidence that Block 4 has proven to be the subject of considerable developmental challenges and difficult to oversee. By not creating a separate program for the engine and thermal management modernization effort, DOD will not be required to establish cost, schedule, and performance baselines that provide decision makers key information to assess progress. Without an acquisition program baseline and regular reporting on progress, it will be difficult for Congress to hold DOD accountable for achieving F-35 engine and thermal management modernization cost, schedule, and performance goals.

In an environment where DOD is striving to quickly acquire and deliver weapons systems and capabilities to the warfighter, it is important that the department and Congress make informed decisions about what cost, technological maturity, and quality risks it is willing to take. Therefore, the importance of oversight and transparency into these decisions and ensuring decisions are fully informed is critical.

Matter for Congressional Consideration

Congress should consider directing the Office of the Under Secretary of Defense for Acquisition and Sustainment to ensure the F-35 engine and thermal management modernization effort is managed as a separate program, with its own distinct cost, schedule, and performance baseline.

Recommendations for Executive Action

We are making the following seven recommendations to the Secretary of Defense to ensure:

The Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program office reports to Congress on cost differences between original estimates and actual costs for a defined group of modernization capabilities over time. (Recommendation 1)

The Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program conducts a technology readiness assessment to evaluate TRLs for all critical technologies and systems for engine and thermal management modernization to inform the military services' modernization decisions. (Recommendation 2)

The Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program matures all critical technologies and systems for engine and thermal management modernization to a TRL 7 prior to starting product development. (Recommendation 3)

The Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program reports the full life-cycle costs, for each engine and thermal management modernization option, including integration and any necessary related aircraft upgrade costs, to inform the military services' modernization decisions. (Recommendation 4)

The Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program obtains an independent cost estimate for all engine and thermal management modernization options, including integration and any necessary related aircraft upgrade costs, to inform the military services' modernization decisions. (Recommendation 5)

The Under Secretary of Defense for Acquisition and Sustainment should direct the F-35 program office to reevaluate its comparative analysis after the military services define their power and cooling requirements, and before proceeding with development of the engine and thermal management modernization effort. (Recommendation 6)

The Under Secretary of Defense for Acquisition and Sustainment should manage F-35 engine and thermal management modernization as a separate program, with its own distinct cost, schedule, and performance baseline. (Recommendation 7)

Agency Comments and Our Evaluation

We provided a draft of this report to DOD for review and comment. DOD provided written comments, which we have reproduced in appendix VIII. DOD concurred with three recommendations, partially concurred with three recommendations, and did not concur with one recommendation, which we discuss below. DOD also provided technical comments, which we incorporated as appropriate.

DOD concurred with our first recommendation and stated that the F-35 program office will evaluate different methods of grouping capabilities to support annual reporting of cost differences between the original estimates and actual costs.

DOD concurred with our second recommendation and described actions it plans to take to evaluate technology readiness levels for critical technologies during various phases of the engine and thermal management modernization acquisition.

DOD partially concurred with our third recommendation stating that it supports maturation of TRLs to the greatest extent possible. It further noted that in instances when some components have a technology readiness level lower than a TRL 7, the program will utilize a risk management process to ensure that technologies continue to mature throughout development. We appreciate the attention that the program intends to focus on technology maturation and risk management. However, we maintain that maturing technologies to a TRL 7 or higher prior to product development would reduce the potential for cost, schedule, and production risks, such as those encountered with the original development program that began development with immature technologies.

DOD concurred with our fourth recommendation and stated that life-cycle cost estimates were included in its assessment of the engine and thermal

management options. DOD also noted that these cost estimates will mature as development begins.

DOD partially concurred with our fifth recommendation that the F-35 program obtain an independent cost estimate for all engine and thermal management modernization options, including integration and any necessary related aircraft upgrade costs, to inform the military services' modernization decisions. DOD stated that in response to congressional direction, the Director of Cost Assessment and Program Evaluation conducted an independent cost estimate and comparative assessment of all propulsion solutions that were the subject of the F-35 Joint Program Office Business Case Analysis. DOD stated that this effort did not include an assessment of thermal management modernization options.

While we recognize that the Cost Assessment and Program Evaluation analysts are finalizing an independent cost estimate focused on engine costs, the engine alone does not comprise the complete propulsion solutions evaluated in the program's assessment. Further, while we appreciate the need to address congressional direction, in doing so, DOD is not precluded from evaluating all aspects of engine and thermal management modernization. As noted in this report, all potential options for resolving the F-35's current and future power and cooling needs involve more than just the engine. For example, the program must still upgrade the PTMS as well as other fuel thermal management components, among others, to support future capabilities. Although the services have made some engine and thermal management decisions, a comprehensive understanding of all costs, particularly integration costs, remains critical as the services continue to evaluate thermal management system options. For these reasons, we continue to believe that our recommendation is valid.

DOD did not concur with our sixth recommendation, which stated that the Under Secretary of Defense for Acquisition and Sustainment should ensure the military services set engine and thermal management modernization requirements and then direct the program office to reevaluate its comparative analysis. DOD stated that setting military service requirements is not within the Under Secretary of Defense for Acquisition and Sustainment's authority and that requirements are developed, approved, coordinated, and validated through a specific DOD governance process. DOD explained that as approved requirements are updated, the F-35 program will reevaluate its analysis as appropriate.

We recognize, as noted in this report, that it is the military services' responsibility for defining their requirements. We also recognize that the F-35 program operates under the Office of the Under Secretary of Defense for Acquisition and Sustainment oversight. As noted in this report, the program has stated that it cannot fully determine how much power and cooling the aircraft will need to support until the military services define their requirements. Until they do so, the program is limited in determining what additional power and cooling are needed to support planned capabilities through 2035. Furthermore, it is unclear how far into the future any thermal management and engine upgrades will be able to support the F-35, which the program expects to operate well into the 2070s. We point out in this report that clearly defined requirements from the military services, would help enable the program to reduce risks of poor program outcomes, such as not meeting future power and cooling needs as well as cost and schedule growth. For these reasons, we revised our recommendation to assert that the Office of the Under Secretary of Defense for Acquisition and Sustainment, as the oversight authority for the program, direct the F-35 program office to reevaluate its comparative analysis, after the military services define their power and cooling requirements, and before proceeding with development of the engine and thermal management modernization effort, as appropriate.

DOD partially concurred with our seventh recommendation that the F-35 engine and thermal management modernization be managed as a separate program, with its own distinct cost, schedule, and performance baseline. DOD stated that it is currently evaluating its options for management of the F-35 engine and thermal management modernization and that management of these activities as a separate subprogram is under consideration. DOD further explained that it plans to provide insight into cost, schedule, and performance data for the effort regardless of how it is managed.

