

March 2021

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A Report of the CSIS DEFENSE-INDUSTRIAL INITIATIVES GROUP

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ISBN: 978-1-5381-4033-8 (pb); 978-1-5381-4034-5 (ebook)

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202-887-0200 | [www.csis.org](http://www.csis.org)

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## Acknowledgements

This project included substantial participation by a senior review group that provided feedback on the research approach, the project's central findings, and the final report. The authors are tremendously grateful to the members of the senior review group for their invaluable assistance, including General John Jumper, United States Air Force (retired), the Honorable Frank Kendall, the Honorable Alan Estevez, the Honorable William J. LaPlante, and Mr. Jim Thomsen. The authors of this study relied upon feedback received at two workshops held at CSIS as well as discussions with other knowledgeable individuals in industry and the defense acquisition community. In addition, the authors would like to thank Daniel Herschlag and Grant McDonald for the research contributions they made to this project.

This CSIS study was made possible by support from United Technologies, General Electric, and the Arconic Foundation.

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# Introduction

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For several decades, the U.S. way of war has been characterized by overwhelming dominance of the air. Air dominance has allowed the United States to carry out a variety of complex military operations with relative impunity and to hold almost any enemy target at risk. This has in turn been a key underpinning of how the United States prosecutes its land and naval operations, allowing U.S. military forces to fight, maneuver, sustain presence, and project power across the globe. Air dominance requires a combination of assets, including basing infrastructure; mobility; aerial refueling; intelligence, surveillance, and reconnaissance; command and control; and strike capabilities. Moreover, it requires the human capital and training to bring all these assets together. One of the critical elements of air power that has enabled many aspects of air dominance has been the development—and improvement over time—of fighter aircraft engine technology.

Aircraft engines come in a variety of designs. These designs are related to one another and align around the performance characteristics of aircraft missions. Much of the Air Force's larger aircraft (such as the KC-135 and C-17) use engines that are basically indistinguishable from those found on commercial airliners. Many large unmanned aerial vehicles and cruise missiles use engines that are similar in most respects to those used by business jets. Engines used for helicopters are specialized to power a rotating shaft and are closely related to commercial turboprop engines. Fighter aircraft engines, however, are relatively unique. They have challenging performance requirements for characteristics such as thrust-to-weight ratio and the ability to rapidly and repeatedly spool power up and down in support of combat maneuvers. In part because of the extraordinary performance demands of the fighter mission, fighter engine development has historically been where the cutting edge of engine technology was defined. For many years, fighter engine development fed technology into the rest of the engine universe, driving overall engine development forward. However, this historical pattern started to break down in the 1980s, and today a very different pattern of aircraft engine development prevails, in which commercial engines are the primary drivers of technology development. This new aircraft engine development pattern presents policy choices to defense decisionmakers considering the future of the fighter engine industrial base, which form the central topic of this report.

For much of the history of fighter aircraft, fighter development has been roughly synonymous with engine development. New fighters have leveraged improvements in engine technology to gain advantages in speed, range, and maneuverability that have translated into combat advantage. Other technologies, such as flight controls and advanced

wing and fuselage designs, have developed alongside and supported advances in engine development. However, developing fighter aircraft that were truly superior to their competitors has historically required significant advances in engine technology. The evolution of fighter technology in the jet engine era is captured in a classification schema that includes five generations of fielded aircraft.<sup>1</sup> Each of these generations represents a significant advance in engine technology—in fact, the most notable industry competition in the fourth generation of fighter aircraft in the United States was not between aircraft manufacturers, but between engine suppliers, known as the Great Engine War.<sup>2</sup>

The alignment between engine technology and generational advancements in fighter technology remained true through the development of fifth-generation fighters, including the F-22, which implemented engine advances to achieve both thrust vectoring and supercruise on a production fighter aircraft for the first time.<sup>3</sup> These improvements enabled the F-22 to meet its design requirements for combat maneuverability and stealth, ensuring that it would be the preeminent air-to-air combat aircraft of its generation. The same engine core design used for the F-22 was used for the F-35 to provide the required thrust-to-weight performance for STOVL (short take off vertical landing) flight and to provide sufficient power for the Air Force's F-35A, which is more than twice the weight of its single-engine predecessor, the F-16.<sup>4</sup>

