Vol. 43, June 2023

MITCHELL INSTITUTE
Policy Paper

Key Points

Air Force fighter modernization is essential given that the bulk of the service's fighter fleet consists of A-10Cs, F-15C/Ds, and F-16C/Ds designed in the 1960s and 1970s. They were mainly produced in the 1970s and 1980s, and now they are averaging 41, 38, and 32 years in age, respectively.

The Air Force's fighter inventory is also too small to meet real-world demand today. In 1990, the service had 4,556 fighters. Today, it has 2,176. U.S. national security leaders must concurrently address multiple threats, none of which can be ignored without risking severe consequences. Combatant commander demands routinely exceed the capacity of the Air Force's fighter fleet.

The Air Force needs to buy new fighters at an aggressive rate. Equally important, it needs to procure the right mix of capabilities to ensure the force will remain relevant over the long term.

A major portion of this modernization must be met by robust F-35 acquisition. After significant development and investment, the F-35 is on the cusp of fielding an extensive array of upgrades via TR-3 and Block 4 that range from improved sensors and enhanced electronic attack systems to the added ability to carry a broader weapons portfolio and connect with more actors across the battlespace.

Accelerating 5th Generation Airpower: Bringing Capability and Capacity to the Merge

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Abstract

The Air Force faces a severe fighter aircraft shortfall. The current inventory is both small and old, a significant problem given today's threat environment. The rapid military rise of China and an increasingly aggressive Russia, paired with nuclear threats posed by Iran and North Korea, demand robust military capabilities in an adequate capacity. This includes modern fighter aircraft, which are crucial for the viable projection of joint military power.

The Air Force arrived at this precarious position over decades in which multiple decisions left fighter modernization efforts curtailed and canceled. Aircraft mostly procured in the 1980s Reagan defense buildup saw their lives extended to cover the gap. Now, after four decades of hard use, their service lives are coming to an end. These aircraft are not viable against modern threats, expensive to sustain, and on the verge of structural exhaustion.

The key to reset this is the F-35 and its latest updates: Technology Refresh 3 (TR-3) and Block 4, involving more than 80 individual upgrades added to the aircraft over the next several years. The combination of stealth, sensors, processing power, and connectivity is essential for success in the modern battle space. The F-35's price point of $80M per unit also means it is affordable in volume. The Air Force has long wanted this model of the aircraft, and with TR-3 and Block 4 capabilities now in the final phases of testing, the program is on the verge of crossing a major threshold into the operational realm. This means any dollar obligated from this point forward will be procuring TR-3-enabled Block 4 F-35s.

The modern threat environment and current force structure shortfalls demand the Air Force rapidly modernize its fighter aircraft inventory at scale. F-35s, especially those equipped with TR-3 and Block 4 capabilities, will form a major portion of that capacity.

Introduction

2023 is set to be a major year of accomplishment for the F-35 Lightning II, America's newest fighter plane currently in production. After significant development and investment, the program is on the cusp of fielding an extensive array of upgrades that range from improved sensors and enhanced electronic attack systems to the added ability to carry a broader weapons portfolio and connect with more actors across the battlespace. Combined, these enhancements will see the F-35 better able to project power and get home safely.[1] Manifesting this growth comes down to two key efforts: Technology Refresh 3 (TR-3), which centers upon a new core computer processor, and Block 4, which involves more than 80 individual upgrades that will be added to the aircraft over the next several years.[2] In general, it is accurate to think of TR-3 as the core hardware required to run the Block 4 applications, most of which are software oriented, with a few physical hardware insertions. This means the F-35 is passing a programmed maturity threshold that allows for substantial capability enhancements critical for engaging and countering modern threats. With this goal met, the Air Force can now work to aggressively build the 5th generation fighter inventory required to meet the demands of the nation's defense strategy. This is important, as the service badly needs this capability and capacity.

The Imperative for a More Capable Fighter Force

To understand why the United States needs greater numbers of more modern, capable fighter aircraft, it is important to recognize the unprecedented security threats posed by the rapid military rise of an assertive China and an increasingly aggressive Russia, along with those of nuclear weapons-ambitious Iran and North Korea. While they are not existential threats, non-state aggressors in the Middle East, Africa, and beyond require attention as well. These concurrent security demands—ranging the full spectrum of the threat envelope—place an extremely high load on the U.S. defense establishment. How well the establishment can manage this load is immensely consequential, for, as the 2022 National Security Strategy aptly describes, "We stand now at the inflection point, where the choices we make and the priorities we pursue today will set us on a course that determines our competitive position long into the future."[3]

Choices U.S. leaders make related to airpower will be particularly important in posturing America to address this burgeoning set of challenges. During periods of peace, airpower plays a vital role deterring adversaries and providing assurance to U.S. allies. At war, airpower underpins the ability to conduct decisive joint operations—ranging from strategic strike and air superiority to gathering intelligence and empowering nuclear deterrence. Key to executing these missions is the Air Force's fighter aircraft inventory. While they are best associated with securing air superiority, modern fighters also execute a broad range of roles that include striking both land and maritime targets; denying an adversary use of the electromagnetic spectrum; and intelligence, surveillance, and reconnaissance (ISR). Combined, these missions significantly empower the joint force for success. While the Navy and Marine Corps have combat aircraft, including fighters, theirs cannot provide the volume and range of capabilities afforded by the U.S. Air Force. Nor do Navy and Marine Corps combat aircraft provide the singular focus to joint objectives, as they are primarily purposed to meet their service component objectives.

As important as the service's combat airpower is to ensure U.S. national security interests, the Air Force's fighter inventory faces major challenges due to years of underinvestment. In fact, the U.S. Air Force

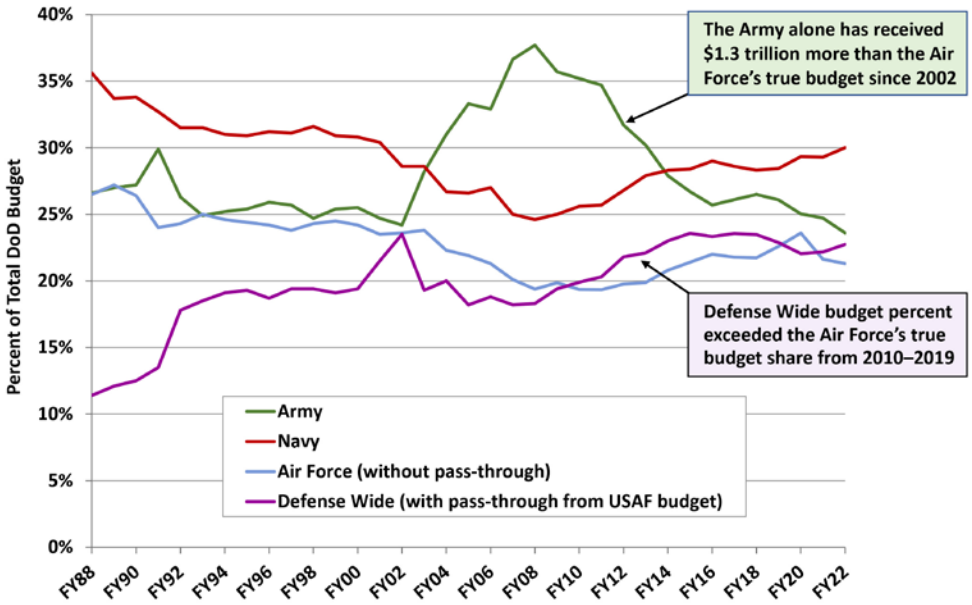

Figure 1: The Air Force's true share (without pass-through) of the defense budget has lagged other services for decades.

Credit: Mitchell Institute figure using data from Office of the Under Secretary of Defense (Comptroller) Greenbook and U.S. Air Force.

has been funded less than the Navy and the Army for over three decades.[4] This fiscal reality comes with a price that can be seen readily on Air Force flight lines. As a result, the Air Force is the oldest, smallest, and least ready in its entire history.

The Air Force now possesses a fighter inventory that is geriatric and on the brink of inadequacy. The bulk of the service's fighter fleet consists of A-10Cs, F-15C/Ds, and F-16C/Ds designed in the 1960s and 1970s. They were mainly produced in the 1970s and 1980s, and now they are averaging 41, 38, and 32 years of age, respectively.[5] "Newer" types, such as the F-15E, a derivative of the F-15C/D, average 30 years old.[6] With each passing year, these aircraft are less available to sustain operations as they become harder to maintain. Time down for repair eats into their availability to fly crucial missions.

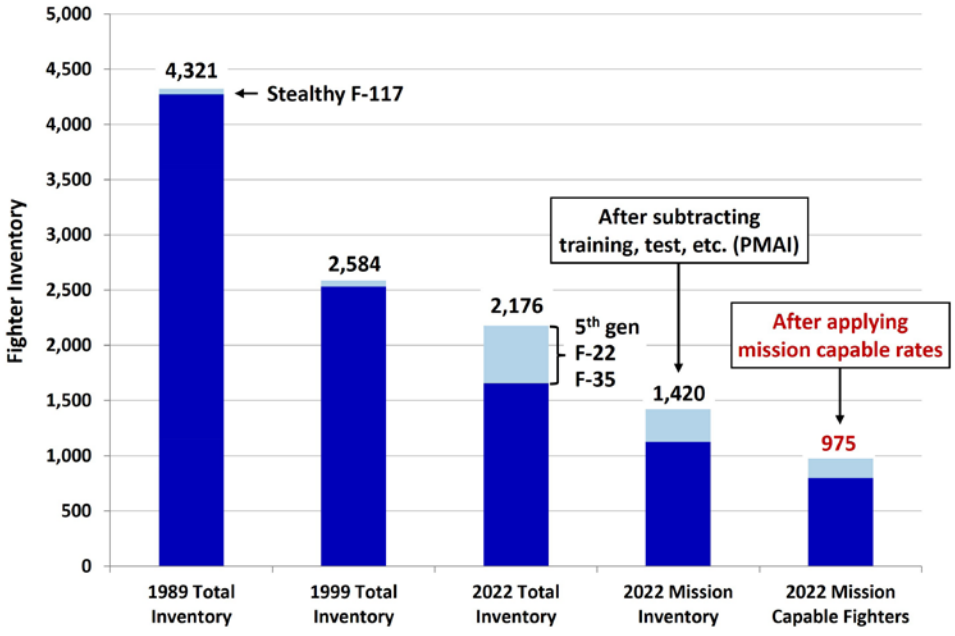

Figure 2: Decline of the Air Force's Fighter Inventory

Credit: Mitchell Institute. Inventory data provided by the U.S. Air Force and mission capable rates from a U.S. Air Force database current as of October 19, 2021. Lockheed Martin provided the mission capable rate for F-35As. Also see John Tirpak, "Fighter Mission Capable Rates Fell in 2021," *Air Force Magazine*, November 22, 2021.

As the aircraft inventory ages, there are only so many modifications and service life extension programs that can be completed to ensure older aircraft can meet modern combat requirements. This is especially true when it comes to survivability. Modern adversary air defense systems are more capable, and older aircraft lack capabilities like stealth that enable them to fight and survive. Simply put, new, clean sheet designs are required to stay ahead of ever-advancing modern threats—a Cold-War combat force is not survivable in the 21st-century battlespace.

The Air Force's fighter inventory is also too small to meet real-world demand today. In 1990, the service had 4,556 fighters.[7] Today, it has 2,176. The Air Force combat fighter force is less than half the size it was 32 years ago. Importantly, this decrease in volume is not matched by a drop in operational demand—quite the contrary, given that the Air Force has been meeting combat requirements non-stop since Desert Storm in 1991. As the number of fighters decreased, the workload assigned to the remaining aircraft increased. They are now physically worn out and must be retired. However, the Air Force has not received the funding necessary to procure a sufficient volume of new fighters that would ensure the outflow of aging aircraft is matched by an inflow of newer replacements in the face of growing threats. In an April 27, 2022, House Armed Services Committee hearing, Representative Rob Wittman (R-VA) and Representative Donald Norcross (D-NJ) both highlighted the Air Force's plan to retire over 600 fighters over the next five years, but only acquire 246.[8] As Representative Wittman remarked, "400 is one heck of a big vulnerability, capacity, and capability gap."[9] Congressional leaders have echoed similar concerns as the 2023 legislative process unfolds and the service continues to seek permission to retire more aircraft than they have money to backfill.