While designating engine and thermal management efforts as a major subprogram would meet the intent of our recommendation, the F-35 program's reluctance to commit to managing the engine and thermal management modernization as a separate program or major subprogram is concerning. While we recognize that DOD policy provides flexibility to manage programs in different ways, managing the engine and thermal management modernization efforts as part of the existing F-35 program could limit opportunities for effective oversight. DOD expects the engine and thermal manage effort to collectively cost billions of dollars. We continue to believe that a development effort of this magnitude should be established as a separate program with its own distinct cost, schedule,

and performance baselines that provide decision makers key information to assess progress. If F-35 engine and thermal management modernization is managed as a distinct program or major subprogram with a separate baseline, it would be easier for Congress and DOD decision makers to track program-specific cost and schedule progress. As a separate program or major subprogram, F-35 engine and thermal management would be subject to key statutory oversight mechanisms—including Nunn-McCurdy unit cost growth thresholds—and DOD would be required to provide regular cost, schedule, and performance reports to Congress. In contrast, if managed as part of the broader F-35 program, engine and thermal management modernization unit cost increases would be compared against the F-35 baseline program, making them less visible. Further, the broader F-35 program is quickly approaching the sustainment phase and will no longer be subject to certain acquisition-related reporting requirements, which are critical to congressional oversight. Therefore, we continue to believe that our recommendation is valid.

Because DOD remains uncertain about how they will manage engine and thermal management modernization efforts to ensure decisionmakers obtain key information to assess progress, we are also making a matter for congressional consideration that Congress should consider directing the Secretary of Defense to ensure that the engine and thermal management modernization effort is initiated as a separate program, which could include designating this as a major subprogram.

We are sending copies of this report to the appropriate congressional committees; the Secretary of Defense; the Under Secretary of Defense for Acquisition and Sustainment; the Secretary of the Air Force; the Secretary of the Navy; and the Commandant of the Marine Corps. In addition, the report is available at no charge on the GAO website at https://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-4841 or ludwigsonj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix IX.

Jon Ludwigson
Director, Contracting and National Security Acquisitions

List of Committees

The Honorable Jack Reed
Chairman
The Honorable Roger Wicker
Ranking Member
Committee on Armed Services
United States Senate

The Honorable Jon Tester
Chair
The Honorable Susan Collins
Ranking Member
Subcommittee on Defense
Committee on Appropriations
United States Senate

The Honorable Mike Rogers
Chairman
The Honorable Adam Smith
Ranking Member
Committee on Armed Services
House of Representatives

The Honorable Ken Calvert
Chair
The Honorable Betty McCollum
Ranking Member
Subcommittee on Defense
Committee on Appropriations
House of Representatives

Appendix I: GAO Reports and Department of Defense Actions

Table 3: Selected Prior GAO Reports on F-35 Joint Strike Fighter and Department of Defense (DOD) Responses

Year, GAO report	Estimated F-35 development costs, development length, and aircraft unit cost[a]	Key program event	Primary GAO conclusions and recommendations	DOD response and actions
2001 GAO-02-39	$34.4 billion 10 years $69 million	Start of system development and demonstration approved.	Critical technologies needed for key aircraft performance elements were not mature. We recommended that the program delay start of system development until critical technologies were matured to acceptable levels.	DOD did not concur with our recommendation. DOD did not delay the start of system development and demonstration stating technologies were at acceptable maturity levels and that it would manage risks in development.
2006 GAO-06-356	$45.7 billion 12 years $86 million	Program sets in motion plan to enter production in 2007 shortly after first flight of the non-production representative aircraft.	The program was entering production with less than 1 percent of testing complete. We recommended that the program delay investing in production until flight testing shows that the F-35 performs as expected.	DOD partially concurred but did not delay start of production because it believed the risk level was appropriate.
2010 GAO-10-382	$49.3 billion 15 years $112 million	The program was restructured to reflect findings from a recent independent cost team and independent manufacturing review team. As a result, development costs increased, test aircraft were added, the schedule was extended, and the early production rate decreased.	Costs and schedule delays inhibited the program's ability to meet needs on time. We recommended that the program complete a comprehensive cost estimate and assess warfighter and initial operational capability requirements. We suggested that Congress require DOD to tie annual procurement requests to demonstrated progress.	DOD continued restructuring, increasing test resources and lowering the production rate. Independent review teams evaluated aircraft and engine manufacturing processes. Cost increases later resulted in a Nunn-McCurdy breach. Military services completed the review of capability requirements and conducted a cost estimate, as we recommended.
2014 GAO-14-322	$55.2 billion 18 years $135 million	The military services established new initial operational capabilities dates. The Marine Corps and Air Force planned to field initial operational capabilities in 2015 and 2016, respectively, and the Navy planned to field its initial capability in 2018.	Delays in developmental flight testing of the F-35's critical software might hinder delivery of the warfighting capabilities to the military services. We recommended that DOD conduct an assessment of the specific capabilities that could be delivered and those that would not likely be delivered to each of the military services by their established initial operational capability dates.	DOD concurred with our recommendation. On June 22, 2015, the Under Secretary of Defense for Acquisition, Technology, and Logistics issued a F-35 software development report, which met the intent of our recommendation.[b]

Year, GAO report	Estimated F-35 development costs, development length, and aircraft unit cost[a]	Key program event	Primary GAO conclusions and recommendations	DOD response and actions
2016 GAO-16-390	$55.1 billion 18 years $130.6 million	DOD planned to begin what it referred to as a block buy contracting approach that was anticipated to provide cost savings. In addition, DOD planned to manage the follow-on modernization program under the current F-35 program baseline and not as its own separate major defense acquisition program.	The terms and conditions of the planned block buy and managing follow-on modernization under the current baseline could present oversight challenges for Congress. We recommended that the Secretary of Defense hold a milestone B review and manage follow-on modernization as a separate major defense acquisition program.	DOD did not concur with our recommendation. DOD viewed modernization as a continuation of the existing program and the existing oversight mechanisms, including regularly scheduled high-level acquisition reviews, would be used to manage the effort.
2017 GAO-17-351	$55.1 billion 18 years $130.6 million	The DOD F-35 program office was considering contracts for economic order quantity of 2 years' worth of aircraft parts followed by a separate annual contract for procurement of lot-12 aircraft with annual options for lot-13 and lot-14 aircraft. However, as of January 2017, contractors stated that they were still negotiating the terms of this contract; therefore, the specific costs and benefits remained uncertain.	Program officials projected that the program would only need $576.2 million in fiscal year 2018 to complete original program development. At the same time, program officials expected that more than $1.2 billion could be needed to commit to Block 4 and economic order quantity in fiscal year 2018. We recommended DOD use historical data to reassess the cost of completing development of Block 3F, complete Block 3F testing before soliciting contractor proposals for Block 4 development, and identify for Congress the cost and benefits associated with procuring economic order quantities of parts.	DOD did not concur with the first two recommendations and partially concurred with the third, while stating that it had finalized the details of DOD and contractor investments associated with an economic order quantity purchase and would brief Congress on the details, including costs and benefits of the finalized economic order quantity approach.

