
F-35A Lightning II test aircraft assigned to 31st Test Evaluation Squadron from Edwards Air Force Base, California, released AIM-120 AMRAAM and AIM-9X missiles at QF-16 targets during live-fire test over range in Gulf of Mexico, June 12, 2018 (U.S. Air Force/Michael Jackson)

# Can the F-35 Lightning II Joint Strike Fighter Avoid the Fate of the F-22 Raptor?

**By Scott Hubinger**

The United States has developed and procured two fifth-generation fighters incorporating stealth or low radar–observable attributes, the F-22 Raptor and the F-35 Lightning II. These two aircraft demonstrate the inherent tradeoffs between single purpose nonjoint aircraft (F-22) and multipurpose joint aircraft intended for multiple U.S. and allied military services (F-35). A review of the F-22 program generates questions and suggests pitfalls that might be common to both programs. For example, why was the F-22 program canceled after only a quarter of the intended number of aircraft had been procured, and does the F-22's fate provide any lessons for the F-35 or identify any risks for program success? Additionally, has the United States made the right choices in our defense industrial base for advanced combat aircraft? Finally, new weapons systems such as the General Atomics MQ-1 Predator and MQ-9 Reaper are highly disruptive in that they represent a new way of waging war

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and were developed and manufactured by a new market entrant. Such disruptive technologies, along with continued technical advances and market changes in semiconductors and robotics, make decades-long design, development, and procurement cycles untenable. The purpose of this article is to highlight and contrast the F-22 and F-35 programs and make recommendations for adapting to rapid technological and market changes. To that end, the article is divided into four sections: the F-22 Raptor; the F-35 Lightning II and joint multinational (F-35) versus single-Service (F-22) acquisition models; semiconductors; and conclusions and recommendations to respond to the issues and concerns raised in sections one, two, and three.

## F-22 Raptor Program

The determination of a requirement for an Advanced Tactical Fighter to replace the Air Force's F-15 Eagle was made by Air Force officials in 1981, and seven aircraft manufacturers were awarded initial concept definition contracts. The seven competitors were reduced to a Lockheed Martin, General Dynamics, and Boeing team and a Northrop and McDonnell Douglas team. The two competing designs emphasized maneuverability (Lockheed's YF-22) and stealth and speed (Northrop's YF-23), respectively, and in 1991, after a competitive fly-off, the Lockheed-led team won the design competition. Creation of formal teams in the design competition allowed the suppliers to share the risk of developing prototype aircraft and specialize in particular aspects of advanced fighter aircraft while also reducing competition. The final design incorporated elements from both design prototypes, with an emphasis on leading-edge stealth, integrated avionics, supercruise (that is, the ability to exceed the speed of sound without using afterburner), and vectored engine thrust (providing improved maneuverability) technologies.[1]

The manufacture of advanced fighter aircraft requires engineering and production expertise and processes not found in civilian aviation with material, avionics, engines, and systems integration technologies that are at the limit of, or beyond, current state of the art. Furthermore, development and acquisition of advanced fighter aircraft are sensitive to changes in technology. In the 1960s, McDonnell Douglas established leadership with its expertise in avionics and guided missiles (for example, the F-4 Phantom II and F-15 Eagle). Similarly, development of innovative stealth technology, first used in the F-117 Nighthawk by Lockheed Martin in the 1980s, shifted leadership to that firm and contributed to its role as prime contractor in both the F-22 and F-35 acquisition programs.[2]

The Air Force planned to procure 790 F-22s. Early post–Cold War cuts reduced this to 648, and by 1997 the Department of Defense (DOD) budget had declined by 38 percent compared to its 1985 budget and procurement had been reduced by two-thirds. This budget tightening put pressure on the F-22 program, but even as late as 2008, the Air Force Chief of Staff publicly stated that at least 381 F-22s were needed to meet operational requirements. Nevertheless, Secretary of Defense Robert Gates announced in 2009 that F-22 production would end at 187.[3] How and why did this happen?