This shortfall was never supposed to happen. The Air Force planned to develop and field a new generation of fighters, the F-22 Raptor and F-35 Lightning II, to replace their aging predecessors. However, circumstances over the past three decades drove down the size of the modern fighter inventory. The original F-22 requirement was for 750 aircraft; it was later reduced to 381, but only 187 were built before the Obama administration and Congress ended production in 2009.[10] Regarding the history of the F-35 program, various factors slowed the aircraft's production rate far below original estimates. To this point, according to original production plans, the Air Force should have had 800 F-35s by 2020, but it ended up with just 272.[11] The net effect of these mainly budget-driven decisions is that the United States now has far less modern fighter capacity than what Air Force planners originally anticipated—and what real-world circumstances demand. In other words, the Air Force is now left trying to make the most of a small, old fighter inventory that is out of balance with modern threats, especially those posed by China.

This situation is compounded by the fact that U.S. national security leaders must concurrently address multiple threats, none of which can be ignored without risking severe consequences. The concurrent demands of the combatant commanders routinely exceed the capacity of the Air Force's fighter fleet. General Kelly highlighted this challenge in a 2022 speech: "It's like a bill that comes to your house … for 60 multirole fighter squadrons."[12] Today, the Air Force falls short of that mark, with just 48 multirole fighter squadrons and nine attack squadrons, the latter of which are equipped with A-10s that are not survivable in highly contested environments.[13]

A Way Forward

The answer to this challenge is clear: the Air Force needs to buy new fighters at an aggressive rate. Equally important, it needs to procure the right mix of capabilities to ensure the force will remain relevant over the long term. Service leaders know they face this challenge, and it's a key reason they released a new fighter modernization plan in 2021, informally termed "4+1," built around the F-35, F-15EX, F-16, and F-22, which will later be replaced by the Next Generation Air Dominance (NGAD) fighter. The "plus one" comes from the retention of the A-10 in the attack role through the rest of the decade. General Kelly explained this vision: "Our fighter force was designed for a Soviet force. We are behind, and our current incremental rate of change is insufficient. … We need to face the realities of a new threat environment, and that requires the fighter force to change."[14]

It is important to note that not all aircraft in this plan are equal, but the plan intends to balance the relative strengths and weaknesses of the various components of this force.[15] The F-15EX can meet homeland defense requirements and carry large volume payloads in forward-deployed regions. However, it lacks stealth, which means it cannot fly too far forward in the threat environment. The F-16 is viewed as an efficient volume capacity filler for the homeland defense mission, plus it can fill in forward roles where the threat is not too high, given that it, too, lacks stealth and other key survivability attributes. The aircraft already exist in the inventory and speak to a specific need at an affordable cost. The F-22 is a vital 5th generation air superiority aircraft designed to fly and fight in extremely contested airspace. It will remain in the inventory until NGAD arrives in the next decade. NGAD is an aircraft that promises to be extremely capable but will not be fielded in large numbers due to anticipated high procurement costs that may reach "multiple hundreds of million dollars" per aircraft.[16] Recent comments by Secretary of the Air Force Frank Kendall suggest the Air Force is targeting an inventory of around 200 NGAD aircraft. This volume would run thin, given high demand across a range of global commitments, growing threats, and vast theaters of operation. That leaves the F-35 at the forefront of the Air Force's fighter modernization strategy.[17] The F-35 is empowered with the right mix of advanced capabilities, including survivability against advanced threats and the ability to empower the information battle space with improved sensors, processing power, and connectivity. It also is priced at around $80 million per unit, which is a competitive price point that allows the mass procurement needed to meet the Air Force's requirement for enhanced capacity.[18]

However, Air Force officials contend that the service's capacity solution is not as simple as procuring F-35s at a faster rate. They want to ensure they are buying high volumes of the most modern version of the aircraft. The program has evolved as part of an orchestrated modernization effort since its first flight in 2006. F-35s built today are far more capable than those that rolled off the production line over a decade ago—*and that is by design*. The Air Force does not want to ramp production aggressively until the next tranche of capability enhancements is available: TR-3 and Block 4. In simplest terms, it is best to think of TR-3 as the hardware infrastructure necessary to host, integrate, and operate capability enhancements collectively known as Block 4. As with any major defense modernization effort, these upgrades have been slower to field than planned. They are also not a single upgrade, but instead a rolling set of capability insertions that will occur over the next several years.[19]

So, the question foremost in the Air Force modernization equation is this: At what point will TR-3 and Block 4 technologies reach a point where the Air Force can boost F-35 production to meet operational demand? The first TR-3 configured F-35 flew on January 6, 2023, with several Block 4 technologies awaiting installation. Current estimates suggest Block 4 software will pass sufficient test milestones in the late 2023 or early 2024 timeframe and be ready to equip on operational jets. This arguably means that the Air Force is now looking at that point where it is time to boost F-35 production. Funds authorized, appropriated, and obligated in the FY 2024 federal budget and beyond will be acquiring TR-3-equipped F-35s and the initial elements of the Block 4 enhancements. This creates the foundation for further planned upgrades. Capability and capacity will now be aligned.

Recognizing the importance of bringing necessary capabilities and capacity to the Air Force fighter inventory as soon as possible, this report recommends the Department of Defense, the Air Force, and Congress execute the following recommendations:

Recommendation 1: Increase the rate of F-35A procurement. The Air Force and combatant commands around the globe require fighter capacity and capability. Boosting the F-35 buy rate is a key part of the solution.

Recommendation 2: Ensure TR-3 and Block 4 efforts remain on schedule. This demands industry partners execute on time and on budget. It also requires DOD and Congress to provide ample, stable, and consistent support. Ample test capacity is also important.

Recommendation 3: Develop and implement a force-sizing construct. It is time to be honest and open about the mismatch between available resources and military requirements. The Air Force needs to develop and implement a force sizing construct that explains the forces it really needs to meet its mission requirements as stipulated by the National Defense Strategy to the Department of Defense, Congress, and the public, not only the forces it can currently afford based on budget.

Recommendation 4: Harness cost-per-effect assessment to build the future fighter force. The best way to develop the most effective, efficient military capabilities demands using "cost-per-effect" analysis to evaluate what it costs to execute various missions using the mix of systems required. Currently, systems are evaluated and bought on a cost-per-unit basis absent operational context.

Recommendation 5: Ensure testing and evaluation does not impede necessary results. While it is imperative that aircraft function reliably and meet necessary performance targets, it is also true that "perfect" is the enemy of "good enough" when it comes to setting the threshold for testing requirements. The Air Force should also consider ways to add more test and evaluation capacity by boosting the number of assigned aircraft and technicians and harnessing live, virtual, and constructive solutions where appropriate.

Recommendation 6: Monitor and steward aerospace industrial base capacity. The Department of Defense needs to carefully consider industrial policy actions that will help ensure capacity elasticity exists in the aerospace production sector. It is crucial to note that the aerospace defense industrial base is currently struggling to meet peacetime objectives. Meeting wartime demand surges would prove impossible unless elasticity can be cultivated within the enterprise.

Recommendation 7: Abandon the "divest to invest" mindset. Additive investment is required. The nation has asked the Air Force to do too much with too little for too long. Additive funding is required in the Air Force budget to meet demand and make up for decades of inadequate Air Force combat aircraft buys that have failed to recapitalize its inventory.

Recommendation 8: Steward human capital as part of the fighter equation. The F-35 will only deliver optimal results if properly crewed. The Air Force currently faces a fighter pilot shortfall of around 1,900 individuals—a gap that has persisted for many years.[20] Similar shortfalls exist within the maintenance community, in part because older aircraft that stay in the inventory past initial projections require more maintenance than newer aircraft.[21] The fighter aircraft enterprise needs more bandwidth to operate in a security environment that is demanding more of it.

Recommendation 9: Empower the total force. The Air Force is presently sized such that there is no operational reserve. While the reserve role is traditionally filled by the Air National Guard and Air Force Reserve, all Air Force active, guard, and reserve units are required to meet our everyday strategy demands. This would be especially true in a time of war as increasing demand would thin these forces further. It is imperative that Air Force modernization efforts are resourced to meet the demands of the Total Force, for the Total Force is what is required to meet the National Defense Strategy.

Recommendation 10: Factor in the allied component. It is time, from an industrial policy perspective, to assess whether the Department of Defense and Congress should invest in additive production capacity. This is particularly relevant for the F-35, with the line presently scaled for the annual production of 156 aircraft.[22] With many countries operating, purchasing, or planning to purchase the aircraft in the coming years, it may be time to grow that cap.

How We Got Here

To understand the current fighter capacity and capability predicament facing the Air Force, it is crucial to understand one thing: this was never supposed to happen. In 1990, at the end of the Cold War, the service had 4,556 fighters.[23] Today, it has less than half that amount at 2,176.[24] This reduction in capacity is matched with a relative decline in capability relative to adversary threats: most U.S. Air Force fighters in service now predate the invention of the worldwide web. This decline can be traced back to the post-Cold War drawdown when defense leadership intended to secure a DOD-wide peace dividend. As former Air Combat Command Commander General Mike Loh, USAF (Ret.) explained, "The collapse of the Soviet Union in 1989 ushered in a whirlwind of actions in the early 1990s to substantially reduce the nation's combat forces. The fighter force size fell victim to this massive drawdown."[25] To give a sense of the scale of these cuts, between FY 1992 and FY 1994, budget cuts drove the Air Force to retire seven fighter wing equivalents, each of which was equipped with 72 aircraft. That was a sum total greater than the Royal Air Force's total fighter inventory at that time.[26] As a RAND report from the era explained, "Within a relatively brief interval, the U.S. Air Force will have discarded close to half of the force structure it maintained."[27]

Leaders were willing to absorb these numerical cuts largely because they believed their fighter force was going to be reset in the late 1990s and 2000s through a recapitalization plan that centered around 5th generation fighter aircraft technology—the combination of stealth, sensors, processing power, connectivity, and superior flight performance.[28] As General Loh explained, "Stealth technology had advanced such that the Air Force saw the benefits of fighter designs with 360 degree radar signature reduction that could nullify the entire radar-based air defense systems of adversaries. Confidence in the operational benefits of stealth, validated by the performance of the F-117s in Desert Storm, during January and February 1991, pushed the Air Force to pursue new fighters, in the form of the F-22 and F-35."[29] In theory, the force could grow smaller if it was going to get better.

The Vision for a 5th Generation Force

Fourth generation types like the F-15 and F-16 comprised the bulk of the Air Force's fighter inventory in the 1990s. Service officials conceived the requirements for them in the 1960s, designed them in the 1970s, and built most of the airframes in the 1970s and 1980s. Their performance attributes were deeply informed by lessons learned from the air war over Vietnam and broader observations regarding Soviet airpower of that era. They were acquired as part of a "high-low mix" acquisition strategy, which recognized the Air Force would never be able to afford the mass volume of its highest performing fighter, the F-15, so sought to augment it in mass with a highly capable, but simpler F-16. This approach was very successful, but Air Force leaders in the post-Cold War era also understood they needed to pursue a new generation of fighter technology because enemy threat systems were continuing to evolve. As 18th Chief of Staff of the Air Force Gen Moseley explained:

> *There's a reason why Air Force Chiefs of Staff, starting with General McPeak and running through me, drew a line in the sand and said fighter modernization had to be 5th gen—no more 4th gen jets. The threats were obviously building. We needed to outpace them. History had taught us this over and over again—buying yesterday's technology kills your airmen and risks the war.*[30]

The quest for enhanced survivability in the face of advanced Russian air defense systems was a long-standing requirement. Going back to results leaders observed in Vietnam, the Air Force lost fifteen B-52 heavy bombers in twelve days to the Soviet-built SA-2 surface-to-air missile (SAM) system during the December 1972 as part of Operation Linebacker II.[31] Less than a year later, Israel lost 102 combat aircraft out of an inventory of 390 in the Yom Kippur War, which lasted less than a month. Of particular concern to U.S. defense officials, 32 of these downed aircraft were F-4 Phantoms and 53 were A-4 Skyhawks, fighters that comprised a significant percentage of the U.S combat aircraft inventory at the time. U.S. commanders applied this loss rate to an assessment of a potential European conflict with the Warsaw Pact and concluded that a similar loss rate would expend the U.S. Air Force's combat aircraft inventory after two weeks.[32] One defense analyst at the time remarked:

> *[This war has] put a big question mark over [NATO's] ability to wage anything but the shortest of conventional wars. Certainly, rates of attrition cannot be expected to be any less high in a war in Europe; and it would be a tragedy not merely for the West but for mankind if NATO, after holding its own tactically, were to be faced with the choice of either surrendering or initiating a nuclear exchange because of insufficient reserves.*[33]

The takeaway from these experiences was clear: the survivability of U.S. combat aircraft needed to increase. While the F-15 and F-16 were tremendous aircraft from a flight performance perspective, they were vulnerable to Soviet-developed air defense systems—all of which grew far more lethal with the passage of time. Air Force leaders understood this and had long been working on a solution. The answer came in the form of stealth technology. The outer mold line shaping, special radar absorbent coatings, and other technologies inherent in stealth aircraft design impeded Soviet air defense

systems from completing their find, fix, track, and target kill chains and achieving a successful intercept. The resulting F-117 stealth fighter and B-2 stealth bomber yielded remarkable results.