Year, GAO report	Estimated F-35 development costs, development length, and aircraft unit cost[a]	Key program event	Primary GAO conclusions and recommendations	DOD response and actions
2018 GAO-18-321	$55.5 billion 18 years $140.6 million	The program office determined that it could not resolve all open deficiencies found in testing within the development program and they would need to be resolved through post-development contract actions. DOD provided a report to Congress outlining preliminary plans to modernize the F-35. It stated that it planned to develop a full acquisition program baseline for the modernization effort in 2018 and provide a report to Congress by March 2019.	The program office planned to resolve a number of critical deficiencies after full-rate production. We recommended that the F-35 program office resolve all critical deficiencies before making a full-rate production decision and identify steps needed to ensure the F-35 meets reliability and maintainability requirements before each variant reaches maturity. We also suggested that Congress consider providing in future appropriations that no funds shall be available for obligation for F-35 Block 4 until DOD provided a report setting forth its complete acquisition program baseline for the Block 4 effort to the congressional defense committees.	DOD concurred with both recommendations and identified actions that it would take in response. The John S. McCain National Defense Authorization Act for Fiscal Year 2019 included a provision limiting DOD from obligating or expending more than 75 percent of the appropriations authorized under the act for the F-35 continuous capability development and delivery program until 15 days after the Secretary of Defense submits to the congressional defense committees a detailed cost estimate and baseline schedule. DOD submitted its F-35 Block 4 report to Congress in May 2019, which contained cost and schedule information responding to this provision.

Year, GAO report	Estimated F-35 development costs, development length, and aircraft unit cost[a]	Key program event	Primary GAO conclusions and recommendations	DOD response and actions
2019 GAO-19-341	$55.5 billion 18 years $140.6 million	For as long as the program has tracked reliability and maintainability performance, minimal, annual improvement had been realized. Half of these metrics are unlikely to meet targets outlined in the Operational Requirements Document by full aircraft maturity. As of December 2018, not all reliability and maintainability metrics within the Operational Requirements Document have been met, nor reevaluated to determine more realistic reliability and maintainability performance metrics.	We recommended that the Secretary of Defense ensure that the F-35 program office assess the feasibility of its required reliability and maintainability targets, identify specific and measurable reliability and maintainability objectives in its improvement plan guidance, document projects that will achieve these objectives, and prioritize funding for these improvements. We also recommended that the Secretary of Defense ensure that the F-35 program office completes its business case for the initial Block 4 capabilities under development before initiating additional development work.	DOD concurred with our four recommendations on reliability and maintainability and identified actions it would take in response. DOD has taken some action, and we have closed three of the four recommendations as implemented. DOD did not concur with our recommendation on Block 4 modernization. DOD stated that the F-35 program has adequate cost, schedule, and technical maturity knowledge to begin the development of initial Block 4 capabilities. Though these items were completed after DOD conducted additional development work, as of July 2020, the F-35 program office has completed an independent cost estimate, an approved test and evaluation master plan, and systems engineering plan. We closed the recommendation as implemented.

Year, GAO report	Estimated F-35 development costs, development length, and aircraft unit cost[a]	Key program event	Primary GAO conclusions and recommendations	DOD response and actions
2020 GAO-20-316	$57.3 billion 19 years $144.7 million	The Autonomic Logistics Information System (ALIS) is integral to supporting the F-35 operations and maintenance. We noted that we previously reported on key risks associated with the system, such as challenges deploying the F-35 with ALIS, inaccurate data that reside in ALIS, and ineffective training for personnel who need to use ALIS. We reported that DOD and the prime contractor had a variety of initiatives underway for redesigning ALIS.	We suggested that Congress consider requiring DOD to develop a performance measurement process for ALIS. We also recommended that DOD track how ALIS is affecting readiness of the F-35 fleet and develop a strategy for the ALIS redesign.	DOD concurred with both of our recommendations and identified actions that it was taking or planned in response. We agreed that DOD was taking positive steps in addressing issues with ALIS, including the decision to replace ALIS with a future system that it has named the F-35 Operational Data Integrated Network (ODIN). In November 2021, DOD published and subsequently submitted to Congress an F-35 ALIS Redesign Strategy. The strategy includes an identification of goals, key risks, and other important aspects of the desired pathway for the redesign. We closed this recommendation as implemented.
2020 GAO-20-339	$57.3 billion 19 years $144.7 million	In 2019, the F-35 program conducted much of its planned operational testing but extended the schedule by 9 months, which delayed the program's full-rate production decision to between September 2020 and March 2021. In addition, the program was not meeting manufacturing leading practices identified by GAO and its Block 4 development cost estimate did not adhere to GAO leading practices.	We suggested that Congress extend DOD's Block 4 modernization reporting requirement beyond 2023 to the end of the effort. We also made five recommendations to the Secretary of Defense to submit production risks to Congress prior to full-rate production, to establish a Block 4 cost estimate baseline that covers all costs, and to take other steps to improve the Block 4 cost estimate. These steps were to complete a work breakdown structure, conduct a risk and uncertainty analysis, and consider technology risk assessments to help inform the Block 4 development cost estimate.	As of April 2023, Congress had not extended the Block 4 reporting requirement beyond 2023. While DOD did not concur with two of our recommendations—including to evaluate production risks and update its Block 4 cost estimate with a program-level plan—it identified actions that, if implemented, will meet the intent of these recommendations. In September 2020, DOD implemented one recommendation by including all Block 4 costs in its cost estimate. Since that time, DOD reverted to its prior process for reporting Block 4 costs. DOD concurred with our two other recommendations, which remain open.

Year, GAO report	Estimated F-35 development costs, development length, and aircraft unit cost[a]	Key program event	Primary GAO conclusions and recommendations	DOD response and actions
2021 GAO-21-226	$56.6 billion 20 years $130.8 million	The program office delayed full-rate production to an unknown date due to ongoing delays with simulator testing. Block 4 cost and schedule increased, and the program faced challenges in tracking Block 4 software development metrics.	We made three recommendations to the Secretary of Defense to direct the F-35 program office to update its Block 4 schedule to reflect historical performance and develop more achievable time frames; identify and implement automated tools to enable access to real-time data for software development metrics; and set software performance target values for critical software quality metrics.	DOD concurred with all three of our recommendations and identified actions it would take in response. In 2021, the program implemented two of the three recommendations: to update its Block 4 schedule and to identify and implement automated tools. The recommendation to establish software performance target values remains open.
2022 GAO-22-151 28	$57.5 billion 21 years $131.3 million	The program continued to delay full-rate production to an undetermined date due largely to simulator delays. Block 4 continued to experience cost growth and schedule delays. The program took steps to improve Block 4 software development, but it was too soon to determine the results. The program is taking incremental steps to improve and modernize its logistics system.	We did not make any recommendations in this report.	

Source: GAO analysis. | GAO-23-106047

[a]The aircraft unit cost is the program's average procurement unit cost estimate, which is calculated by dividing the procurement amount by the procurement aircraft quantities. This is different than the negotiated price for F-35 aircraft.

[b]Under Secretary of Defense for Acquisition, Technology, and Logistics is now the Under Secretary of Defense for Acquisition and Sustainment.

Appendix II: F-35A and A-10C Comparison Testing

In 2015, facing budget constraints, the Department of Defense (DOD) proposed divesting the A-10 aircraft. The A-10 is a single-seat, fixed-wing aircraft specifically designed for close air support and defeating enemy armor. The Air Force describes the A-10 as a highly accurate and survivable weapons-delivery platform with excellent maneuverability at low air speeds and altitude, a wide combat radius, and extended loiter times.