The DOD 1993 Bottom-Up Review (BUR) reduced the Air Force's total fighter strength to 20 fighter wing equivalents and the F-22's production total to just 442 aircraft. The major criticism of the F-22 was that the post–Cold War threat environment did not justify its cost, and the BUR specified DOD's major responsibilities as deterring major regional conflicts, maintaining an overseas presence, conducting small-scale interventions, and preventing attacks involving weapons of mass destruction. None of these major responsibilities included a need to battle superior numbers of advanced Soviet fighters and attack aircraft.[4]

Continuing perturbations caused by technical challenges and funding instability forced the Air Force to restructure the F-22 program in 1993, 1994, 1996, and 1997, and rising costs resulted in the creation of a joint estimating team (JET) in 1996 to estimate the program's future costs and determine ways to control the growth of such costs. The 1998 National Defense Authorization Act used the JET estimate and imposed a $43.4 billion limit on production costs, lowered by Congress in 2009 to $37.6 billion to account for lower than expected inflation. Thus, a requirements-driven procurement process became a budget-driven process and, under this "buy-to-budget" strategy, decreased production numbers would have to fund any additional production costs (that is, in order to stay under the cap).[5] Such a buy-to-budget strategy is colloquially referred to as a "death spiral" in procurement parlance as decreasing unit production numbers lead to increasing per unit production costs, which in turn lead to further cuts in unit production numbers and so on and so forth.

Compounding the budget problems, the F-22 faced political pressures. In 2001, Donald Rumsfeld became Secretary of Defense with a mandate to reform DOD. During Congressional testimony he used the word "transformation" in describing his efforts to prepare the department for the new and different threats of the post–Cold War world and emphasized the need to recapitalize important weapons systems such as the Tomahawk cruise missile, the F-15, the F-18, and the F-16, developed in the 1970s. The Secretary's testimony did not include the Air Force's highest acquisition priority (the F-22). More cost overruns, along with an embarrassing tanker acquisition scandal involving a senior Air Force civilian leader and the Boeing Corporation (Lockheed Martin's manufacturing team partner on the F-22 program), led to Presidential Budget Directive 753, which removed production funding after fiscal year 2008, ending production at 183 units (the Air Force spent the next 5 years trying to overturn this decision but only got 4 additional F-22s).[6]

## F-35 Lightning II Program

The F-35 Lightning II, also known as the Joint Strike Fighter (JSF), is the result of the merger of programs started in the 1980s and early 1990s. During this period, a plethora of programs tried to develop new tactical aircraft for the

F-35A Lightning II pilot assigned to 4th Expeditionary Fighter Squadron dons anti-gravity suit in preparation for first combat sortie in U.S. Air Forces Central Command area of responsibility, Al Dhafra Air Base, United Arab Emirates, April 26, 2019 (U.S. Air Force/Jocelyn A. Ford)

U.S. Air Force, the U.S. Navy, the U.S. Marine Corps, and the United Kingdom's (UK's) Royal Navy. Starting in 1983, the Defense Advanced Research Projects Agency (DARPA) began looking for available technologies for a follow-on supersonic replacement for the Marine AV-8 Harrier advanced short takeoff/vertical landing (ASTOVL) aircraft. This program would eventually become a joint U.S.-UK collaboration. Next, in the late 1980s, Lockheed Martin's Skunk Works became involved in a classified "black" program with the National Aeronautics and Space Administration (NASA), looking into the technical feasibility of a stealthy supersonic fighter (SSF) with short takeoff/vertical landing (STOVL) capability utilizing the Skunk Work's expertise in stealth and NASA facilities and capabilities, including wind tunnels, skilled personnel, and supercomputers. This highly classified program showed that supersonic stealth was possible. The DARPA ASTOVL and NASA/Skunk Works SSF design concepts were originally intended as replacements for the U.S. Marine AV-8B fighter and the UK Harrier II jump-jet. However, when multiple variants capable of meeting other service needs (that is, joint) were suggested in 1993, the two programs were consolidated as the Common Affordable Lightweight Fighter (CALF) program and managed by DARPA due to the experimental nature of the concepts. The goal of the CALF program was to develop the technologies and concepts needed to manufacture ASTOVL aircraft for the U.S. Marines and the Royal Navy and at the same time use those technologies and concepts to develop and manufacture a highly common conventional takeoff and landing (CTOL) variant for the U.S. Air Force.[7]

The U.S. Navy began its Advanced Tactical Aircraft (ATA) program in 1983 to develop a long-range, very-low-observable, high-payload attack aircraft to replace its carrier-based Grumman A-6 Intruder. Dubbed the A-12 Avenger II, this flying wing design was intended as a long-range subsonic aircraft with a large internal weapons load including air-to-surface and air-to-air weapons, but after major cost and schedule overruns and technical problems, the program was canceled in early 1991. During this same time period, the Navy also agreed, after Congressional intervention, to evaluate a version of the Air Force's Advanced Tactical Fighter (now the F-22) under the Naval Advanced Tactical Fighter (NATF) program as a possible replacement for the Navy F-14 Tomcat in return for the Air Force's evaluation of a derivative of the Navy's ATA as a replacement for the Air Force F-111