This new generation of aircraft displayed its unparalleled combat efficiency on the first night of Operation Desert Storm when, during the same time it took 41 non-stealth aircraft to hit one target, 20 F-117s struck 28 separate targets. Their stealth design gave them the ability to penetrate enemy air defenses without the need to rely on many escort aircraft to provide defensive support. Moreover, precision strike technology allowed the F-117s to hit their targets with great lethality: they only used one or two bombs per target. By comparison, the first non-stealth aircraft attack package required 41 planes for escort, radar jamming, SAM suppression, and counter enemy air operations. Only eight of those aircraft dropped bombs to hit a single target during the same exact timeframe.[34] By the end of Desert Storm, F-117s flew less than 2 percent of the air campaign's combat sorties but struck over 40 percent of the fixed targets.[35]

B-2s netted similarly impressive results on their first combat missions in Operation Allied Force over Kosovo in 1999 and in subsequent employments over the ensuring years.

With the power of stealth and other advanced technologies foremost in their mind, Air Force leaders in the 1990s focused on transforming their fighter inventory around a new high-low fighter mix. This yielded the F-22 and F-35, respectively. The two designs represented a step function in capability increase as multi-role fighters that embraced stealth and sought major capability advancements regarding flight performance, sensor technology, onboard processing power, real-time connectivity with the rest of the force, and the ability to execute a broad range of missions. As

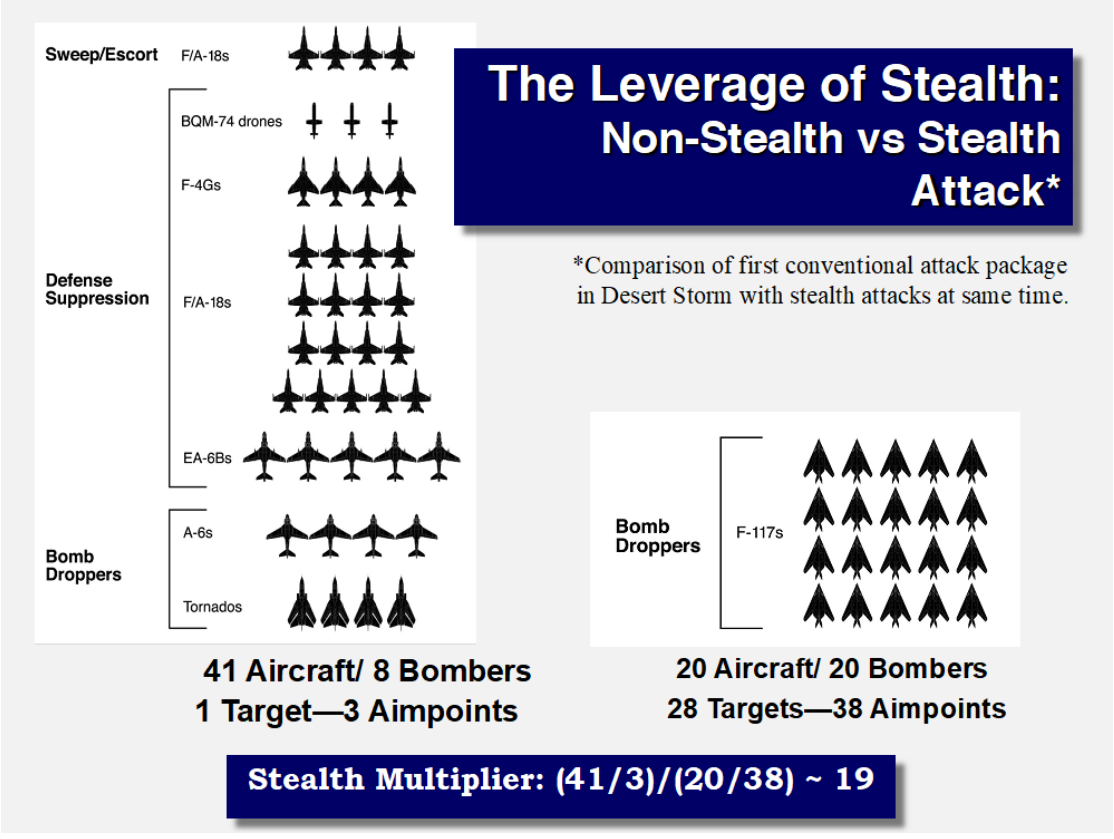

Figure 3: The value of a stealthy Combat Air Force.

Credit: Lt Gen David A. Deptula, USAF (Ret.)

General Loh remarked:

> *The strategy for pursuing both new fighters was to replicate the "High-Low" mix so successful with the F-15 and F-16 strategy of the 1980s. This matched the more capable, but more costly, F-15 with the lower cost F-16 to meet the force capacity requirements within budget constraints. The plan was to procure 750 F-22s complemented with 1,763 F-35s to provide a more capable, stealthy high-low mix in sufficient numbers to be able to handle all projected threats.*[36]

The Enduring Air Force Fighter Challenge

From *The Future Fighter Force Our Nation Requires: Building a Bridge*

"The service now lacks the numbers of combat aircraft required to cover the vast geography and high operational tempo of a complex and multipolar world. For example, there are only five physical squadrons of F-22s in the Air Force; five active-duty units and five associated Guard and Reserve units share the same jets. Additionally, as a rule of thumb, an inventory loses roughly 35 percent of its operational capacity to testing and training and to depot maintenance. That means that of the 186 Raptors available today, only 120 are operationally available. If these remaining aircraft have an 80 percent mission capable rate, then 96 are combat ready. Considering that at least 16 aircraft are required to execute a single lane of continuous air defense patrols, the current force of F-22s could not sustain robust combat operations of any duration, especially when combat losses and battle damage are taken into account. When it comes to facing the more advanced threats and peer adversaries of today at operationally effective concentrations and tempos, the U.S. fighter inventory is woefully outmatched."[135]

A key aspect of the move from 4th to 5th generation technologies is evolving the industrial age of air warfare tactics to information age tactics by using sensors to gather data, process it into actionable information, and team with the broader force. This focus on information dominance was a major advancement over Cold War-era aircraft. In the words of an F-22 pilot:

> *A complete, comprehensive information picture of the adversary threat environment is what we need to best position ourselves to fight and win. Fifth generation's sensors, processing power, and fusion with other assets in the region does that… it helps the pilot identify points of weakness in the adversary system by analyzing it as an integrated ecosystem.*[37]

The desire for enhanced situational awareness goes back to the origins of combat aviation. However, radical information age technological advancements empowered theories on information warfare to become a reality.

The 5th Generation Force that Failed to Materialize

While Air Force leaders were unified about the need for the F-22 and F-35, officials outside the service were less convinced. 750 aircraft was the original requirement for the F-22. The lack of a pressing national security threat, combined with a desire to limit defense spending in the 1990s, saw the requirement reduced to 381 through a series of cuts largely tied to defense planning exercises like the 1989–1990 Base Force assessment, the 1993 Bottom Up Review, and the 1997 Quadrennial Defense Review.[38] In December of 2004, the Office of the Secretary of Defense program budget

decision (PBD) 753 cut significant out-year funding for the F-22 as part of an effort to support combat operations in Afghanistan and Iraq through a major transfer of Air Force and Navy budget resources to the Army. Only 187 F-22s were eventually built, but the official requirement for the aircraft never fell below 381 aircraft.[39]

Gen Moseley explained the danger of this capacity erosion:

> *People need to understand the Air Force's entire airpower modernization plan was premised on buying enough F-22s. Air superiority, that aircraft's core mission, is the bedrock the rest of the enterprise needs to function. We made force composition decisions, individual aircraft attribute calculations, and overarching risk calculations on the assumption that we'd have enough F-22s to keep the rest of the air team safe. When the floor fell out on that buy, we assumed tremendous risk as a nation.*[40]

A final fight over the F-22's ultimate fate occurred during the Obama administration in 2009, when then-Secretary of Defense Robert Gates argued that the advanced 5th generation fighter was not relevant for "the wars we are in today and the scenarios we are likely to face in the years ahead."[41] Circumstances since proved this incorrect, given the rise of China and Russia's aggression, but, nonetheless, the F-22's capacity within the Air Force inventory was capped at less than 25 percent of the original requirement. This was a decision that would portend significant adverse consequences for the Air Force and the national security community, who now face a future threat environment that requires 5th generation technologies to address.

With the F-22 production officially terminated, the Air Force had to develop a new approach to meeting future fighter requirements. First, legacy aircraft types like the F-15 and F-16 were upgraded and their projected service lives extended.[42] Second, the Department of Defense doubled down on the F-35, the F-22's 5th generation complement. As Secretary Gates explained at a July 16, 2009, speech to the Economic Club of Chicago, unambiguously communicating his desire to terminate the F-22:

> *The F-35 is 10 to 15 years newer than the F-22, carries a much larger suite of weapons, and is superior in a number of areas—most importantly, air-to-ground missions such as destroying sophisticated enemy air defenses. It is a versatile aircraft, less than half the total cost of the F-22 and can be produced in quantity with all the advantages produced by economies of scale—some 500 will be bought over the next five years, more than 2,400 over the life of the program. And we already have eight foreign development partners. It has had development problems to be sure, as has every advanced military aircraft ever fielded. But if properly supported, the F-35 will be the backbone of America's tactical aviation fleet for decades to come if—and it is a big if—money is not drained away to spend on other aircraft that our military leadership considers of lower priority or excess to our needs.*[43]

From that point forward, top U.S. leadership welded the future of the fighter mission to the fate of the F-35. This was a path that would not tolerate failure, for there were

no viable alternate paths that would meet the need for capacity and capability required by the future operating environment. This was especially true given the advancing age of the F-15 and F-16 inventories. Lt Gen Donald Hoffman, then-Assistant Secretary of the Air Force for acquisition, and Lt Gen Daniel Darnell on the air staff directly spoke to the challenges the F-22's premature truncation would precipitate when they testified to the Senate Armed Services' Airland Subcommittee in April 2008:

> *Capitalization of our 5th generation fighter force is essential to meet our commitment of securing the national defense. F-35s will not achieve full production rates until 2015, yet we are already retiring F-15s and F-16s and will continue to do so well into the out-years. During this period of retiring aircraft before F-35 full rate production, F-22 production is capped, effectively interrupting our ability for 5th generation recapitalization until the middle of the next decade. By 2025, most of our legacy airframes will be retired. The Air Force position remains that a 2,250-combat aircraft inventory is the required force. However, Airmen realize this will be a difficult challenge based on likely budget availability.*[44]

Their warning was prescient, but it turned out to be an optimistic portrayal of events. Fifteen years later, with the F-35 never hitting planned full production rates, the modernization gap is even wider. General Moseley summarized the situation well when he remarked, "The day the F-22 line closed, all eyes turned to the F-35. It had to deliver, which meant industry, DOD, and Congress were obligated to do everything possible to accelerate its development and buy it in large numbers to make up for where we should have had more F-22 capacity." Moseley further explained, "It was obvious the 4th generation aircraft were on borrowed time—that means combat viability and structural integrity—given their age and high use rate."[45]

Fighter Reductions Have Compounded Risk

While the cuts made to the Air Force's legacy fighter force were the most dramatic in the years immediately following the Cold War, they were not the end of fighter aircraft reductions. The service has routinely pared back the number of fighters in its inventory in a quest to secure budget resources for competing priorities. One of the most famous cuts occurred in 2010, when the Air Force retired around 270 legacy fighters for budgetary purposes. This left remaining aircraft to balance the operational load—demands that saw no proportional reduction. Looking back on this experience, former Air Combat Commander General Herbert "Hawk" Carlisle remarked, "We [thought we had] a brief period where, given the counterterrorism fight and other situations in the world…. we could take risk in the fighter force structure and get to 5th generation. We took that risk, we never got to 5th gen, and by the way, the world changed and is significantly more challenging and demanding than…we thought it was going to be in 2010."[136] There comes a point where doing "more with less" does not work.[137]