However, the fifth generation of fighters also represented a significant departure from the historical engine development trend for two reasons. First, fifth-generation fighters have entered the operating force very slowly due to program delays, funding constraints, and the early termination of F-22 production. This delay means that the fifth-generation fighter era has extended much longer than previous eras, delaying progress to the next generation and limiting opportunities to deploy upgrades and improvements on fifth-generation engines. Second, in the fifth generation of fighter development, the focus on fighter performance (and therefore a significant share of development funding) shifted decisively toward areas other than engines. In particular, the development of stealth technology and sophisticated electronics and avionics systems became substantial competitors for fighter development funding.<sup>5</sup> The additional competition for funding has placed a constraint on incorporating recent advances into fighter engines. As a result of these factors, while commercial aircraft engine technology deployment in the last two decades has continued to progress at roughly the same pace as in the past, fighter engine technology deployment has substantially slowed. The previous historical pattern of fighter engine development feeding the

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<sup>1</sup> John Tirpak, "The Sixth Generation Fighter," *Air Force Magazine*, October 1, 2009, <https://www.airforcemag.com/article/1009fighter/>.

<sup>2</sup> Robert Drewes, *The Air Force and the Great Engine War* (Washington, DC: National Defense University Press, 1987), <https://apps.dtic.mil/dtic/tr/fulltext/u2/a187934.pdf>.

<sup>3</sup> Guy Norris, "F-22 fights back with supercruise success," *Flight Global*, July 27, 1999, <https://www.flightglobal.com/f-22-fights-back-with-supercruise-success/27719.article>.

<sup>4</sup> Pratt & Whitney, "Pratt & Whitney and Rolls-Royce F135 STOVL Team Completes Propulsion System Test," *Defense-Aerospace.com*, June 12, 2007, [http://www.defense-aerospace.com/articles-view/release/3/83186/pratt\\_rolls-advance-f135-stovl-engine-tests.html](http://www.defense-aerospace.com/articles-view/release/3/83186/pratt_rolls-advance-f135-stovl-engine-tests.html).

<sup>5</sup> Julian Turner, "Innovation at the Edge: The Top Air Defence Trends by Domain," *Airforce Technology*, May 3, 2018, <https://www.airforce-technology.com/features/innovation-edge-top-air-defence-trends-domain/>.

development of commercial engines has essentially been reversed; the pace of technology deployment in commercial engines has dramatically outpaced that of fighter engines, and the flow of technology is largely traveling in the opposite direction. This inversion in engine technology development—both in its causes and its effects—suggests that the United States is at a critical inflection point in the military engine industrial base.

The robust U.S. industrial base for large commercial aircraft engines includes the same companies that produce advanced fighter engines in the United States: General Electric Aviation and Pratt & Whitney. This has meant that engineering expertise in aircraft engine technology has remained robust even as the deployment of new technology in fighter engines has slowed. However, the operational demands placed upon fighter engine designs are distinct from those required for commercial airline operations. While advances in materials science and manufacturing technologies have clear applications to all aircraft engines, the design and development of commercial engines is a necessary—but not sufficient—support to the technical and engineering effort required to develop advanced fighter engines. With the completion of design work on the F135 engine for the F-35 and the cancellation of F136 engine development (that was to provide an alternative design), there was a significant dip in the level of fighter engine design work planned in the 2010s. To address this gap, senior leadership at the Department of Defense (DoD), including Deputy Secretary of Defense Ashton Carter and Under Secretary of Defense for Acquisition, Technology, and Logistics Frank Kendall, directed the Air Force to fund successive programs to develop and prototype fighter engine technology targeted at significantly improving fuel efficiency and thermal management. Beginning in 2012 with the Advanced Engine Development Program and followed in 2016 by the Adaptive Engine Transition Program (AETP), the Air Force funded General Electric Aviation and Pratt & Whitney to develop prototypes of new advanced adaptive engines.<sup>6</sup> The AETP program is scheduled to conclude in 2021 with the delivery of working prototypes from both vendors, at which point the DoD will have to decide the answer to several critical questions relating to whether and how it will support the military engine industrial base going forward.