Aardvark. However, in early 1991, the Navy realized that a series of upgrades to its F-14s could meet air superiority needs through 2015, and consideration of the NATF was dropped. Similarly, in the early 1990s, the Air Force initiated a Multi-Role Fighter program to develop a low-cost replacement for the F-16 Fighting Falcon, with a per unit flyaway cost (that is, including only the cost of production and production tools essential for building a single unit) from $35 million to $50 million. However, the end of the Cold War made the service life situation for the F-16 much less critical, and the program was put on hold in August 1992 and then canceled after the 1993 BUR.[8]

After cancellation of both the ATA and the NATF programs, the Navy Secretary ordered commencement of a new A-6 replacement program. This program, dubbed the A-X program, was designed to develop an advanced, "high-end," carrier-based multimission aircraft with day/night, all-weather capability, low observables, long range, two engines, two crew, and advanced integrated avionics and countermeasures. With the Air Force's participation (it was still seeking a replacement for the F-111), the program became known as the A/F-X program, but it too was canceled by the 1993 BUR, and the A/F-X efforts were directed toward transitioning applicable experience and results to the upcoming Joint Advanced Strike Technology (JAST) program.[9] The goal of the JAST program, which became the JSF program with the merger of the CALF and JAST programs, was to create a common technology platform that would, in theory, gain economies of scale and require simpler logistics due to interchangeable spare parts that could be used to replace three distinctly different aircraft: the F-16 as a multirole light fighter; the F-18 carrier-based, multirole fighter; and the Harrier as a STOVL, with a high degree of commonality among the three different versions. This merging of aircraft types was made possible (rationalized) by the consolidation of the U.S. defense industry after the end of the Cold War; this created larger, more capable companies, but also further limited competition in a market not particularly susceptible to competitive market forces.[10]

***Setting Requirements.*** The F-35 Lightning II is intended (designed) to be a relatively affordable fifth-generation (stealth) strike fighter that can be manufactured in three different versions for the Air Force, the Marines, and the Navy, respectively, with a high degree of commonality (70–90 percent) in their airframes, weapons systems, avionics, powerplants, and software to avoid, in theory, the greater expense of developing, procuring, and operating and sustaining three completely different aircraft designed to meet each Service's similar but different operational requirements. Thus, in November 1996, DOD selected Lockheed Martin and Boeing to compete in the JAST Concept Demonstration phase and issued contracts so each company could independently build and test-fly two aircraft to validate their competing concepts for all three planned variants. Separately, the department also contracted with Pratt and Whitney to provide propulsion hardware and engineering support. In October 2001, DOD selected Lockheed's design as the competition winner, and the Joint Strike Fighter program entered the System Development and Demonstration phase, with contracts to Lockheed Martin for the aircraft and Pratt and Whitney for the powerplant.[11]

The F-35A, developed for the U.S. Air Force, is a CTOL aircraft. As the least technically challenging of the three variants, it is also the least expensive. The F-35As are intended to replace F-16 Fighting Falcons, A-10 Thunderbolt IIs, and perhaps some of the older F-15 Eagles. The F-35A is reported not to be as stealthy or as capable in air-to-air combat as the F-22, but better at air-to-ground combat than the F-22 and stealthier than the F-16. The F-35A is intended as a more affordable complement to the F-22 Raptor, but such affordability will depend on how many units are eventually procured. The F-35B, developed for the U.S. Marines, is a STOVL aircraft and is the most expensive and most technically challenging of the three variants. F-35Bs are intended to replace the AV-8B Harrier STOVL aircraft, the F/A-18A/B/C/D CTOL strike fighters, and the UK Royal Navy Harrier II aircraft. The F-35B's more sophisticated sensor suite and very-low-observable qualities are wanted by the Marines in order to enhance support for U.S. forces. The F-35C, developed for the U.S. Navy, is a carrier-based CTOL aircraft and is midway in cost and technical complexity between the A and B versions. The Navy believes that commonality designed into the F-35 will minimize development, procurement, and operating costs and enhance interoperability both with the U.S. Air Force and with allied partner nations. Finally, the F-35's integrated avionics software is intended and designed to automatically combine information from on-board sensors with information from Aegis and other air defense systems (for example, from other combat aircraft) to enhance combat capability and disruptively change the way U.S. combat aircraft work with each other and with allied aircraft.[12]