A Disappearing Fighter Force Capability

A rapidly sunsetting 4th generation fighter inventory was problematic for past Air Force leaders, but presents even graver challenges now. The service essentially stopped procuring meaningful quantities of fighters in the early 1990s. The newest F-15C/D in the Air Force's inventory was acquired in 1985.[46] A highly concentrated production window during the Reagan-era

The Expense of Sustaining an Aging Force

There comes a point where sustaining an aging force prices out the ability to procure new aircraft. As General Mosely explains:

> *The costs of the aging combat aircraft inventory were becoming obvious in the 2000s. Jets that were designed for a total service life of 3,000 to 5,000 hours were all well past that. Just think of the years of non-stop combat operations they sustained—from 1990 to 2021. We saw those bills come due in time, manpower, money, opportunity cost, and increased inefficiency. I mean an F-16 in the late 1990s was taking nearly a year to get through the depot. That's because we were wearing them out. Those expenses were definitely starting to crowd out money available to buy new airplanes.*[138]

The Congressional Budget Office determined that when it comes to aging aircraft, sustainment costs compound at a real rate between 2.7 percent and 6.8 percent. Given that the Air Force inventory consists of so many aging aircraft, the service is seeing dramatic escalation of operations and maintenance costs. Note that in FY 2022, the Air Force spent $22.87 billion on procurement, of which only $5.96 billion was dedicated to new aircraft. By comparison, the service spent $63.22 billion on operations and maintenance (O&M) during the same period, of which $12.30 billion was directed towards weapons systems sustainment, not including other O&M activities.[139] The burgeoning bill of caring for old aircraft is displacing the ability to buy new ones. According to Lt Gen David Nahom, who recently served as the Air Force's A8, the directorate of Strategic Plans, Programs, Analysis, "about 44 percent of the Air Force inventory is now flying beyond its design service life."[140] Referencing the original design service life of the A-10, F-15, and F-16, over 80 percent of the Air Force inventory is actually flying beyond its design service life.

saw mass quantitites build up over 30 years ago. These aircraft are now nearing the end of their lives all at once.

To understand the scale of this acquisition drop-off, it is useful to consider comments then-Air Force Deputy Chief of Staff for Research, Development, and Acquisition Lieutenant General Robert Russ said at the height of the Reagan build-up in 1984: "To flesh out, modernize, and sustain our goal of a 40 tactical fighter wing force, as well as equip our air defense forces, we need to procure 260–280 aircraft per year."[47] While the actual buys never hit those marks, they did near 200 aircraft per year for multiple years in the 1980s. The problem was that the service acquired very little in the following decades.

The Reagan-era concentrated block of aircraft carried a tremendous load through many years and multiple wars, but hard use took its toll (see Figures 5 & 6).

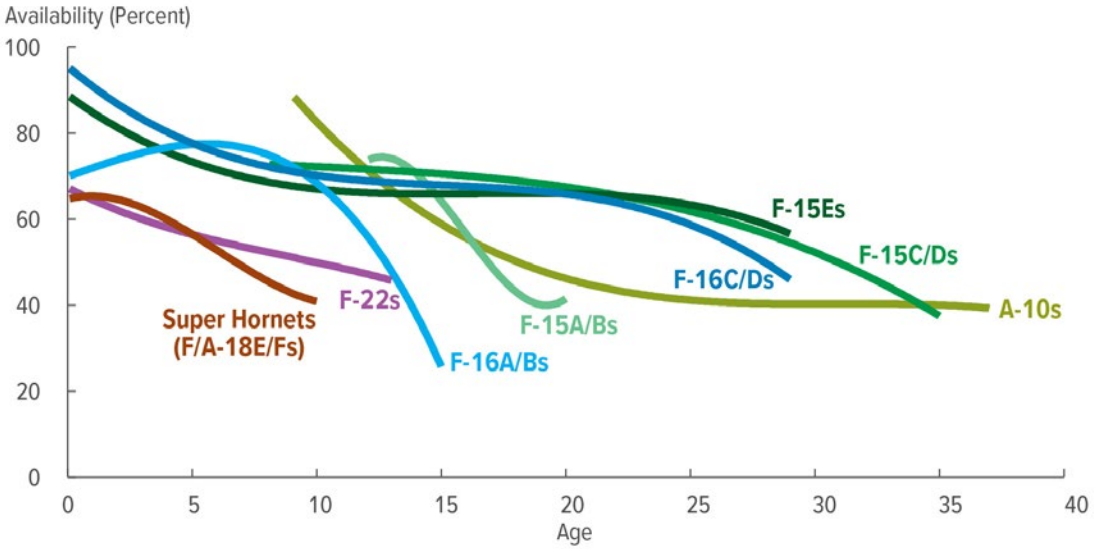

Figure 4: Fighter aircraft availability rates by age. As aircraft age, they cost more to sustain and deliver less capability.

Credit: Congressional Budget Office (CBO), *Availability and Use of the F/A-18E/F Super Hornet Fighter Aircraft* (Washington, DC: CBO, February 2023), p. 6.

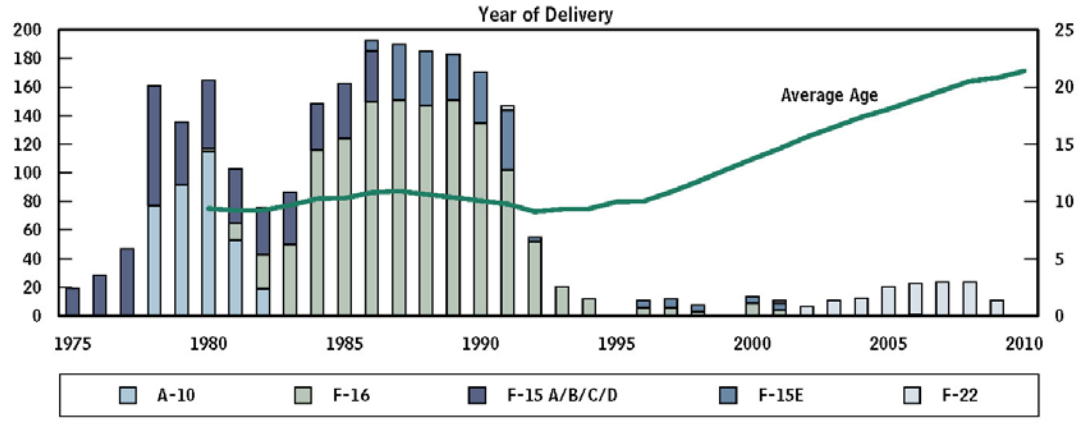

Figure 5: Air Force fighter buys according to the Congressional Budget Office (CBO).

Credit: CBO, *Alternatives for Modernizing U.S. Fighter Forces* (Washington, DC: CBO, 2009), p. 9 Figure 1-2.

As one Air Force officer observed in reviewing these findings, "By 2009, 80 percent of the fleet's aircraft had used more than 50 percent of their originally planned service life. Clearly, the Air Force's fighter fleet is wearing out."[48] In 2023, over a decade later, circumstances are more dire, as aircraft consumed service life absent sufficient new buys to replace worn out airframes. As General Kelly explains, "We literally ate the muscle tissue of the Air Force in the form of reduced fighter capacity, reduced readiness, putting hard miles on older aircraft, driving more extensive sustainment efforts."[49]

Aircraft are structurally designed to endure a specific number of hours. Past that, their useful life ends due to structural integrity concerns. Fighter aircraft are flown hard every single sortie, with missions that involve high speeds, aggressive maneuvering, and the carriage of significant payloads that all induce stress on the airframe. They also spend most of their lives outside, subject to the weather. These aircraft also sustained non-stop combat use from Operation Desert Storm in 1991 to the present day. At some point, they simply wear out. The last F-15C/D is slated to retire by 2026, and a significant percentage of older F-16s including the Block 25, 30, and 32 series that predominantly populate the Air National Guard face retirement in that same period.

Recapitalize or Continue to Assume Risk

Defense leaders in the new millennium addressed the need for modernization by doubling down on F-35 production plans. From FY 2009 to FY 2010, Secretary Gates planned to boost F-35 acquisition quantities by approximately 160 aircraft in the future

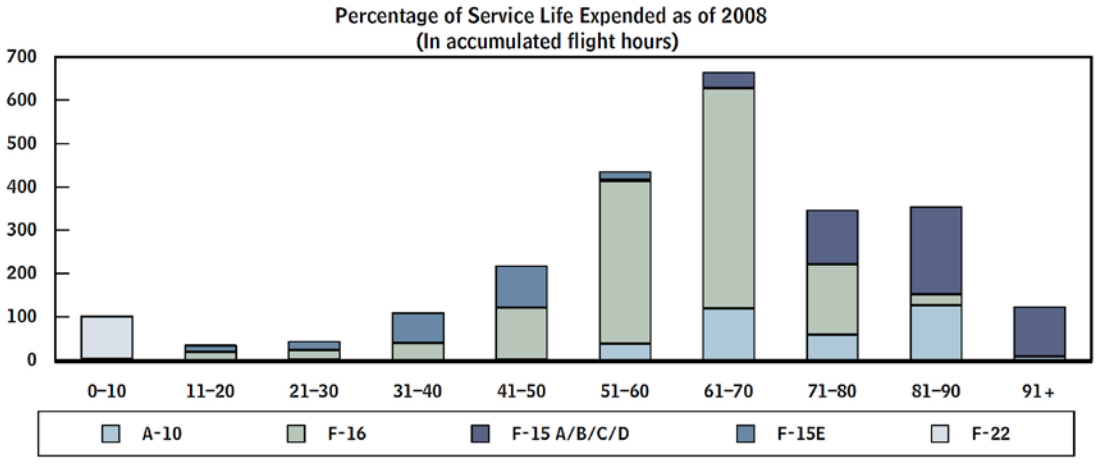

Figure 6: Air Force fighter service life was largely consumed by the later 2000s according to CBO.

Credit: CBO, *Alternatives for Modernizing U.S. Fighter Forces* (Washington, DC: CBO, 2009), p. 9 Figure 1-2.

years' defense plan (FYDP), DOD's five-year budget forecast.[50] This plan projected the Air Force procuring 80 F-35s per year from 2015 through the 2020s, with the final Air Force F-35As procured in 2034. This covered the entire projected buy of 1,763 F-35s, which would have effectively replaced the majority of the Air Force's existing 4th generation fighter aircraft inventory. Secretary Gates alluded to this in his 2009 speech to the Economic Club of Chicago, when he explained "some 500 will be bought over the next five years."[51]

This vision never materialized. Instead of the Air Force having 800 F-35As in its inventory by 2020, it had only 272.[52] The Air Force has never exceeded acquiring more than 60 F-35s per year: the service's official request for FY 2023 was 33, and the FY 2024 request was 48. While this growth is positive, it is too little to meet demand too late. Mitchell Institute analysis shows that achieving even a 20-year refresh cycle for 2,176 fighters would require a steady, annual procurement of 109 fighters. This means that by the end of 20 years, the oldest fighter of the 2,176 would be 20 years old, and the cycle would start over again.[53] The goal is to refresh such that ***no*** fighter is older than 20 years, because that's when sustainability starts to go downhill. This also allows for tech insertion and other upgrades.[54] The current Air Force FY 2024 budget request seeks funding for only 72 fighters, a combination of F-35s and F-15EXs.

Air Force leaders know they face serious challenges. That is why in 2017 then-Secretary of the Air Force Heather Wilson explained, "The stark reality is the United States Air Force is too small to do all that the nations expects of it."[55] Air Combat Commander General Mark Kelly described the effects of these capacity challenges: "Many people envision today's Air Force as the one that went to Desert Storm—a force that featured 134 Fighter Squadrons. The reality is that we only have 56 now, and I can point to comparative force reductions in nearly every other mission area."[56] Of those 56 squadrons, eight are attack units populated by the A-10—a type not survivable in a high-end peer fight. So, when General Kelly seeks 60 multi role fighter squadrons, he is seeking to grow a significant tranche of new capacity. There comes a point where the solution simply comes down to buying more aircraft. The Air Force has been on the precipice of this requirement for too long. Resources are required to meet demand.