In the fiscal year 2015 budget request, DOD and the Air Force prioritized modern multi-role aircraft, such as the F-35, and proposed divesting the A-10 fleet. In addition to the A-10, the Air Force currently has two other fighter aircraft that conduct the close air support mission (F-16 and F-15E) and plans to use the F-35 for this mission in the future. In August 2016, we reported on the mission capabilities the A-10 and its pilots currently provided; efforts to mitigate potential gaps that could result from A-10 divestment; and the uncertainty of the effectiveness of mitigation efforts due to lack of quality information, such as specific mission requirements.[1]

Subsequently, Congress requested more information from DOD about how the Air Force planned to replace A-10 mission capabilities. The National Defense Authorization Act (NDAA) for Fiscal Year 2017 required two reports: (1) the Director of Operational Test and Evaluation (DOT&E) was to provide a report to the congressional defense committees that includes the results and findings of the F-35A initial operational test and evaluation and of comparison tests and evaluation of the F-35A and A-10C in conducting close air support, combat search and rescue, and airborne forward air controller missions; and (2) the Secretary and Chief of Staff of the Air Force was to submit a plan for addressing deficiencies and corrective actions identified in the DOT&E report, and short- and long-term strategies for preserving the Air Force's capability to conduct the close air support, combat search and rescue, and airborne forward air controller missions.[2]

In 2019, DOD conducted testing to compare the F-35A and A-10C in conducting close air support, combat search and rescue, and airborne

[1]GAO, *Force Structure: Better Information Needed to Support Air Force A-10 and Other Future Divestment Decisions*, GAO-16-816 (Washington, D.C.: Aug. 24, 2016).

[2]The Fiscal Year 2022 NDAA amended DOD's reporting requirement, eliminating the Air Force Chief of Staff from the reporting requirement. Pub. L. No. 114-328, § 134 (e)(1)(A)(B), as amended by Pub. L. No. 117-81, § 1046 (b)(2).

forward air controller missions. In February 2022, DOT&E issued a classified report to the congressional defense committees summarizing its assessment of the testing, which resulted in a number of classified recommendations to the Air Force. We reviewed this classified report. According to Air Force officials, they reviewed and assessed the DOT&E report and recommendations. DOT&E's report discussed the differences between the two aircraft as well as the strengths and limitations of each jet in the comparison testing. DOT&E's report noted that the F-35A had advantages in some areas of the comparison testing while the A-10C had advantages in others.

The Air Force, however, did not complete a report indicating its plans for addressing those recommendations as required. According to Air Force officials, the Air Force determined that addressing DOT&E's recommendations did not require any changes to the Air Force's current plans for improving the F-35A. Because the Air Force did not issue a plan as required by Congress, we could not asses the Air Force's report. As a result, it is unclear to what degree, if at all, the Air Force considered or addressed DOT&E's recommendations to the Air Force.

Appendix III: F-35 Block 4 Earned Value Management Analysis

Earned value management (EVM) measures the value of work accomplished in a given period and compares it with the planned value of work scheduled for that period and with the actual cost of work accomplished. As a key management concept, EVM provides improved oversight of acquisition programs.

Our EVM analysis focused on Lockheed Martin's Integrated Program Management Report data for Follow-On Modernization Phase 2.3—the contract for developing and testing selected Block 4 capabilities—from June 2021 through May 2022, as well other supporting documentation, such as system certification information and surveillance reports.[1] Specifically, we compared program and contractor documentation with EVM best practices as identified in GAO's *Cost Estimating and Assessment Guide*.[2] To learn more about the program's EVM system, we met with officials from the F-35 program office.

Our research has identified a number of best practices that are the basis of effective earned value management and should result in reliable and valid earned value management data that can be used for making informed decisions. These best practices have been collapsed into three high level characteristics of a reliable earned value management system:

- **Establish a comprehensive EVM system.** If the EVM data are to be used to manage a program, the contractor's (and subcontractors') EVM system should be certified to ensure that it complies with the agency's implementation of the American National Standards Institute guidelines. In addition to a certified system, an integrated baseline review must be conducted to ensure that the performance measurement baseline accurately captures all of the work to be accomplished.[3] To develop the performance measurement baseline, an integrated network schedule should be developed and maintained. This schedule should reflect the program's work breakdown structure, clearly show the logical sequencing of activities, and identify the

[1]The Integrated Program Management Report contains data for measuring contractors' cost and schedule performance on Department of Defense acquisition contracts. The Integrated Program Management Report is the primary means of communicating program cost and schedule information between the prime contractor and the government.

[2]GAO, *Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs,* GAO-20-195G (Washington, D.C.: March 2020).

[3]A performance measurement baseline is used in EVM to detect deviations from the plan and to give insight into problems and potential effects.

resources necessary to complete the activities to develop the time-phased budget baseline.[4] Lastly, there should be a rigorous EVM system surveillance program in place. Effective surveillance ensures that the contractor is following its own corporate processes and procedures and confirms that the contractor's processes and procedures continue to satisfy the guidelines.

- **Ensure that the data resulting from the EVM system are reliable.** To ensure the data are reliable, it is important to make sure that the data make sense and do not contain anomalies that would make them invalid. If errors are not detected, then the data will be inaccurate, resulting in bad decision-making. In addition to checking for data anomalies, the integrated program management report data between the different formats should be consistent. Reliable EVM data are important to generate estimates at completion. Managers should rely on EVM data to generate estimates at completion at least monthly. Estimates-at-complete are derived from the cost of work completed along with an estimate of what it will cost to complete all unaccomplished work.
- **Ensure that the program management team is using earned value data for decision-making purposes.** For EVM data to be useful they must be reviewed regularly. Cost and schedule deviations from the baseline plan give management at all levels information about where corrective actions are needed to bring the program back on track or to update completion dates and estimates at completion. Management should focus on corrective actions and identify ways to manage cost, schedule, and technical scope to meet program objectives. Management also needs to ensure that the performance measurement baseline is updated accordingly as changes occur. Because changes are normal, the American National Standards Institute guidelines allow for incorporating changes to the performance measurement baseline. However, it is imperative that changes be incorporated into the EVM system as soon as possible to maintain the validity of the performance measurement baseline.

EVM data are considered reliable if the overall assessment ratings for each of the three characteristics are substantially or fully met. If any of the

[4]The time-phased budget baseline, against which performance is measured, is formed from the performance measurement baseline, which is essentially the resource consumption plan for the program. Deviations from the baseline identify areas where management should focus attention. A performance measurement baseline represents the cumulative value of a program's planned work over time. It takes into account the program activities that occur in a sequenced order, based on finite resources, with budgets representing those resources spread over time.

characteristics are not met, minimally met, or partially met, then the EVM data cannot be considered reliable.