***Joint Multinational vs. Single-Service Acquisition Models.*** The F-22 Raptor was designed, developed, manufactured, and procured as a single-Service, single-role fighter. The F-35 Lightning II was designed and developed and is being manufactured and procured as a joint (multi-Service), multirole, multinational combat aircraft. However, this does not alter or eliminate the fundamental challenges, as described earlier, that contributed to the F-22 program's failure to procure the planned quantity of aircraft and, in some respects, makes them worse. One of the reasons for this is that potential savings[13] in overall life cycle costs for a joint acquisition program versus a set of single-Service programs—achieved by cutting out duplicative research, development, test, and evaluation costs and gaining greater economies of scale in manufacturing and sustainment efforts—may be reduced by the need for greater design, manufacturing, and sustainment complexity to accommodate multiple Service requirements in a single "common" design. For example, the original design goal for the F-35 was

KC-135 Stratotanker refuels F-22 Raptor over Nevada Test and Training Range during U.S. Air Force Weapons School's Deliberate Strike Night, June 16, 2016 (U.S. Air Force/Kevin Tanenbaum)

to achieve a commonality of 80 percent, but at milestone B, the three variants varied from 45 percent to 70 percent commonality by airframe weight; by July 2008, airframe commonality ranged from 27 percent to 43 percent.[14] Furthermore, the number of combat aircraft prime contractors in the United States has decreased from eight in the 1980s to only three today (Lockheed Martin, Northrop Grumman, and Boeing), and currently only Lockheed Martin is a prime contractor for the manufacture of an advanced fifth-generation manned combat aircraft. This reduction in the number of prime contractors has reduced competition, may discourage innovation, and makes it more difficult for the U.S. Government to control costs.[15]

Another challenge faced by the F-35 program is the need for the same manufacturer to produce the three different variants. Production of an inhomogeneous product can complicate the acquisition of learning by manufacturing plant workers and managers and speed the depreciation of any learning acquired due to the need to halt production of one product in order to produce a different product. This learning process is particularly important in the manufacture of combat aircraft where highly skilled labor accounts for a large percentage of total costs and accumulated manufacturing experience yields progressively greater reductions in manufacturing costs as experience increases productivity and reduces per unit costs. If the differences among the three different variants were slight, as was originally planned, negative effects on learning might be minor. However, with significant differences, a slower learning process and accelerated depreciation of accumulated production experience significantly adds to program costs and, therefore, program risk.[16]

Finally, an important and significant difference between the F-22 program and the F-35 program is the internationalization of both the F-35's development and its procurement. Currently, the F-35 program has three levels of international partnership. The United Kingdom is the only level 1 international partner, contributing approximately $2 billion toward development costs. Italy and the Netherlands are the only level 2 international partners, contributing approximately $1 billion and $800 million, respectively, toward development costs. Level 3 international partners include Turkey, Canada, Australia, Norway, and Denmark, contributing, among them, approximately $725 million toward development costs.[17] Anticipated purchases of F-35s by U.S. military Services and by our international partners and allies include 1,763 F-35As by the U.S. Air Force; 353 F-35Bs and 67 F-35Cs by the U.S. Marines; 260 F-35Cs by the U.S. Navy; 138 F-35As by the United Kingdom; 100 F-35As by Turkey; 60

F-35As and 30 F-35Bs by Italy; 72 F-35As by Australia; 52 F-35As by Norway; 50 F-35As by Israel; 42 F-35As by Japan; 40 F-35As by the Republic of Korea; 37 F-35As by the Netherlands; 34 F-35As by Belgium; and 27 F-35As by Denmark.[18] However, the cost of all F-35s produced by Lockheed Martin, both for domestic use by U.S. military Services and for use by foreign governments, is negotiated between the U.S. Government and Lockheed Martin, while the price each foreign government pays is negotiated between the U.S. Government and each respective foreign government. The "export" version of the F-35 may also not include all the features of the "domestic" version, thus creating even more variants and further complicating the manufacturing learning process.