Anyone doubting the severity of these circumstances should consider what happened in the fall of 2022, when F-15C/Ds were withdrawn from Kadena Air Force Base, a key operating location in the Pacific, due to a lack of fighter aircraft to directly afford backfill.[57] For a variety of reasons ranging from airframe age that exceeded thirty years per jet to pilot manning problems due to small inventory dynamics, the F-15C/Ds in question had to be retired.[58] Knowing it must bridge this gap, the Air Force is now maintaining a fighter presence in the region by rotating units through Kadena—a solution that further stresses finite aircraft and crews.

The time has come to surge 5th generation Air Force fighter production. General Moseley summarized circumstances well when he remarked, "The threat is incredibly serious, and we are vastly underprepared. You can't skip three decades worth of Air Force modernization and then try and compress everything into a few years. It doesn't work. That said, here we are and so we must do our best."[59]

Understanding the Pacing Threat and the Key Role for 5th Generation Aircraft in Deterring China

The challenges facing the U.S. fighter force coincide with an increasingly dangerous global threat environment. Whether assessing Russia's invasion of Ukraine, the nuclear ambitions of Iran and North Korea,

or continued risks introduced by non-state actors in the Middle East and Africa, the U.S. faces several concurrent threats. 5th generation fighter aircraft are key to reaching our defense objectives across this spectrum.

Leading the list of challenges is an increasingly aggressive China—an opponent that has specifically optimized its military to blunt U.S. forces operating in the Indo-Pacific, with aspirations to extend its power globally.[60] DOD refers to this Asian superpower as a "pacing threat"—the measure against which the U.S. should assess its own military capabilities and capacity. As the 2022 National Security Strategy explains, China "Is the only competitor with both the intent to reshape the international order and, increasingly, the economic, diplomatic, military, and technological power to do it."[61]

The Intelligence Community's 2023 Annual Threat Assessment asserts that China "will continue efforts to achieve President Xi Jinping's vision of making China the preeminent power in East Asia and a major power on the world stage."[62] This includes a stated goal of reintegrating Taiwan into mainland China and the pursuit of unilateral territorial claims across the Indo-Pacific that include the Arunachala Pradesh region on the Sino-Indian border, the Japanese Senkaku islands, and numerous claims throughout the South China Sea. Backing up these claims, China has willingly turned to military force several times already. Allowing this pattern to continue unchecked would effectively cede control of a region that contains more than half the global population and almost two-thirds of the world's economy.[63] This clearly conflicts with U.S. and allied interests.

The roots of China's modern military ascent date back to the U.S. military's decisive Operation Desert Storm victory.[64] As a Defense Intelligence Agency assessment explained, the results of the conflict clearly demonstrated the "lethal effectiveness of information-enabled weapons and forces, particularly mobility and precision-strike capabilities."[65] This saw China invest in a number of technologies to empower an "assassin's mace" military blunting strategy to achieve air and sea denial—the core strengths of U.S. power projection.[66] To achieve this, they traded off PLA end strength in favor of "a leaner, more mobile force."[67] As Liu Huaqinq, Vice Chairman of the Central Military Commission and member of the Politburo

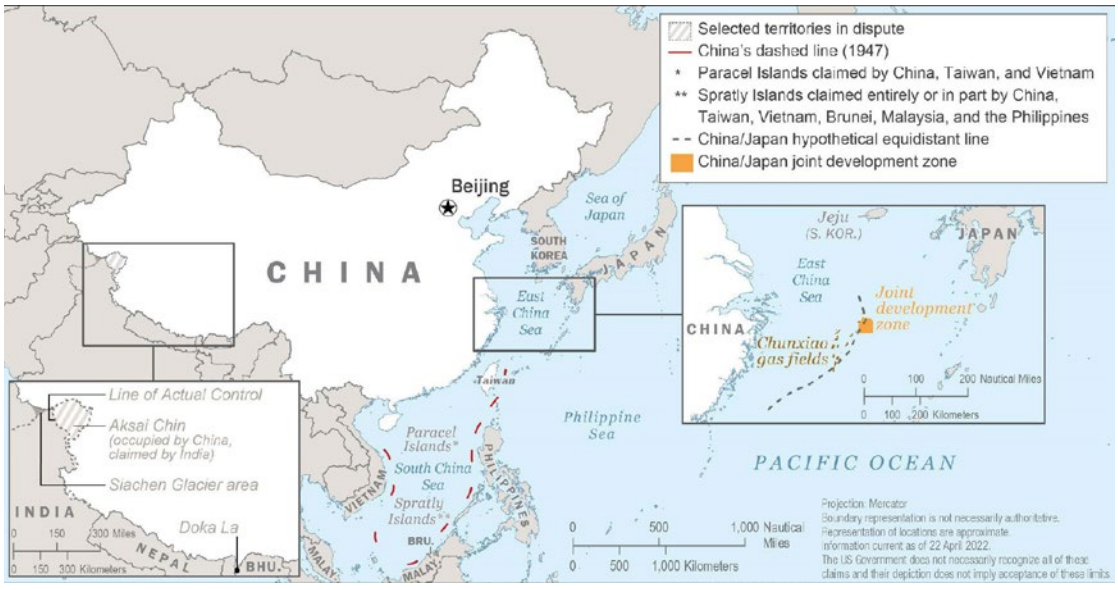

Figure 7: The People's Republic of China's territorial claims.

Credit: Office of the Secretary of Defense (OSD), *Military and Security Developments Involving the People's Republic of China*, Annual Report to Congress (Washington, DC: DOD, 2022), p. 17.

Standing Committee, noted in 1993, "Priority must be given to the strengthening of the Navy and Air Force and to strengthening the building of technical arms. … We must put the modernization of the Navy and Air Force in priority position."[68]

Three decades later, according to DOD's annual report to Congress on China's military strength, the Asian superpower is now approaching its goal of fielding a military designed to "limit U.S. access in the broader Indo-Pacific region."[69] Their capabilities are designed to deny U.S. air and naval forces the ability to operate within the first island chain, while steadily increasing their own ability to project force abroad.

In the 1990s and 2000s, China went to work developing a wide array of long-range precision strike missiles.[70] Types like the DF-21D IRBM and hypersonic YJ-21 currently allow the PLA to credibly threaten U.S. carrier strike groups throughout the first island chain. Land-attack missiles like the DF-26 IRBM similarly enable the PLA to attack U.S. bases as far afield as Guam and Okinawa. This combines to make U.S. maritime force projection exceedingly difficult while simultaneously forcing the disaggregation of U.S. air assets from large regional bases to smaller, more distributed airfields. They also hold surface forces and logistics hubs in the region at risk. Space and cyber capabilities are not immune to the threat, with China specifically developing capabilities to kinetically and non-kinetically degrade these systems as part of a broader effort to deny the U.S. access to important information, especially tied to command-and-control (C2) functions.

Importantly, China has developed robust anti-access integrated air defense systems that make projecting airpower difficult. Kinetic weapon systems such as the Russian-made S-300 and S-400 and indigenous HQ-9 surface-to-air missiles, and Chinese J-20 5th generation fighters equipped with PL-15 air-to-air missiles pose a significant threat to non-stealthy aircraft. Threats also include electronic warfare and cyber capabilities to jam aircraft navigation, communications, target acquisition, and guidance systems.[71] These measures could enable the PLA to degrade U.S. C2 and make it harder for current U.S. and allied forces to close their kill chains.[72]

China has made it doctrinally clear that it increasingly views warfare as "confrontation[s] between opposing operational systems, rather than…war[s] of annihilation between opposing mechanized military forces."[73] Key in realizing this theory of warfare will be a continued emphasis on harnessing big data and artificial intelligence to improve the PLA's own data collection, analysis, and targeting processes, while simultaneously exacerbating U.S. information enterprise vulnerabilities further.[74]

China's modernization efforts thus far pose significant challenges, but it is important to understand they are not complete. Leaders have outlined a goal to reach a fully modernized military by 2027, and a "world class military" by 2049.[75] Combined, the People's Liberation Army Air Force and People's Liberation Army Navy Aviation now represent the "largest aviation force in the Indo-Pacific region." Their collective force capabilities could present insurmountable operational challenges for the United States and its allies in the event of an overt conflict with China.[76] Successful strategies will increasingly rely on advanced aircraft like the F-22, F-35, B-21, NGAD, and other new types empowered with the attributes necessary to survive—stealth, the ability to decipher the battlespace, and the ability to team with other actors. Success against this sort of threat places a premium on securing air superiority over friendly operating locations and key components of the joint force, as well as maintaining the ability to project power in volume against key adversary targets.

Air Force's Current Fighter Modernization Plan 4+1

The Air Force recognizes the importance that both fighter capability and capacity bring to meeting this threat. Air superiority and the ability to project offensive power are key imperatives. The service has responded by outlining a modernization plan informally known as "4+1." Given the fragility of the current fighter inventory, this plan must work. There have been numerous fighter modernization efforts outlined by past Air Force leaders, but for a variety of reasons, most budgetary in nature, they failed to manifest. The net effect is three decades of failed fighter modernization, a growing set of risks, and platitudes about a future solution. As former Air Combat Command Commander General John Corley, USAF (Ret.) remarked, "If it's always about 'program next,' you'll never have a program at all."[77]

Falling back upon fighters bought in the Cold War is no longer viable because most of those aircraft will not extend into the next decade: they are not viable from a threat perspective, relevant from a mission execution perspective, or structurally sound given decades of hard use. The time has come for a fundamental reset. Current ACC leadership concurs, with General Kelly explaining, "Extensive analysis unambiguously shows that the current fighter fleet will not succeed. We must change now to provide the capability, capacity, and affordability required to meet the peer threat."[78]

Discussing fighter modernization is a complex topic because it involves several missions, diversity of applicable threat environments, cost factors, and risk considerations. The Air Force's current plan seeks to balance each one of these elements to yield a set of capabilities and capacity to meet future demands effectively and sustainably. It comes down to building a team of aircraft that can execute the air-to-air mission, air-to-ground attack, close air support, and electronic warfare. The team must also be able to gather and process information and participate as nodes in the joint all domain command and control (JADC2) construct. No longer are these aircraft just "fighters" in the classic sense; they are multi-role sensor-shooters with fighter-like attributes.

At the top end of the 4+1 spectrum, the F-22, replaced by NGAD in the 2030s, will provide air superiority in the highest threat zones of the conflict. Attributes important in this mission include low radar signature through stealth, advanced electronic warfare capabilities, improved sensors and greater processing power to understand the battlespace, better connectivity to afford teaming and data exchange, the ability to project significant offensive power both kinetically and non-kinetically, the flight performance attributes necessary to employ and survive against incredibly advanced threats, and finally sufficient range and payload functionality. This is an incredibly demanding set of requirements that drives high acquisition and sustainment costs. The F-22 has always garnered attention in this regard, but its mission value is unrivaled. That said, money matters.

NGAD will likely face cost-related capacity challenges, with Secretary of the Air Force Frank Kendall suggesting that the aircraft could cost more than $200 million per unit.[79] Initial predictions also suggest an inventory of around only 200 aircraft.[80] That said, it is an essential investment. As Gen Kelly explained:

> *I can tell you what is not happening in China today. They are not debating the importance of the relevance of 6th generation air superiority, and they are deadly serious about it.… The cost of us fielding a 6th generation platform and continuing to be first [in the air superiority contest] is significantly cheaper than being second and losing as a nation.*[81]

The historical record supports this assertion. The United States needs the F-22 now more than ever, and it will need NGAD. In fact, the joint force will not be able to succeed without these fighter aircraft.