After reviewing documentation the F-35 program office agency submitted for EVM, conducting interviews, and reviewing relevant sources, we determined that F-35 EVM data "partially met" one and "substantially met" two of the three characteristics of a reliable earned value management system, as shown in table 4.[5]

Table 4: Results of GAO's Assessment of F-35 Earned Value Management (EVM) Data against Best Practices

EVM characteristics	Overall assessment	EVM best practice	Best practice assessment
Comprehensive: Establish a comprehensive EVM system	Substantially met[a]	The program has a certified EVM system.	**Fully met.** The Defense Contract Management Agency Cost & Pricing Regional Command determined that the EVM system is acceptable in accordance with the terms and conditions of Defense Federal Acquisition Regulation Supplement 252.234-7002.
		An Integrated Baseline Review verified that the baseline budget and schedule captured the entire scope of work, risks were understood, and available and planned resources were adequate.	**Partially met.** The Integrated Baseline Review was conducted in November 2019. However, the Integrated Baseline Review out brief listed numerous concerns including a lack of holistic Block 4 program-level perspective. In addition, we were able to match some but not all names of the capabilities in Decision Memorandum 90—the Department of Defense (DOD)-approved list of Block 4 capabilities—to elements in the contract shown in the May 2022 Integrated Program Management Report. Further, even though the program office provided a list of capabilities awarded on the Phase 2.3 contract, we were unable to trace all of the capabilities through the Integrated Program Management Report. If the performance measurement baseline is not validated through an Integrated Baseline Review, there will be less confidence in the accuracy and soundness of EVM reporting.
		The schedule reflects the work breakdown structure, the logical sequencing of activities, and the necessary resources.	**Partially met.** The schedule includes numerous soft constraints and has high convergence and long durations. An excess number of parallel relationships can indicate an overly aggressive or unrealistic schedule. The schedule tracks contractor resources as hours; however, we found many tasks do not have resources assigned. If the current schedule does not allow insight into the current or projected allocation of resources, then the risk of the program's schedule slipping is significantly increased.

[5]Not Met – The F-35 program provided no evidence that satisfies any of the criterion, Minimally Met – The F-35 program provided evidence that satisfies a small portion of the criterion, Partially Met – The F-35 program provided evidence that satisfies about half of the criterion, Substantially Met – The F-35 program provided evidence that satisfies a large portion of the criterion, and Met – The F-35 program provided complete evidence that satisfies the entire criterion.

EVM characteristics	Overall assessment	EVM best practice	Best practice assessment
		EVM system surveillance is being performed.	**Fully met.** The Defense Contract Management Agency is engaged in program oversight. The program office indicated that it is also active in oversight and provided Defense Contract Management Agency with reports, including the validation steps used to monitor the program.
Accurate: Ensure that the data resulting from the EVM system are reliable	Partially met	EVM system data do not contain any anomalies.	**Partially met.** While there are explanations for some anomalies[b] and the program office reviews the data for these, we found numerous anomalies in every report that we reviewed. If the contract performance report data contain anomalies, the performance measurement data may be inaccurate.
		EVM system data are consistent among various reporting formats.	**Substantially met.** The data are consistent across formats for recent reports, but there were inconsistencies in past reports that we reviewed.
		Estimates-at-complete (EAC) are realistic.	**Partially met.** As part of our assessment, we developed a range of EACs based on the data provided. The contractor EAC[c] is at the low end of the realistic range. Further, staffing challenges create risks of further EAC growth. According to GAO's *Cost Estimating and Assessment Guide*, unless a contractor's EAC is compared with independent estimates, completion, and trend data, management may lack insight into its reasonableness. In addition, requests for additional funds, if necessary, may lack credibility.
Informative: Ensure that the program management team is using earned value data for decision-making purposes	Substantially met	EVM system data are reviewed on a regular basis.	**Fully met.** The program office submitted three monthly analyses of current and cumulative performance that reference earlier monthly reviews as well as the latest performance. The May 2022 report suggests a deterioration in performance and concludes with the need to continue monitoring the contractor's estimate for realism.
		Management uses EVM system data to develop corrective action plans.	**Partially met.** Program management relies on analysis of delinquent tasks to anticipate future delays. However, the analysis does not consider how to address them. Unless management knows the reasons for variances, they may not be able to make informed decisions about the best course of action.
		The performance measurement baseline (PMB) is updated to reflect changes.	**Partially Met.** The PMB is updated to reflect changes. The program has a baseline control process that provides a disciplined control process to preserve the integrity of the PMB. However, we found that large increases to the PMB and frequent baseline plan changes make the data difficult to interpret. Unless EVM is implemented at the program level, rather than solely at the contract level, the program may not have an effective means to measure how well the government and its contractors are meeting a program's approved cost, schedule, and performance goals.

Source: GAO analysis of DOD documentation. | GAO-23-106047

[a]Not Met – The F-35 program provided no evidence that satisfies any of the criterion, Minimally Met – The F-35 program provided evidence that satisfies a small portion of the criterion, Partially Met – The F-35 program provided evidence that satisfies about half of the criterion, Substantially Met – The F-35 program provided evidence that satisfies a large portion of the criterion, and Met – The F-35 program provided complete evidence that satisfies the entire criterion.

[b]Data anomalies are potential data errors that, if not detected, can skew the data, resulting in erroneous metrics and poor decision-making. Examples of data anomalies include negative values, large month-to-month swings in the data, missing data, mismatches between planned and actuals, and data inconsistencies, such as data to date exceeding at completion values. If the contract performance reports data contain anomalies, the performance measurement data may be inaccurate.

[c]Estimate-at-complete is the latest revised estimate of cost at completion including estimated overruns and underruns for all authorized work. It is calculated by adding the forecasted cost of work remaining (budgeted cost for work remaining) to actual costs using an appropriate forecasting method. Contractors are typically required to provide three EACs—a best case, a worst case, and a most likely case.

Appendix IV: Objectives, Scope, and Methodology

This report fulfills four mandates:

- The National Defense Authorization Act (NDAA) for Fiscal Year 2015 included a provision for GAO to review the F-35 acquisition program annually until the program reaches full-rate production. This is the eighth report under that provision.
- The NDAA for Fiscal Year 2017 included a provision for GAO to assess the Department of Defense's (DOD) report on the initial operational test and evaluation of the F-35 program; and a comparison test and evaluation that examines the capabilities for the F-35A and A-10C aircraft in conducting certain missions.
- The NDAA for Fiscal Year 2020 includes a provision for GAO to submit a report on the F-35 program's production and Block 4 progress within 30 days of the President's budget submission for fiscal years 2021 through 2024. This is the fourth report under that provision.
- The James M. Inhofe NDAA for Fiscal Year 2023 included a provision that we conduct an audit of the efforts of the DOD to modernize the propulsion, power, and thermal management systems of the F-35 aircraft.

In this report, we (1) describe any remaining risks with completing the original development program, including production and manufacturing risks, as it progresses towards full-rate production; (2) assess DOD's progress in developing, testing, and delivering modernization capabilities and risks that remain; and (3) evaluate DOD's plans and assessment of the options for modernizing the F-35 engine and thermal management system.

To identify any remaining risks with the original development program as it progresses towards full-rate production, we reviewed the costs, schedule, and performance plans and compared progress in certain areas with the goals established in its 2012 baseline to identify any significant trends. We reviewed test schedules and program briefings to assess progress on test events completed and those that remain. We conducted interviews with DOD test authorities and pilots at Edwards Air Force Base. We spoke with officials from the program office, the office of the Director of Operational Test and Evaluation (DOT&E), the officials responsible for developing the Joint Simulation Environment and other testing officials at Naval Air Station Patuxent River, Lockheed Martin (the prime airframe contractor), and Pratt & Whitney (the prime engine contractor) to discuss key aspects of operational testing progress. For

example, we discussed flight testing results, future test plans, and progress of Joint Simulation Environment development and testing.