Offsets are also negotiated separately between Lockheed Martin and each respective foreign government. While perhaps unprecedented in global scale in the case of the F-35 program, offsets in both defense and nondefense industries are fairly common. An *offset* is an agreement wherein the buyer includes within the contract the condition that the seller has to perform certain activities that benefit the buyer. The agreement can take the form of coproduction, subcontracting, licensed production, technology transfer, and other forms of industrial cooperation such as training.[19] In the case of the F-35, Lockheed Martin is incentivized to offer offsets in return for increased orders from each foreign government and also by the possibility of cheaper production, assembly, or other costs outside the United States. Foreign buyers are incentivized by the possibility of technology transfer to and/or increased jobs for their domestic industries. This complex multiparty matrix of negotiated prices between the U.S. Government and Lockheed Martin, negotiated prices between the U.S. Government and each foreign government, and negotiated offsets between Lockheed Martin and each foreign government makes managing costs even more difficult and may benefit foreign buyers at the expense of the U.S. taxpayer.

***Program Turbulence.*** The JSF program has been restructured three times so far: in December 2003, March 2007, and March 2012. The last restructuring became necessary when, in early 2010, unit cost estimates exceeded critical thresholds set by statute—an event known as a Nunn-McCurdy breach. Pursuant to that statute and to avoid termination of the program, the Secretary of Defense certified to Congress in June 2010 that the program was essential to national security.[20] As required by statute, DOD then revoked the prior milestone approval, established a new acquisition baseline, and began restructuring the program to extend testing and delay delivery schedules, and reduced near-term aircraft procurement quantities by deferring the procurement of aircraft into the future (for example, through 2044), but did not decrease total aircraft procurement numbers. According to the U.S. Government Accountability Office's (GAO's) April 2015 report on the JSF program, the F-35's significant cost, schedule, and performance problems are due, in the GAO's judgment, to decisions made at key program milestones without sufficient product knowledge. Specifically, Lockheed Martin's design was selected in October 2001 before the aircraft's design and critical technologies had been sufficiently developed. In addition, initial program scheduling called for a concurrent acquisition strategy with a high degree of overlap between development, testing, and manufacture, and, although the degree of concurrency has been reduced, it has not been eliminated.[21]

Furthermore, sustainment costs for the three U.S. military Services over the 60-year life cycle for each aircraft are estimated at $1.12 trillion. Thus, DOD is working to implement an affordable sustainment strategy that can meet the needs of U.S. military Services and of our international partners and allies, and that can sustain more than 3,100 F-35 aircraft over the F-35's 100-year development, production, and service life cycle. However, this strategy faces challenges, including reliance on prime contractor Lockheed Martin for sustainment support in addition to product integration and dependence of all F-35 customers, domestic and foreign, on a shared global pool of assets managed by Lockheed Martin that are unique to the F-35 program.[22] Reducing sustainment cost is crucial to avoiding downward pressure on production numbers to pay for increased or unfunded sustainment costs. There are also asymmetries between the different U.S. military Services and our international partners and allies regarding the number of aircraft to be purchased and sustained, which will result in asymmetric dependencies on the success of the F-35 program. Both of these factors could result in significantly fewer aircraft being purchased than currently anticipated and lead to significant unit cost increases as production volumes decrease, as happened with the F-22 Raptor program.

Finally, the F-35's integration of sensors and weapons, both internally and with other aircraft, is believed to be its most important capability, and this enhanced capability to integrate sensors and weapons is achieved, primarily, via complex software.[23] Functionality provided by software has grown significantly since the 1960s. Starting at less than 10 percent with the introduction of the F-4 Phantom II in 1960, this functionality grew to 10 percent with the introduction of the A-7 Corsair II in 1964, to 20 percent with the introduction of the F-111 Aardvark in 1970, to 35 percent with the introduction of the F-15 Eagle in 1975, to 45 percent with the introduction of the F-16 Fighting Falcon in 1982, to 65 percent with the introduction of the B-2 Spirit in 1990, and to 80 percent with the introduction of the F-22 Raptor in 2000.[24] According to an April 2014 review by the Congressional Research Service, writing, validating, debugging, and upgrading the F-35's software (that is, from the Block 1 version providing the aircraft's basic flying capabilities installed in early F-35 deliveries all the way through to Block 3F, which is intended to provide the full suite of warfighting capabilities) will be among the JSF program's greatest and most expensive challenges.[25] In its April 2017 review of the program, the GAO also stressed the importance of software and raised concerns about testing delays and increased costs for the complete development of the F-35's software.[26]