Further down the 4+1 spectrum, the Air Force will continue to rely on 4th generation aircraft, both new-build and legacy airframes. The reason for this is simple: capacity for a given fiscal cost. F-15EX, and perhaps F-15Es depending on the scale of the F-15EX buy, will afford enhanced carriage capacity and the ability to haul larger munitions. They would also play a role in the homeland defense mission. F-16s classified as "post-Block," which include Blocks 40/42 and 50/52, would be retained and modernized to provide affordable mass for contingencies where the threat environment would be permissive enough for their effective use. It is important to highlight that 4th generation aircraft, even new-builds like the F-15EX, will lack key survival attributes necessary to send them into zones of the highest, densest threats.[82] While advanced electronic warfare systems will help them better survive against many lower and mid-tier threats, the most challenging environments the U.S. will likely face in a competition with China demand a combination of stealth, high situational awareness, and electronic warfare to stay alive. 4th generation fighter designs can be modified to include the latter two attributes to a degree, but they will never be able to be stealthy. Stealth is an attribute that is inherent to the fundamental design of the aircraft from day one.[83]

This leaves the F-35 as the key player in terms of recapitalizing the combat fighter forces with sufficient mass *and* survivability. As Air Force Chief of Staff General CQ Brown has explained, the F-35 will be "the cornerstone of the fleet."[84] While the imperative for 5th generation fighter aircraft technology was often debated over the past three decades, that is no longer the case. In many ways, it comes down to demonstrated results. As General Kelly explained:

> *The voices of the 5th generation pilots, or those who have flown with 5th gen and had it help clear a path to the target, or those who have flown against it and gotten shot in the face and were not sure where it was coming from—those voices started to spread out, and the believers of 5th gen are growing rapidly.* [85]

These aircraft can penetrate defended airspace at lower risk, understand the battlespace through better sensors and processing power, team with other actors, secure mission tasks both kinetically and non-kinetically, and get home safe.

The F-35 is an advantageously unique player in this regard given its relative affordability with an acquisition price of about $80 million per aircraft. This is actually less than some new-build but analog design 4th generation types.[86] The highly integrated 5th generation aircraft includes the sensors fully built into the aircraft, not as separately costed bolt-on pods needed for legacy types. For this reason alone, F-35 pricing may be more competitive than direct comparisons with 4th generation types suggest. Current government models do not factor these important variables and should be updated to allow for more accurate direct comparisons.[87]

The Air Force rightly points out that F-35 sustainment costs must continue to decline to better match costs seen with 4th generation aircraft.[88] That said, indicators are moving the right way, with F-35's "cost-per-tail-per-year" declining 37 percent from 2015 through 2021, and officials are aiming to net an additional 25 percent reduction by 2026.[89] While that news is promising, it is also important to recognize that

superior technologies and design allow F-35s to secure mission effects that would otherwise take multiple, less capable aircraft to achieve—and at higher risk. In this way, F-35s drive value across many dimensions of the greater warfighting system. Instead of unit or flight hour costs, it becomes more appropriate to consider what it takes to execute missions and secure goals through a cost-per-effect approach.[90] This approach was first formally introduced as an alternative to unit cost as a measure of merit by then-Brig Gen David A. Deptula at the 2001 Congressional hearings on military transformation.[91]

Explaining TR-3 and Block 4

The F-35s currently on the production line are highly capable aircraft, but given evolving mission demands, it is time for a new set of upgrades. As General Moseley explained, "There's no question that the F-35 capability enhancements are crucial. We always counted on them from the early days of the program. The threats continued to advance, so it's all about ensuring we maintain an advantage."[92] Current Air Force leaders are exceedingly focused on these improvements as well, with service officials slowing F-35 procurement in their FY 2022 budget request until TR-3 and Block 4 capabilities are available for aircraft coming off the production line. Most recently, Air Force leaders have paused F-35 production acceptances until Block 4 software completes tests, which should occur by the end 2023 or early 2024. This reflects the frustration the Air Force has with the numerous delays and cost increases these programs incurred in recent years.[93] While the service ultimately expects to update approximately 384 of its existing F-35s with TR-3 and Block 4 capabilities, they seek to limit retrofit expenses by ensuring future aircraft acquired contain the these upgrades.[94] In the words of Secretary of the Air Force Frank Kendall, "The Block 4 capabilities are what we really need for the pacing challenge—for China and their advanced systems. So, we need to get that done."[95]

As with nearly every other successful combat aircraft, the F-35 was designed to be upgraded over time. This process involves the evolution of both hardware and software. The current round of F-35 upgrades, known officially as "capability insertions," are no different. TR-3 generally speaks to the hardware portion of the modernization. It comprises a new integrated core processor (ICP) that is 25 times more powerful than its predecessor and provides an associated memory boost. It is the backbone required to run a series of upgrades known as Block 4, which are generally focused on new software, with a limited number of hardware additions.[96] While it is a simplistic comparison, it is fair to think of TR-3 like acquiring a new smartphone that is powerful enough to run the next round of software updates and use a few new hardware widgets. These upgrades really matter particularly because system performance increasingly depends on software. As a recent DOD report explained, "The F-35 is estimated to rely on software for 90 percent of its avionics specification requirements. This has grown significantly over the last four decades when the F-15A had just 35 percent software reliance in 1975."[97]

Between TR-3 and Block 4, there are approximately 75 specific upgrades that occur as part of this process. Importantly, there is no single goal line for all these deliverables, but instead a rolling set of capability insertions that will happen over the next few years.[98] As the service holds out for TR-3 and Block 4 capable aircraft, what it needs to consider instead is *whether aircraft built can accept the rolling set of capability upgrades in a minimally invasive fashion*. That comes down to ensuring TR-3 hardware insertions

It All Comes Down to Propulsion

While TR-3 and Block 4 afford tremendous capability improvements, they also drive new requirements. It comes down to the need for increased thrust to offset weight gain and the demand for more electrical power and cooling to service new avionics. All of that requires jet engine performance growth as well as a more capable power and thermal management system (PTMS). This is a standard challenge facing combat aircraft as they evolve over time. Consider the F-16: when it entered service, it was powered by the Pratt and Whitney F100 engine, which produced 23,770 pounds of thrust. Current models are powered by a significantly upgraded F100 and the General Electric F110, both of which produce 29,000 lbs of thrust and accommodate far more power and cooling. (See A RAND Note Prepared for the United States Air Force, 1993.) The Department of Defense knows that the F-35 requires a significant propulsion upgrade to keep pace with the aircraft's evolution. While the current Pratt and Whitney F135 is an incredibly capable engine, the origins of the design predate the millennium (given its evolution from the F-22's F119 engine). Current demands are stretching the present engine variant past its design limits, with the Government Accountability Office reporting, "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 answer lies with a new propulsion solution and associated PTMS. As far as the engine is concerned, Pratt and Whitney is offering an enhanced F135, known as the Engine Core Upgrade (ECU), which would be able to serve all three variants through an evolutionary technical path. Another solution also exists through the Adaptive Engine Transition Program (AETP), with both General Electric and Pratt and Whitney involved with their own respective efforts. This latter option pursues the next step in turbine design through a new approach that delivers enhanced thrust, power, and cooling that markedly boosts the aircraft's range and endurance thanks to greater fuel efficiency. This is a concept that has been in development and testing since 2007. The current design would not work for the vertical lift B model, which means regardless of the AETP decision, ECU would still be required for a portion of the F-35 inventory. (See Congressional Research Service, "F-35 Joint Strike Fighter (JSF) Engine Options," December 2, 2022.)

The FY24 budget request failed to include funding for AETP, but Congress is reconsidering the issue. It is an incredibly difficult choice given current fiscal pressures, with Secretary of the Air Force Frank Kendall remarking, "If we had the opportunity to reconsider that, I think that would be something I'd like to have another shot at." Lockheed Martin has made the following statement in relation to this issue: "AETP technologies deliver more power and greater cooling capability, which is required as we modernize the F-35 beyond Block 4." There are also significant implications for the defense industrial base given the outcome of this decision.

are on new-build aircraft coming off the line. The smartphone example is useful; the new device with greater hardware power is the threshold that allows new software packages to run. As everyone with a smartphone or computer understands, loading new software is not a major ordeal. Even with the most recent delays factored in, the program now stands at a point where any dollar budgeted, authorized, appropriated, and obligated for an F-35 will secure a TR-3 and Block 4 capable aircraft. This represents a key milestone for the F-35 program and should give the Air Force confidence in boosting the procurement rate of the aircraft, especially when considering the cost of not boosting production—a drop in capacity.

It is also important to highlight that the upgrades, which are managed by the F-35 Joint Program Office's (JPO) Continuous Capability Development and Delivery (C2D2) effort, will provide the F-35 fleet with a common configuration amongst all three variants, the A, B, and C models. This will avoid the costs associated with maintaining multiple aircraft configurations at operating locations in the United States and around the world. That makes the aircraft more mission-effective *and* cost-effective.[99]

While many of the specific details regarding TR-3 and Block 4 are classified, what is clear is that their combined implementation will give combatant commanders, pilots, and maintainers the

ability to operate with greater lethality and survivability in current and future highly contested environments. They will be especially dominant in the electromagnetic spectrum (EMS). As ACC commander General Mark Kelly emphasized, "Most of what we need the F-35 to do rests on the Block 4 electronic warfare capabilities."[100] The investments China and other adversary nations are making in information-centric combat capabilities are changing the future battlespace in fundamental ways. The F-35's ability to keep pace with the demands of the combat environment and secure desired mission effects is crucial to U.S. forces' survival, much less success. According to one media report, "Lot 16 aircraft arriving in 2024 and 2025 come with a three-times-more powerful electronic warfare (EW) processor. And Lot 17 fighters will be delivered after 2025 bristling with 20 EW receivers, a 75 percent increase, to dramatically boost signal coverage and accuracy."[101]

A significant part of the Block 4 upgrade involves replacing a majority of the F-35's external optical sensors and active/passive radar antenna suites with new robust, low-maintenance, state-of-the-art hardware. Think of these as the "eyes and ears" of the aircraft—the tools by which the pilot and other actors harnessing the data gain situational awareness. These systems and the improved capabilities they provide depend on the increased computational speed of the jet's new processor and its expanded memory, both of which are part of the ongoing TR-3 upgrades. For example, a majority of the new Block 4 hardware upgrades are controlled via the F-35's mission system computer, where the new TR-3 processor hosts artificial intelligence (AI) software that analyzes all incoming and outgoing sensor data and external secure communications. The sheer volume of the data flows in question demand AI to meet processing speed requirements. It then combines or "fuses" the results for presentation to the pilot on the panoramic cockpit display touch screen, with much of this information also displayed virtually on the pilot's helmet visor, which provides significantly improved situational awareness.[102] This unprecedented long-range multi-spectrum view of the electromagnetic environment enables real-time battle management that can be shared with other friendly air or surface entities. Not only does this help pilots employ both their offensive and defensive weapons in accelerated battle-relevant timeframes, but it also enables faster decision-making cycles across the force.

Understanding the War-Wining Boost in Block 4 Technology

Any dollar authorized, appropriated, and obligated for F-35 acquisition today will now buy a TR-3 aircraft with many Block 4 capabilities and the ability to receive future upgrades. These capability insertions are exactly in line with the F-35 program's design, and the resulting capability boost keeps the aircraft and its pilots ahead of the threat. While many enhancements are classified, the following description illustrates how TR-3 and Block 4 vastly increase the F-35's combat power and survivability.

Advanced Radar. The electromagnetic spectrum is arguably going to be the most contested domain in any modern battlespace. Block 4 includes a new active electronically scanned array (AESA) fire control radar called the AN/APG-85 that multiplies the capabilities of the legacy AN/APG-81 it will replace by a factor of two.[103] It is a powerful cornerstone of the F-35's sensor suite. The difference from an operational perspective is comparable to switching from 1990s-era dial-up to 5G internet. This plus-up will provide F-35 pilots with a dominating view of the

electromagnetic battlespace. Additionally, these modern components greatly improve reliability, thereby reducing maintenance and repair demands.[104]

In its air-to-ground role, the AESA radar improves functionality for air, land, and sea tactical operations. During synthetic aperture radar ground mapping operations, it will reduce the pilot's workload to accurately locate and identify stationary or moving surface targets at further ranges. In many ways, it is like a next generation ground moving target indicator (GMTI) at the fingertips of not just a single pilot, but anyone else with connectivity to the F-35. This is a crucial capability for the effective employment of precision weapons.[105]

Air-to-air engagements will similarly see a benefit from the new radar in aiding the pilot's timeline to achieve a first shot targeting solution sooner and further out. This helps fill, in part, the air-to-air mission gap created by drastically truncating F-22 procurement.

Past these applications, the radar's enhanced capability and increased power output substantially increase the F-35's utility for standoff electronic attack. The AN/APG-85 can suppress, defeat, and deny the enemy's use of the broad electromagnetic spectrum. This also enables better targeting of surface or airborne radars at further ranges. Additionally, standoff threat suppression operations will be significantly more effective in the support of a strike package and improve the survivability of terminally guided weapons being employed against high-value surface-to-air (SAM) missile sites.[106] Netting mission effects outside the most dangerous zones of the battlespace is a key to smart operations.