To identify potential production and manufacturing risks in the original development program, we obtained and analyzed the production metrics from the program office, Lockheed Martin, Pratt & Whitney, and the Defense Contract Management Agency on aircraft and engine delivery rates from 2017 through 2022 and discussed reasons for any delivery delays and plans for improvements. We also obtained documentation from DOD and the contractors regarding completed airframe and engine delivery schedule. We analyzed these data to determine how many airframes and engines the contractors delivered per year as well as how many deliveries were late. Further, we analyzed DOD's production schedule to determine how, if at all, DOD modified its production schedule. We discussed steps taken to improve manufacturing quality and on-time deliveries with Lockheed Martin and Pratt & Whitney contractor representatives.

To identify new F-35 technical risks, progress in addressing previously identified technical risk, and progress in resolving deficiencies, we interviewed the same officials mentioned above and discussed progress since April 2022. We reviewed program and contractor information on deficiency reports, mitigations, resolutions, and the deficiency resolution process. We obtained reliability and maintainability metrics from the program office and corroborated those with the same metrics that we requested from Lockheed Martin. We obtained the most recent data available within our time frame for conducting the assessment. We compared reliability and maintainability metrics with those we reported in our April 2022 report to assess progress made in achieving those goals. We met with officials to discuss any outliers in the data and any other circumstances that would contribute to a particular metric rising or falling since we last reported on these data.

To assess DOD's report on the initial operational test and evaluation of the F-35 program as well as a comparison test and evaluation that examines the capabilities for the F-35A and A-10C aircraft in conducting certain missions, we reviewed the classified DOT&E comparison testing report and recommendations to the Air Force. We met with DOT&E to discuss additional details of how it conducted the testing, to learn about DOT&E's findings, and to better understand its recommendations. The Air Force did not submit to Congress a plan for addressing deficiencies and corrective actions identified in the DOT&E report and short- and long-term strategies for preserving the Air Force's capability to conduct the close air support, combat search and rescue, and airborne forward air controller

missions. Consequently, we could not address that part of the mandate. We met with Air Force officials to discuss their perspectives on DOT&E's recommendations, to understand the extent to which they are addressing those recommendations, and to understand the reasons why they did not submit a report to Congress.

To assess DOD's progress in developing, testing, and delivering modernization capabilities as well as remaining risks, we reviewed program documentation, including cost and schedule estimates for Block 4 capability development and testing. Specifically, we compared DOD F-35 Block 4 development cost estimates from June 2021 and August 2021 to identify cost increases. We reviewed Block 4 reports to Congress from 2018 through 2022 and program cost estimates from those same time periods to analyze how the program reported the cost of individual Block 4 capabilities changing over time compared with their original baseline estimates.[1] We evaluated the extent to which this cost reporting aligns with GAO cost estimating best practices. We also reviewed program documentation to analyze how the capabilities involved in Block 4 have evolved since 2018 and how the program expects to continue F-35 modernization in the future. See appendix III for a summary of the methodology and findings of our assessment of the F-35 program's earned value management data and practices compared with best practices.

We interviewed officials within the program office, DOD test authorities at Edwards Air Force Base, Defense Contract Management Agency officials who oversee the airframe contractor, and Lockheed Martin contractor representatives to discuss the Block 4 software development process and schedule. Specifically, we discussed the progress of Technology Refresh 3 development and testing, preparations to incorporate Technology Refresh 3 into the production line, the process for identifying and resolving defects associated with Block 4 software, the progress of Block 4 capability testing and delivery, and the intended changes to the upcoming Block 4 contract. We also spoke with test pilots and DOT&E officials about Block 4 testing and changes to the development time frames.

To evaluate DOD's plans and assessment of the options for modernizing the F-35 engine and thermal management system we reviewed program office, Air Force, and Navy reports on engine modernization. We spoke

[1]The F-35 program office provides this annual report to Congress in response to the Block 4 Modernization annual reporting requirement. National Defense Authorization Act for Fiscal Year 2017, Pub. L. No. 114-328, § 224(d)(2017).

with program officials about their process for conducting the assessment, which they refer to as a Business Case Analysis. Because we found the analysis (1) did not meet GAO's definition of a business case analysis, (2) did not follow specific DOD guidance, and (3) the program did not complete an analysis of alternatives, we compared the analysis with general acquisition leading practices such as those from GAO's *Cost Estimating and Assessment Guide* and *Technology Readiness Assessment Guide*.[2]

At the time of this review, DOD had not completed all components of its modernization evaluation, such as its finalized independent cost estimate. Instead, we assessed detailed briefings on the contents and outcome of DOD's comparative analysis of engine and thermal management modernization options. We met with program officials to ask detailed clarifying questions about the summary documents and to gain an understanding of the variables considered, how they arrived at their findings, the outcomes, and the work that remains. Some details of the comparative analysis were considered sensitive or proprietary, like cost or the extent to which cooling and power capacity is increased, because the program had not made source selection decisions for engine and thermal management modernization in time for our review. Therefore, we could not report on those elements. Furthermore, we did not report on some aspects of the mandate because not all information was available at the time of our review. Specifically, we could not report on the outcomes of DOD's independent cost estimate for each option or the extent to which partner nations would be affected by the various modernization options because DOD had not yet assessed those. In addition, the cost data at the time of our review did not provide a breakdown by variant and DOD did not report on costs for spare parts.

We determined that all the data we used were sufficiently reliable for the purposes of responding to our reporting objectives. For example, we collected and analyzed the program's production data for all production lots and corroborated these metrics by interviewing contractor representatives and DOD oversight offices, such as the Defense Contract Management Agency. In addition, we reviewed official F-35 program documentation and corroborated it through interviews with officials across

[2]GAO, *Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs*, GAO-20-195G (Washington, D.C.: March 2020); and *Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects [Reissued with revisions on Feb. 11, 2020.],* GAO-20-48G (Washington, D.C.: Jan. 7, 2020).

DOD involved in the effort, such as the Director of Operational Test and Evaluation.

We conducted this performance audit from May 2022 to May 2023 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Appendix V: Status of F-35 Open Deficiencies

According to program officials as of January 2023, the F-35 program had 821 open deficiencies, which is slightly lower than the 826 we reported in April 2022.[1] Deficiencies represent specific instances where the weapon system either does not meet requirements or where the safety, suitability, or effectiveness of the weapon system could be affected. The test officials categorize deficiencies according to their potential effect on the aircraft's performance.

- Category 1 deficiencies are critical and could jeopardize safety, security, or another requirement.
- Category 2 deficiencies are those that could impede or constrain successful mission accomplishment.

In June 2018, we recommended that the program office resolve all critical deficiencies before making a full-rate production decision, in part, to reduce the potential for additional concurrency costs stemming from continuing to produce aircraft before testing is complete.[2] The Department of Defense (DOD) concurred with our recommendation and stated that the resolution of critical deficiencies identified during testing would be addressed prior to the full-rate production decision.[3]

As of January 2023, of the 821 open deficiencies, the program office characterized five of these as category 1 and 816 as category 2. This represents one more open category 1 deficiency than we reported in April 2022. The program plans to address three of the category 1 deficiencies in 2023. One of these will require flight testing in the spring of 2023, while the other will require further testing expected in the third quarter of 2023. The program has not yet determined a closure timeline for the remaining two category 1 deficiencies because closure depends on requirements documentation and one of the two will also need additional funding. The program office does not plan to resolve all of the category 2 deficiencies because the program office, in consultation with the warfighters and contractors, have determined that they do not need resolution.[4] Figure 12 shows the total number of category 1 and 2 deficiencies that the program

[1]GAO, *F-35 Joint Strike Fighter: Cost Growth and Schedule Delays Continue,* GAO-22-105128 (Washington, D.C.: Apr. 25, 2022).