***Current Program Status.*** The F-35 program has made progress. As of September 28, 2018, more than 320 aircraft were operating from 15 bases globally, approximately 680 pilots and 6,100 maintainers had been trained, and the fleet had more than 155,000 cumulative flight hours.[27] Initial operational capability was declared by the U.S. Marines for the F-35B in July 2015 and by the U.S. Air Force for the F-35A in August 2016.[28] Additionally, prime contractor Lockheed Martin has improved manufacturing efficiency and demonstrated learning as it continues producing aircraft. Average labor hours per aircraft delivered have decreased significantly from 2012 to 2017. Total hours for scrap, rework, and repair per aircraft delivered have also decreased. Likewise, Pratt and Whitney has demonstrated improvements in manufacturing efficiency and decreased labor hours. The F-35 program office is also investing in projects to lower production and sustainment costs and is pursuing economic order quantity purchases of components that will be used across multiple procurement lots of aircraft.[29] Thus, for low rate initial production (LRIP) Lot 11, with deliveries scheduled to begin in 2019, the F-35A unit price including aircraft, engine, and fee, will be $89.2 million, a 5.4 percent reduction from the $94.3 million for LRIP Lot 10. The F-35B unit cost will be $115.5 million, a 5.7 percent reduction from the $122.4 million for LRIP Lot 10. The F-35C unit cost will be $107.7 million, an 11.1 percent reduction from the $121.2 million for LRIP Lot 10.[30] Finally, a statistical analysis by the RAND Corporation for Project Air Force has shown that significant cost savings are achievable by making investments in design and manufacturing improvements to reduce the per unit cost and by purchasing F-35 aircraft in multiple lots, to name just two examples.[31]

## Semiconductors

As stated in the introduction, technical advances and market changes in semiconductors and robotics make decades-long design, development, and procurement cycles for advanced weapons systems like the F-35 Lightning II untenable and will require shorter production cycles with or without cost savings. Today, the cost to build a manufacturing facility or fabrication plant (otherwise known as a fab) with leading-edge technology for the manufacture of semiconductors is $10 billion and rising. Because of these costs, companies that cannot produce at scale or afford to operate a fab themselves take advantage of the fabless model, where production is shifted to a global ecosystem of companies creating microchip designs, microchip design tools, components and materials, and operating fabs dedicated to the manufacture of other company designs. Consequently, the global semiconductor manufacturing sector at the leading technology edge has consolidated dramatically, and only four firms globally manufacture at 14 nanometer (nm) or have the potential to go to the 10 and 7 nm nodes: Intel in the United States; Taiwan Semiconductor Manufacturing Company in Taiwan; Abu Dhabi, United Arab Emirates–owned Global Foundries in New York state; and Samsung Electronics in South Korea. Because of this consolidation and the fact that over 98 percent of demand for semiconductors comes from the private and commercial sectors, not the U.S. Government or Defense industry, access to genuine noncounterfeit military computer chips and assured access to manufacturing capabilities for advanced weapons systems is increasingly at risk. Therefore, as noted in a Spring 2016 electronics industry study report published by National Defense University's Eisenhower School for National Security and Resource Strategy, major U.S. weapons systems are exposed to obsolescence in their semiconductor-based electronic and software subsystems.[32]

Furthermore, guaranteed access to leading-edge silicon foundry processes is critical to the Nation's ability to maintain the technological edge and dominance enjoyed by U.S. Armed Forces on the modern battlefield. These processes make possible the development of new capabilities in navigation, sensing, and electronic warfare, just to name a few. In 2014, trusted access to both leading-edge silicon technology and legacy silicon technologies under DOD's Trusted Foundry Program was limited to only a single company, IBM. After 2014, the sale of IBM's semiconductor facilities to Abu Dhabi–owned Global Foundries could have dealt a critical blow to DOD's ability to access technologies at 65 nm and below. The agreement between the Trusted Foundry Program and Global Foundries to form Global Foundries 2 appears to provide current and near-term access down to the 14 nm node. However, the long-term economic viability of this arrangement is questionable in the face of pressures to achieve commercial profitability within the former IBM facilities.[33]

These changes in the semiconductor industry and market are also affecting DOD's F-35 modernization program, termed Block 4, as officials openly state that the F-35's current data processor is operating at maximum capacity and will need to be replaced with an updated processor with increased capacity in order for the first increment of Block 4 to function as intended.[34] Given its low market share (2 percent or less), DOD is entirely dependent on Global Foundries 2 and small volume producers of legacy computer chips for its data processor and other semiconductor needs.