Improved Passive Sensing. Block 4 provides an extensive hardware upgrade of the F-35's ability to passively collect threat radar emissions and cooperatively correlate their identities, locations, and threat range capabilities that are then graphically displayed in real time to the pilot. This is important because passive sensing does not reveal the aircraft's location like an active sensor: a radar beaming out a signal could be detected, tracked, and targeted.[107] Given that the aircraft will have three times greater processing power, the sensitivity of these new receivers will dramatically improve the functionality of the aircraft's mission system computer and empower it to build a more accurate, timely picture of the battlespace for the pilot.

Similarly, six distributed aperture system (DAS) infrared external perimeter cameras, part of the Block 4 upgrades, enable the pilot to have a virtual 360-degree external view around, above, below, and through the aircraft. Additional displays within the helmet assist the pilot in visually acquiring surface or airborne targets for employment of precision guided munitions and air-to-air weapons, or it can warn them of a potential inbound threat. This next generation capability is built around higher-resolution components that deliver far better performance and reliability. These not only feed the mission system's fusion process to aid in target identification and warning of approaching threats, but it also delivers a much-improved day-or-night level of video fidelity to the pilot's panoramic cockpit display screen and helmet-mounted display.

Improved Target Tracking. Target identification and tracking is a critical element for many tactical operations, like searching for mobile targets, identifying friend from foe in the air or on the ground, and even surveilling key enemy combatants for high-value targeting missions. Block 4 provides a significantly upgraded replacement for the F-35's combined infrared imager and laser designator called the electro-optical targeting system (EOTS).[108] Used for automatic or manual tracking of designated surface or air targets, improvements include new super higher-definition day-or-night

video, increased optical zoom magnification, and improved stability/reliability features that are displayed on the pilot's panoramic cockpit display. The system can also provide fast and accurate real-time targeting data and 4K video for friendly forces on the ground. Consider how these improvements will help on a mission like hunting for mobile missile launchers that can target U.S. forces and air bases. Keeping a safe distance, high-fidelity optical and infrared imaging can be used to search into hiding spots and through camouflage to identify launchers. The F-35's laser designator can be used to precisely guide munitions from any aircraft in the strike package. F-35s equipped with this technology can also detect threats relevant to ground forces and share very high-fidelity video to support ground maneuver.

Improved Panoramic Cockpit Display. Central to the pilot's control and monitoring of the F-35's flight parameters and mission systems is the interface with the panoramic cockpit display (PCD). Block 4 provides an important upgrade for this capability. The bottom line is that an F-35 pilot is presented with more real-time information than any other pilot of any other aircraft ever in the history of combat aviation. The difference between harnessing this as an asset, versus drowning the pilot in too much data to the point where mission performance degrades, comes down to how the information is presented.[109] Presentation is designed to help make the increased data flows gathered and processed by the aircraft's enhanced sensor suite make sense as useful or actionable information. Much of this occurs through enhanced brightness and resolution of the colored tactical symbology on the display and a better selecting system menu application.[110] This may sound basic but is absolutely critical given the importance of real-time high-fidelity information comprehension at mass levels in a demanding combat environment. A new higher-fidelity touch-sensitive screen allows the pilot to better maneuver through compartments of information and configure presentation based on needs and preferences. These features enable the pilot to more easily interpret critical movements in high-density environments, leading to increased situational airspace awareness during day or night operations. The easier-to-read screen also reduces pilot workload.[111] In combat, situational awareness is often the difference between getting shot down or making it back to base. Additional improvements include a more capable mission recording capability that captures PCD and systems video for post-mission pilot, maintenance, and intelligence debriefs. This allows crews to learn better from their experiences and hone their skills as a team.

Expanded Weapon Compatibility. At the end of the day, the effectiveness of an F-35 comes down to mission effects—putting weapons on targets. However, not all bombs and missiles are the same. It takes the right munition in given circumstances to deliver the desired effects. That is why it is so important that Block 4 allows the aircraft to carry a more diverse load of weapons inside the F-35's two carriage bays—upwards of 16 new types.[112] While the F-35 can carry weapons externally if circumstances warrant, internal carriage is important to survivability. Stores carried on external racks degrade the aircraft's stealth. Gaining internal carriage capacity preserves stealth and adds more firepower. To this end, one of the most important upgrades adds dual-rail missile racks for each of the weapon bays. This permits the carriage of one additional missile similar in size to an AIM-120 Advanced-Medium-Range Air-to-Air Missile (AMRAAM) in each bay. This raises the current limit of two to three in each bay, and the limit of the full internal F-35 load of AIM-120 missiles from four to six, a 33 percent increase.[113]

Block 4 also provides for internal weapons bay carriage of the AIM-9X Block II. This is a major advantage given the need to preserve stealth attributes. Pre-Block 4 F-35s require external carriage of these missiles. The upgrades net this new capability by allowing the aircraft's sensors to feed data to the missile while it is still in the bay, thereby allowing it to lock onto an adversary aircraft before launch, and then helping to manage the transition to missile sensors post launch.[114] Similarly, new integration will enable the employment of the GBU-53/B Small Diameter Bomb Block II (SDB II) Stormbreaker. This is a network-enabled glide bomb capable for all-weather environments with options for guidance via laser, GPS coordinates, or millimeter wave target discrimination radar.[115] The weapon is optimized for striking adversary ground forces, particularly armored vehicles. Block 4 also enables the use of the AGM-154C-1 Joint Standoff Weapon (JSOW). Its precision guidance can be directed through GPS coordinates and imaging from its infrared seeker head.[116] An even more significant weapon capability enabled by Block 4 is the integration of the B-61 Mod 12 nuclear gravity bomb that will make the F-35 a dual-capable aircraft for both conventional and nuclear strike rolls.[117] This capability is timely given China's nuclear breakout, Russia's nuclear saber rattling, and the nuclear ambitions of Iran and North Korea.

Improved Processing Power. The key to unlocking the F-35's capability enhancements comes down to improved processing power. The aircraft is effectively a flying computer system, so there comes a point where adding new hardware is necessary to meet the increased processing demands imposed by improvements involving new systems and software. In the F-35's case, TR-3 upgrades via the integrated core processor are delivering 25 times more computational speed and memory. This is essential to power the intense fusion process that gives the F-35 its distinct operational advantage.[118]

Enhanced computing power unleashes an array of information-centric elements of the aircraft, like the enhanced mission date file (MDF). This is the primary database the aircraft uses to make sense of the battlespace.[119] For example, using AI and rapid fusion, the MDF allows the F-35 to harness real-time sensor data and cross reference it with known enemy system attributes to rapidly assess what surface or air systems are in a given region. Importantly, the process to build and validate the MDF at the U.S. Reprogramming Laboratory (USRL) requires the installation of actual Block 4 sensors and TR-3 hardware on aircraft—the systems are ultimately interdependent on each other. Adversaries are always evolving their systems, and it is crucial we keep pace by recognizing and capturing this new knowledge.

The increased sensitivity, quality, and speed of the Block 4 sensors to gather electronic signals from adversary radars also enhance the F-35 post-mission debrief process. Upon landing, the aircraft's mission can be retrieved for review and stored on the pilot's portable memory device (PMD). This encrypted module is brought back to mission debrief for review by maintenance to check the health of the jet, conduct pilot debrief, and assess signals exploitation by intelligence that may provide timely and actionable information on the enemy's electronic order of battle.[120] This Block 4 data can be further uploaded and saved for future reference on the Operational Data Integrated Network (ODIN), a logistics and operational management information system supporting F-35 global operations. To put it simply, this is the maintenance, sustainment, and logistics brain of the F-35 enterprise. It is core to how the aircraft operates, and it represents a major

improvement over an earlier system known as the Autonomic Logistics Information System (ALIS). Improvements mean the new system can upload data from the PMD to the main server twice as fast as the legacy system.[121] This reduces the amount of time a maintainer is delayed waiting for information to load and speeds up post-flight maintenance activities. Speed counts for a lot in combat.

Finally, another Block 4 upgrade replaces the current Mission System's Communication, Navigation, Identification Processor (CNIP) with an Advanced CNIP that increases processing capabilities to support Concurrent Multi-Netting operations.[122] That comes down to the F-35 being able to talk seamlessly to a broader range of actors in the operational environment. This specifically addresses the notorious challenges involved with real-time 5th to 4th generation aircraft data sharing.[123] This will also extend to new types like the B-21 and NGAD. This is very important, for as powerful as an F-35 may be singularly, they realize their true potential as part of a broader team. Given their ability to gather data, process it into actionable information, and do so behind enemy lines thanks to their survivability, this notion of the F-35 as a connected data node is a powerful contributor to the broader force as an enabler of innovative networked warfighting concepts of operation.

Applying the Technology

While all of these specific upgrades are important in their own right, their real value is measured in operational effectiveness. From a kill chain perspective, the Block 4 upgrades to the F-35's mission system sensors as well as its collaborative networking, automated location and identification, and target tracking functions will greatly enhance the pilot's ability to battle manage the prosecution of multiple targets simultaneously in contested environments. The improved Block 4 electro-optical targeting system and distributed aperture system cameras will give the pilot a clearer picture at longer ranges when assessing weapon success against surface or air targets. These capabilities, combined with the Block 4 advanced passive/active sensors and faster fusion, will improve target discrimination between the desired target and a decoy.

With fidelity improvements realized from the AN/APG-85 in reducing target location errors, and a significant increased jamming capability against targeted threat radars, the aircraft will gain improved weapon delivery accuracy and can attain an increased probability of kill (Pk). That means a more efficient use of weapons per aircraft and the ability to service more single weapon targets per sortie. This is a big deal when commanders will need to expand the number of aim points that can be hit in a concentrated period of time. Striking large volumes of targets fast severely stresses an enemy's war-making capacity and degrades their ability to pursue fallback options—it is all about overloading their decision-making bandwidth.

More than ever, the Block 4 upgrade will promote joint interoperability and mutual support between 5th and 4th generation aircraft, to include those of partner nations and coalitions, and better support surface forces on land or at sea. Improvements to the AN/APG-85 radar to track and classify moving targets on both land and maritime domains make it the perfect platform for a growing number of missions that emphasize information superiority over kinetic results. The F-35 does not accomplish this in a vacuum—it is specifically designed to share data to other aircraft and other friendly ground or sea combatants. The net result is superior battlespace situational awareness for the joint team. When circumstances allow, an

F-35 pilot can also perform critical node duties as a centralized or de-centralized battle manager given the aircraft's information attributes.

F-35s with the Block 4 suite are equipped to provide a shared high-resolution off-board view of the battlespace with other friendly aircraft with a compatible encrypted receiver. Any recipient of this data would enhance their targeting capability and thus improve mission effectiveness. Knowing where the threat is, what it is, where it is looking, when it is firing, and who it is firing at is a capability that Block 4 offers, and one that is key to survival for any jet in a densely contested battlespace. However, to share the same view of the battlespace amongst a flight of F-35's, they should all be in the same Block 4 configuration due to the increased passive and active detection capabilities of a Block 4 vehicle. Additionally, a non-Block 4 jet will not be using the exact same MDF as a Block 4 jet, so when comparing each view of the battlespace there will be differences, which, in a wartime environment, could cause confusion and increased pilot workload.

As mentioned, the electromagnetic spectrum will be the most contested domain in the future, the F-35 will be well equipped when employing its Block 4 offensive and defensive capabilities. However, these attributes can also be extended through mutual support to protect other non-stealthy 4th generation platforms during the initial days of a conflict until air superiority is achieved. The capabilities of Block 4 are well-suited for this role. Similarly, this capability can be exercised to reduce weapon attrition when employed against Target Tracking Radars (TTR) co-located at a high-value SAM site.

Finally, the importance of the F-35's kinetic arsenal expansion cannot be overstated, especially when it comes to stores that can be carried in the internal bays. Block 4 brings significant growth to the internal carriage weapons mix. The aircraft will be able to carry AIM-9X Block II and maintain its stealth signature. Similarly, a Block 4 missile carriage rack modification provides the option of loading one additional AIM-120-sized air-to-air missile into each weapons bay. The GBU-53/B Small Diameter Bomb Block II will also be integrated on the jet and mounted inside the weapons bay. It gives the F-35 a capability against medium-range targets that are either moving or stationary, day or night, and in any weather condition with its triple seeker head. When seeking longer-range and larger warhead options, the F-35 will now be able to employ the AGM-154C-1 Joint Standoff Weapon. Its significantly longer stand-off capability is suitable for larger targets, like ships during maritime operations. Finally, as previously discussed, incorporation of the nuclear capable B-61 Mod 12 weapon will empower commanders with an important set of enhanced stealthy strike options and a valuable tool in the deterrence equation.