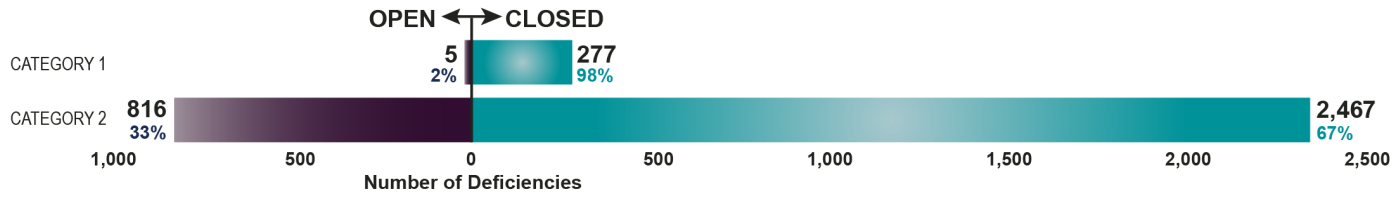
[2]GAO, *F-35 Joint Strike Fighter: Development Is Nearly Complete, but Deficiencies Found in Testing Need to Be Resolved*, GAO-18-321 (Washington, D.C.: June 5, 2018).

[3] GAO-18-321.

[4] GAO-22-105128.

has closed since testing began in December 2006 and the number of deficiencies that remain open as of January 2023.

Figure 12: Progress Made in Closing Deficiencies Identified Since December 2006, as of January 2023



Source: GAO analysis of Department of Defense data. | GAO-23-106047

Appendix VI: Status of Selected F-35 Technical Risks

The F-35 program continues to address technical risks identified in the field. Since our 2022 report, the program office identified new risks with a main fuel throttle valve malfunction and panel cracking, as well as additional risk on issues we previously reported, such as canopy delamination issues**.** The program office also incorporated design changes to mitigate technical risks we previously highlighted. The status of the Department of Defense's (DOD) efforts to address these issues is as follows.

Newly Identified Technical Risks

Fuel tube vibration. The failure of a high-pressure fuel tube occurred on a production aircraft in December 2022 due to a malfunction with the main fuel throttle valve. The program originally discovered this issue in 2020, and the contractor mitigated the issue by identifying and removing problematic valves. However, this mitigation approach has failed on at least one occasion. The program is working to determine a root cause and uncover any broader issues contributing to the vibration.

F-35A gun blast panel cracking. Originally observed on earlier delivered aircraft, some newer aircraft are again experiencing blast skin cracking on the redesigned area next to the F-35A internal gun. This cracking is a result of higher than designed for pressure conditions when firing the gun. The program observed these cracks on Lot 13 aircraft and it expects the issue to affect Lot 14 and Lot 15 aircraft due to similar designs. There is risk that undetected crack growth could result in part of the panel breaking off, with material potentially going into the engine; however, the program has not identified any foreign object debris among the panels that have had issues. The program is managing the risk by post-flight inspections of the panel after gun use and by replacement of cracked panels by contractor field teams.

Technical Risks Identified in GAO's Previous Reports

Electro-Optical Targeting System window durability. The program office identified a problem with window coating durability on the Electro-Optical Targeting System when operating in certain environments—like those with high amounts of sand and dust—at a level beyond requirements for those environments. The program office is using recurring inspections to mitigate the issue. The program is also working with Lockheed Martin to increase its ability to repair the issue in 2023.

Air Separation Module delamination. The Air Separation Module, common to all F-35 variants, is part of the On-Board Inert Gas Generating System, which provides nitrogen enriched air to the fuel tanks. Within the module, a fiber bundle has been separating from the unit's core, affecting the amount of nitrogen being produced, degrading the inerting—changing

gas from a flammable to non-flammable state—of the aircraft fuel tanks. This degradation increases the risk of explosion in the event of a lightning strike. According to program officials, a software fix in 2022 provided a solution for one of the issues related to lightning restrictions and the program office uses air separation module life limits as an additional partial mitigation. The program is in the early planning phase for an air separation module redesign.

Canopy delamination issues. Some F-35 canopies have experienced delamination of the external coating, which affects the pilots' ability to see clearly through the canopy and can reduce mission effectiveness. In 2019, the contractor added a vent hole in the canopy of production aircraft to help prevent delamination, as a temporary modification. According to program officials, the program approved a new cockpit laminate as a permanent fix and is in the process of approving another supplier to produce more canopies.

Rudder hinge pin retention hardware. On an F-35A aircraft, the middle rudder hinge bolt was found to have moved out of place, which could lead to aircraft damage or loss of the rudder surface in flight. The program completed a one-time inspection to address this risk for all F-35 variants. The program is repairing any damaged aircraft. The program identified changes to the bolt locking hardware as a fix for this issue and will incorporate it into production in the third quarter of 2023.

Appendix VII: F-35 Reliability and Maintainability Metrics

The F-35 program is meeting about half of its reliability and maintainability (R&M) metrics. The Joint Strike Fighter Operational Requirements Document, which outlines the requirements Department of Defense and the military services agreed the F-35 should meet, defines all eight R&M metrics. Reliability is the probability that a system will be able to perform a required function under certain conditions, and maintainability is the ability to maintain the system to a specific condition.

Since 2021, the program's R&M performance improved for mean flight hours between removals for the F-35A but declined for mean time to repair for the F-35C, which went from being above metric targets to being below metric targets. The reliability and maintainability goals are aimed at ensuring that an aircraft will be available for operations as opposed to out-of-service for maintenance. The F-35A and F-35C are at or above the goals for mean flight hours between maintenance events. The rest of the metrics stayed the same since August 2021. Although the program is still not meeting 11 of its 24 R&M goals, measurable improvements in these goals can take time to manifest.[1] For example, fielded aircraft must be modified and flown for many hours before the program can measure improvements. Table 5 shows each F-35 variant's performance against these metrics' targets, as of June 2022, the most recent available metrics.

[1]Department of Defense officials stated that, while none of the variants are at or above the current targets established in the Joint Strike Fighter Operational Requirements Document—which outlines the F-35 baseline program requirements the Department of Defense and the military services agreed the F-35 should meet—they do meet some minimum targets approved by the F-35 Joint Executive Steering Board.