In addition to being at risk of obsolescence in their semiconductor-based electronic and software subsystems, current manned combat aircraft, including the F-35, are also at risk of obsolescence in their technological edge and dominance on the battlefield due to these same trends in semiconductors and the electronic devices that incorporate them. For example, the development and deployment of the General Atomics MQ-1 Predator and MQ-9 Reaper would not have been possible without the greatly increased performance and decreased weight of today's semiconductor-based devices. Unmanned military aircraft such as the Predator and Reaper are also highly disruptive in that they represent a new way of waging war and were developed and manufactured by a new, non–Lockheed Martin market entrant.

U.S. Air Force F-35A Lightning II assigned to 4th Expeditionary Fighter Squadron taxis down flightline before taking off from Al Dhafra Air Base, United Arab Emirates, April 24, 2019 (U.S. Air Force/Chris Drzazgowski)

Further disruptions can be easily anticipated and predicted. For example, a decade ago the idea that drones could act as stationary "air mines" or even act collectively as self-guiding swarms would have seemed as ridiculous and as tactically useless as the barrage balloons and wind-blown fire balloons of the previous century. However, algorithms already exist today for programming drones to "see and avoid," and an ability to see and avoid can just as easily be turned into a see-and-not-avoid ability. Moreover, drone swarming was demonstrated by the Naval Postgraduate School in August 2015, when 50 drones were manually controlled with a single controller. Subsequently, in November 2016, the Intel Corporation created a holiday light show for Disney Springs, Florida, with 300 drones moving in complex choreographed three-dimensional formations, also with just a single controller. Complex choreographed three-dimensional drone formations were also demonstrated at the 2017 Super Bowl halftime show that starred Lady Gaga. Furthermore, any collision between an aircraft and a drone will be much more destructive than a comparable collision with a bird due to the material composition of the drone. In collisions with aircraft, birds behave more like fluids upon impact, such that the disintegration of the bird absorbs much of the impact energy. In contrast, drones are made from metal, plastic, and other relatively nondeformable materials, so any aircraft struck by a drone will be exposed to a much greater impact energy.[35] Lastly, it has been suggested that a tactically autonomous, machine-piloted combat aircraft could bring new and unmatched lethality to air-to-air combat, and by continuously sending telemetry to a ground or airborne control station, the putative autonomous combat aircraft could learn from its own death and in near real time provide adaptations to other autonomous combat aircraft in the fight.[36]

## Conclusions and Recommendations

With a total planned procurement of all F-35 variants on the order of 3,000 units, short-term, small-volume procurements are not advisable once full rate production begins as it disincentivizes Lockheed Martin and its suppliers from making long-term investments in equipment and worker learning that could lead to lower per unit costs. The Defense Department should, therefore, work with the White House and Congress to authorize, but not require, longer term multiyear procurements for major weapons systems like the F-35. The F-35 program office should also continue to expand upon projects aimed at lowering production and sustainment costs and economic order quantity purchases of components that will be used across multiple aircraft types and multiple procurement lots.

In addition, DOD's development and acquisition efforts in the area of combat aircraft are too slow in the face of rapid changes in combat aircraft capabilities, driven largely by advances in semiconductors and the electronic devices and software that utilize them. Therefore, DOD should shift its acquisition focus for combat aircraft to the following:

- sixth-generation weapons systems, assemblies, sub-assemblies, and software for current fifth-generation F-22 and F-35 aircraft using U.S. Government–owned intellectual property and related design authority rights for these aircraft
- drones, which can be used in defensive and/or offensive antiaircraft capacities
- autonomous combat aircraft capable of remotely targeting and destroying enemy aircraft.

The purpose of these three suggested initiatives is to expedite the development and procurement of new innovative weapons and tactics and to provide opportunities for new defense market entrants.

Finally, many reports in the literature, including most recently a comprehensive analysis by the RAND Corporation under Project Air Force, have indicated that savings from joint acquisition of major weapons systems such as the F-35 are at best an open question and are extremely difficult to achieve given the need to meet divergent Service and country requirements within the same design. Instead, the focus should be on common weapons systems, assemblies, subassemblies, and software that can be shared by different platforms and on the very real nonfinancial benefits of joint acquisitions to include greater tactical and operational interoperability between military Services and greater military-industrial cooperation between the United States and its allies. JFQ

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