Recommendations and Conclusion

The Air Force needs to increase the rate at which it acquires fighter aircraft. While the service is relying on a variety of aircraft types to comprise its future fighter force, only the F-35 is imbued with the requisite combination of stealth and information superiority—and is in current production. These attributes are baseline requirements to execute missions in the modern threat environment, then return to base and regenerate for another mission. Types like the F-16, F-15EX, and A-10 can have specific roles to play, but they lack the combination of 5th generation capabilities necessary to penetrate the threat and create the range of desired effects. Given the global demand signal for fighters and the fragile nature of the current inventory, it is critical that the Air Force rapidly modernize.

Given the reality of the global security environment and the state of our inadequate combat air forces, the Air Force should boost the F-35 procurement rate. With TR-3 in the final stages of its test regime and already on the production line, Block 4 capability insertions are clearly executable. Block 4 software tests will pass these thresholds in a matter of months. Given the schedule of defense spending authorization, appropriation, and obligation, any dollar committed to F-35s in the FY 2024 defense budget and beyond will be procuring a TR-3 jet with Block 4 capabilities. Further components of Block 4 can be inserted with minimal difficulty—most are simply software upgrades. It is how the program was designed, which allows for rapid, seamless evolution at this stage of the program. Considering these important variables, the following recommendations are offered:

Recommendation 1: Increase rate of F-35A procurement. The Air Force and combatant commands around the globe require fighter capacity and capability. While the Air Force's 4+1 fighter plan is a viable solution, its successful implementation is underpinned by a high-volume F-35 presence. That can only be achieved by boosting the F-35A procurement rate. While the FY 2024 request to boost the buy rate back to 48 F-35s per year is a positive vector, the Air Force needs to further accelerate procurement. Mitchell Institute analysis shows that procurement of 109 aircraft per year is required to arrest the current capacity downward spiral and build back the proper mix of modern capability and capacity. F-35s should form the bulk of that annual buy given their 5th generation attributes and affordable acquisition cost.[124]

Recommendation 2: Ensure TR-3 and Block 4 efforts remain on schedule. Predictable and consistent funding, stable requirements, and clear schedules are the foundational elements on which any healthy defense acquisition program is built and executed. As part of this equation, it is crucial that the defense industry meet its aim points. It is no secret that the F-35 has struggled with this, especially with TR-3 and Block 4 capabilities. All involved actors must work to maintain that trajectory. Test capacity is also important to reach this goal.

Recommendation 3: Develop and implement a force sizing construct. The Air Force's 2018 plea for more capacity was a stark indicator that there is a mismatch between available resources and the scope of demand to meet our security commitments around the globe. The Air Force needs to develop and implement a force sizing construct that explains the scale of forces it requires to meet the mission requirements as stipulated by the National Defense Strategy to the Department of Defense, Congress, and the public.[125] Resourcing that demand is a separate issue. Honestly acknowledging real requirements at strategic and operational levels and understanding the risks being assumed by allowing capacity gaps to exist is crucial for empowering smart decision-making, especially in an era where national security threats are on the rise. As the Ukraine conflict illustrates, once a war starts, it is very hard to surge production of sophisticated defense systems.

Recommendation 4: Harness cost-per-effect analysis. Cost is a predominant factor governing the scale and scope of the Air Force's future fighter inventory. This is not a new development—it is what led to the high-low mix compromise of the 1970s that resulted in the development of both the F-15 and F-16. In recognizing this dynamic, it is crucial to ensure leaders are accurately balancing mission effectiveness. Often the lowest per-unit cost yields higher operational expenses and lower mission effectiveness. These factors need to be acknowledged and recognized, otherwise the United States risks buying systems that win on the spreadsheet but lose in the real world.

The attributes that comprise modern combat aircraft are increasingly difficult to assess from a pure unit-cost approach—things like sensors, computing power, and connectivity. However, they are the attributes that will determine whether a combat aircraft succeeds or fails in combat and shape the type of force packages employed. If it takes dozens of lower-cost aircraft operating at higher risk to net what a handful of F-35s can achieve, the "lower-cost" solution actually drives higher overarching expenses in terms of acquisition, operations, and attrition loss when viewed from a mission perspective.[126] The best way to account for these realities is using cost-per-effect analysis to evaluate the true operational costs to execute various missions. The alternative is to buy individual aircraft absent that analysis of their overall impact on the warfighting system and incur greater expense as a result. A cost-per-effect approach will properly shape the ratio of aircraft that comprise the 4+1 fighter force structure mix. The Department of Defense, the Air Force, the Office of Management and Budget, and Congress will deliver better warfighting results if they harness this analytical methodology. It should also become a methodology for oversite entities like the Congressional Budget Office, the Government Accountability Office, and others as they assess both cost and operational value when it comes to evaluating military aircraft.

Recommendation 5: Ensure testing and evaluation does not impede necessary results. The Air Force is moving a significant number of new aircraft, as well as updated models, through test and evaluation at a time when combatant commanders need these types on their flight lines fast. While it is imperative that aircraft function reliably and meet necessary performance targets, it is also true that "perfection" is the enemy of "good enough." The current inadequacy of the Air Force fighter force is so dire that the Air Force may need to consider ways to streamline testing to ensure capacity gaps do not proliferate because of test and evaluation bottlenecks. In part, test and evaluation needs a major refresh to handle information-age systems more efficiently than through the current test and evaluation enterprise rooted in the industrial age. The Air Force should also consider ways to add more test and evaluation capacity through boosting the number of assigned aircraft and technicians or harnessing live, virtual, and constructive solutions where appropriate.

Recommendation 6: Monitor and steward aerospace industrial base capacity. The Air Force is not alone in procuring a significant number of aircraft in a short window of time. A post-COVID expansion in commercial air travel, along with increased activity in national security and commercial space activities, are driving a surge in aerospace production demand. Prime aerospace contractors often rely on a shared set of subcontractors with limited capacity. These firms were severely impacted by the effects of COVID, and several were forced to lay off staff in response to the collapse in commercial air travel demand. It is difficult to recruit and experience a new generation of engineering and manufacturing talent normally, and it is especially true given the strong post-COVID labor market. The Department of Defense will face major problems meeting its force structure requirements if the aerospace sector lacks elasticity. This further echoes the need for predictable, steady orders to help these firms manage their human capital and production infrastructure, and it suggests the Department of Defense needs to carefully consider industrial policy that will help ensure the viability and health of the aerospace production sector. It is crucial to note that these supply-side strains are occurring in peacetime. Meeting wartime demand surges would prove impossible unless the defense industrial sector can establish greater elasticity to handle increased demand. It is instructive to look to the challenges weapons manufacturers are

experiencing now as they try to meet demands for the Ukraine conflict. Years of efficiency efforts shaved away the production elasticity in the armament industry in a similar way to the aerospace industry impeding production. Aircraft are even more complex to manufacture. It is clear to those working in this sector that this problem needs to be solved proactively—it will be practically impossible in the middle of a global security event, and implementing fixes takes years.

Recommendation 7: Divest to invest is not the answer. Increased investment is necessary. The nation has asked the Air Force to do too much with too little for too long. The Air Force's budget has been less than those of the Navy and Army for the last 31 years in a row. In fact, the Army received about $1.3 trillion more than the Air Force between 2002–2022 after removing pass-through.[127] Lacking cash, the Air Force is retiring systems to make room in its budget for new systems, essentially cannibalizing itself to acquire new capabilities. While this may have made sense when aircraft inventories were far larger, like at the end of the Cold War, inventories are now so far reduced that further cuts are not possible without undermining the viability of many mission areas. This approach increases the risk of failure when military options are needed to defend the nation. Fighter aircraft and their crews are squarely in this zone. In FY 2022, the Air Force sought to divest 137 of its legacy fighters but only buy 60 new ones.[128] Congress opposed most of the cuts. In the FY 2023 Air Force budget request, the service sought to retire 1,468 aircraft and only buy 467 across the FYDP—a net reduction of over 1,000 aircraft, of which many would be fighters.[129] Congress did not approve most of these retirements. The FY 2024 Air Force budget submission to Congress requests the ability to retire 131 fighters, but only procure 72—a combination of F-35s and F-15EXs.[130] These dynamics illustrate the pressure the Air Force faces as it seeks to make up for years of deferred and curtailed modernization programs with too small a budget. The result is a capacity death spiral. Increased Air Force funding is required to meet demand today, modernize for the future, and make up for decades of anemic aircraft buys.

Recommendation 8: Stewarding human capital is part of the fighter equation. While headlines often focus on aircraft, it is crucial to remember that it takes pilots, maintainers, and a broad array of other highly trained personnel to operate the fighter enterprise. The F-35 will only deliver optimal results if properly manned. The Air Force currently faces a shortfall of around 1,900 fighter pilots—a gap that has persisted for many years.[131] Worse shortfalls exist within aircraft maintenance, especially as older aircraft stay in the inventory past planned projections.[132] This means existing personnel are not able to transition to newly acquired aircraft, which adversely impacts readiness rates. It is worth noting, again, that these shortfalls exist during peacetime, which suggests the Air Force would face severe challenges handling wartime demand surges as well as force attrition. It is time for the Air Force, the Department of Defense, and Congress to tackle these shortfalls with concrete actions. This includes assessing talent retention efforts, training capacity, force sizing, and manpower sizing. Ensuring that crews are able to meet necessary flight hours to ensure proficiency is also important.

Recommendation 9: Empower the total force. The Air Force is about to walk off a fighter aircraft inventory cliff, where multiple units will find themselves without aircraft absent a major uptick in production. The departure of the F-15C/Ds from Kadena Air Force Base in the fall of 2022 serves as a stark warning. Air National Guard units will likely bear the next major shortfalls as the capacity gap cascades, given that they generally operate older aircraft. The Air

Force is presently sized in such a way that there is no operational reserve. While that role is traditionally filled by the Air National Guard and Air Force Reserve, all Air Force active, guard, and reserve units are currently required to meet our strategy demands. In a time of war, as capacity runs very thin, there will be no option but to employ traditional operational reserve forces, which could leave the United States with a shortfall for other important missions like homeland defense. It is imperative that Air Force modernization is resourced to meet the demands of the Total Force, not just the active component. To do otherwise will inject high levels of risk into the demands of the National Defense Strategy. The Air National Guard has a powerful and credible voice on Capitol Hill. Now is the time for those leaders to signal the severity of the problem. This is not an Air Force or an Air National Guard problem—it is a national security problem.

Recommendation 10: Factor-in the allied component. The U.S. Air Force does not stand alone in facing a fighter aircraft modernization crisis. Many of our allies are dealing with similar challenges. The rapid rise in international F-35 buys speaks to the scale of this issue. Counties still reliant on Cold War-era aircraft realized that the global security environment demanded immediate action. The Department of Defense must ensure that F-35 production can meet the growing demand from international partners and allies in addition to our own nation's requirements. If allies cannot procure aircraft from the United States, they will go elsewhere. This is not in our interest, considering our requirements for warfighting interoperability, cooperation, partnership, and economy could be met by a common airframe. To meet global demand, the Department of Defense and Congress should invest in additive production capacity to boost F-35 manufacturing throughput above the current rate of 156 aircraft per year.[133]

Conclusion

The Department of Defense, the Air Force, and Congress face a fighter aviation crisis. Left unchecked, it will undermine every facet of joint force operations. Even cyber and space forces will struggle to function if their forward operating locations are subject to attack from the sky. The F-35 is a key element of a recovery in the Air Force fighter force. Fortunately, progress with TR-3 and Block 4 means that the Air Force will be able to procure the most capable versions of the aircraft as they boost capacity. Congress needs to ensure necessary resources are available, and it is imperative that the involved contractors meet schedule, performance, and budget targets. This is not a solution the Department of Defense and the Air Force can net on their own—it will take a total team effort.

Those who question this solution path, especially on budget grounds, should consider the cost of the alternative. Look at the costs being borne in Ukraine by both sides as they lack the ability to effectively employ airpower and achieve air superiority.

If the nation expects effective airpower, it needs to buy relevant aircraft now. Too much is on the line to consider any other course of action. As many Air Force leaders explain: "The only thing more expensive than a first-rate Air Force is a second-rate Air Force."[134]

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