Table 5: The F-35 Reliability and Maintainability Metrics' Performance as of June 2022

	Contractually required	F-35A	F-35B	F-35C
Mission reliability—measures the probability of successfully completing a mission of average duration	✓	◓	●	●
Mean flight hours between failure (design controlled)—measures time between failures that are directly attributable to the design of the aircraft and are considered fixable with design changes	✓	●	●	●
Mean time to repair—measures the amount of time it takes a maintainer to repair a failed component or device	✓	◓	◓	○
Maintenance man hours per flight hour—measures the average amount of time spent on scheduled and unscheduled maintenance per flight hour[a]	✓	●	●	●
Mean flight hours between maintenance events—also referred to as the logistics reliability metric, measures time between maintenance, unscheduled inspections, and servicing actions	-	●	●	●
Mean flight hours between removals—measures the time between part removals from the aircraft for replacement from the supply chain	-	●	○	◓
Mean flight hours between critical failure—measures the time between failures that result in the loss of a capability to perform a mission-critical capability	-	○	◓	●
Mean corrective maintenance time for critical failure—measures the amount of time it takes to correct critical failure events	-	○	○	○

Legend

●: Metric is at or above current targets

◓: Metric is at or above minimum targets

○: Metric is below minimum targets

✓: Metric is contractually required

—: not available

Source: GAO analysis of contractor data. | GAO-23-106047

Note: Each metric is measured using a 3-month average and reported on a monthly basis; this table summarizes the Joint Reliability and Maintainability Evaluation Team's review of reliability growth and maintainability improvement data from April 2022 through June 2022.

[a]Maintenance man hours per flight hour is tracked as unscheduled, scheduled, and total. We report the total metric in this table because it is an F-35 Operational Requirements Document requirement.

Appendix VIII: Comments from the Department of Defense

OFFICE OF THE ASSISTANT SECRETARY OF DEFENSE
3600 DEFENSE PENTAGON
WASHINGTON, DC 20301-3600

MAY 0 8 2023

ACQUISITION

Mr. Jon Ludwigson
Director, Contracting and National Security Acquisitions
U.S. Government Accountability Office
441 G Street, N.W.
Washington, DC 20548

Dear Mr. Ludwigson:

The Department has completed a security and accuracy review of Government Accountability Office (GAO) Draft Report "More Actions Needed to Explain Cost Growth and Support Engine Modernization Decisions".

The Department finds that the DRAFT Report is UNCLASSIFIED and cleared for public release, pending the GAO addressing the security and sensitivity concerns provided. Enclosed is a copy of the Department's official security review. Additionally, comments and recommended changes to the content of the Draft report are enclosed.

The Department has enclosed responses to the seven GAO recommendations. The Department concurs with three of the GAO's recommendations, partially concurs with three of the recommendations, and non-concurs on one recommendation.

Sincerely,

Tanya M. Skeen
Performing the Duties of the Assistant Secretary
of Defense for Acquisition

Enclosures:
As stated

GAO DRAFT REPORT DATED APRIL 7, 2023
GAO-23-106047 (GAO CODE 106047)

"F-35 JOINT STRIKE FIGHTER: MORE ACTIONS NEEDED TO EXPLAIN COST GROWTH AND SUPPORT ENGINE MODERNIZATION DECISIONS"

DEPARTMENT OF DEFENSE COMMENTS
TO THE GAO RECOMMENDATION

RECOMMENDATION 1: The GAO recommends that the Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program office reports to Congress on cost differences between original estimates and actual costs for a defined group of modernization capabilities over time.

DoD RESPONSE: Concur. The F-35 program office will evaluate different methods of grouping capabilities to support annual reporting of cost differences between the original estimates and actual costs. The existing F-35 program office process for Annual Cost Estimates will serve as the implementing mechanism.

RECOMMENDATION 2: The GAO recommends that the Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program conducts a Technology Readiness Assessment to evaluate TRLs for all critical technologies and systems for engine and thermal management modernization to inform the military services' modernization decisions.

DoD RESPONSE: Concur. An updated TRL evaluation will be required as an entrance criteria to the Air System Modernization (ASM) Preliminary Design Review (PDR). To successfully close out PDR, the design solution must demonstrate the readiness of the technology to proceed to detailed design in support of a successful Critical Design Review (CDR). As part of CDR, a TRL update will again be required to support conclusion of that design review and will allow for the initiation of assets to be used for qualification, validation and verification. Therefore, TRL assessments are integral to program execution.

RECOMMENDATION 3: The GAO recommends that the Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program matures all critical technologies and systems for engine and thermal management modernization to a TRL 7 prior to starting product development.

DoD RESPONSE: Partially Concur. DoD supports maturation of TRLs to the greatest extent possible within each phase of acquisition for modernization of the engine and thermal management systems. In order to meet warfighting requirements, these specific modernization efforts are pushing the leading edge of cooling technology available for tactical aircraft. Earlier design and product development stages may include some components assessed to have a technology readiness lower than TRL 7. In these instances, the government will utilize risk management processes to ensure that components mature their TRLs throughout development and prior to full rate production of the components.

RECOMMENDATION 4: The GAO recommends that the Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program reports the full lifecycle costs, for each engine and thermal management modernization option, including integration and any necessary related aircraft upgrade costs, to inform the military services' modernization decisions.

DoD RESPONSE: Concur. Lifecycle cost estimates for engine and thermal management modernization options were included in the F-35 program office Air System Modernization Business Case Analysis. These cost estimates will mature as development activities commence, and they will be reported to inform program stakeholder decisions.

RECOMMENDATION 5: The GAO recommends that the Under Secretary of Defense for Acquisition and Sustainment should ensure the F-35 program obtains an independent cost estimate for all engine and thermal management modernization options, including integration and any necessary related aircraft upgrade costs, to inform the military services' modernization decisions.

DoD RESPONSE: Partially Concur. The House Committee on Appropriations Report 117-388 accompanying the Fiscal Year (FY) 2023 Department of Defense (DoD) Appropriations Bill tasked the Director of Cost Assessment and Program Evaluation (CAPE) to conduct an independent cost estimate (ICE) and comparative assessment of all propulsion solutions that were the subject of the F-35 Joint Program Office Business Case Analysis. CAPE analysts have completed this effort and will submit it to the congressional defense committees. The tasking does not include an assessment of thermal management modernization options.

RECOMMENDATION 6: The GAO recommends that the Under Secretary of Defense for Acquisition and Sustainment should ensure the military services set engine and thermal management modernization requirements and then direct the program office to re-evaluate its comparative analysis.

DoD RESPONSE: Non-Concur. Setting military Service requirements is not an USD(A&S) authority. Requirements are developed and approved by the military Services, validated by the Joint Requirements Oversight Council, and coordinated through the governance processes for the cooperative F-35 program. As approved requirements are updated, the F-35 program will perform any necessary re-evaluation of business case analysis to ensure acquisition solutions are best suited to satisfy warfighter performance requirements within cost and schedule constraints.

RECOMMENDATION 7: The GAO recommends that the Under Secretary of Defense for Acquisition and Sustainment should manage F-35 engine and thermal management modernization as a separate program, with its own distinct cost, schedule, and performance baseline.

DoD RESPONSE: Partially Concur. DoD is currently evaluating acquisition strategy options for management of F-35 engine and thermal management modernization, and management of these activities as a separate sub-program is under consideration. DoD plans to provide insight into distinct cost, schedule, and performance data for this modernization effort regardless of the management strategy pursued.

Appendix IX: GAO Contact and Staff Acknowledgments

GAO Contact

Jon Ludwigson, (202) 512-4841 or ludwigsonj@gao.gov

Staff Acknowledgments

In addition to the contact name above, the following staff members made key contributions to this report: Justin Jaynes (Assistant Director), Jillena Stevens (Analyst-in-Charge), Daniel Chandler, Emile Ettedgui, Laura Greifner, Tonya Humiston, William Laing, Jennifer Leotta, Natalie Logan, Christine Pecora, Aaron Rochow, and Alyssa Weir.

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