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<sup>6</sup> Jim Mathews, “Engines of Innovation,” *Air Force Magazine*, August 2017, <http://www.airforcemag.com/MagazineArchive/Pages/2017/August%202017/Engines-of-Innovation.aspx>.



# The Four Key Policy Choices for Military Engines

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## Priority

The first choice the DoD will confront is what priority to place on the continuing development of fighter engine technology. The increasing focus of fighter development on technologies related to stealth and situational awareness—and in the future, potentially to technologies such as secure networking, artificial intelligence, and directed energy—suggests that a rapid advance of fighter engine technology may be less important now than it was in prior decades. Achieving advantage in future air campaigns may depend as much, or more, on other technologies. There is a case for investing in fighter engine technology, however. It revolves around operational need and international advantage.

An advanced fighter engine design offers the potential for improvement in two key operational needs of importance to future warfighting. The first is range. The engine designs prototyped during the AETP program offer significantly reduced fuel consumption—at least a 25 percent reduction in specific fuel consumption compared to the current baseline. Improved fuel efficiency translates to increased range for U.S. fighter aircraft, along with the ability to dwell longer over the battlefield as part of combat patrols or when providing air support to ground and naval forces. The second is power generation and thermal management. The engine designs prototyped during the AETP program can generate substantial power to run onboard electronics—potentially including directed energy systems—and can manage the significant heat generated by these systems due to their ability to dissipate heat into an additional stream of cool air running through the engine. The advanced technologies that compete with engine technology for resources are all massive users of power and massive generators of heat; in this sense, advancing engine technology is complementary to, and potentially necessary for, the advancement of these other technologies. Significant opportunities also exist to develop new engine designs and to improve existing engine designs, in a wide range of other operational parameters, if the DoD were to determine that such improvements offered an important warfighting advantage.

The other reason to invest in fighter engine technology is that the United States currently has a significant international advantage in it, and that this advantage is sustainable. Fighter engines are designed and produced in only a few countries, and the main U.S. fighter engine companies—General Electric and Pratt & Whitney—are generally

acknowledged to have the world's leading fighter engine designs and manufacturing capabilities. The United Kingdom's Rolls Royce (which also produces engines in the United States) produces high-technology fighter engines as well, although it was not selected for the AETP program. The U.S. technological advantage in fighter engines, however, could substantially erode if U.S. development were to stand still. Russia and China are aggressively investing in fighter engine development.<sup>7</sup> Still, although the engines currently produced by these nations can deliver engine performance similar to U.S. engines in individual flights and engagements, the United States retains a critical advantage in the reliability of its engines and their ability to perform over time. This translates into a major difference over the course of an air campaign, resulting in dramatic increases in U.S. aerial capability due to superior sortie generation, performance margin, and reliability in critical engagements. The U.S. advantage is built on both design expertise and manufacturing sophistication. There is every reason to believe that if the United States invests in fighter engine technology development, it can maintain it.

The fighter engine industrial base requires support from government customers to sustain world-class design and production capabilities. There are key differences between fighter engines and engines designed and produced for the commercial market, and without government investment, advances in these capabilities will not develop and existing capabilities will decay. This is particularly true in engine design, where current DoD programs supporting new engine designs are concluding and a decision is pending on how and whether to move ahead on a new engine development program.

In the next few years, U.S. policymakers will need to determine how big an investment in fighter engine technology they are willing to make. This decision should be based on the need to obtain the operational advantages new engine technology can deliver, the desire to maintain the United States' clear lead in this technology, and the necessity to maintain the capabilities of the U.S. industrial base to produce fighter engines.

## Allocation of Resources

The second choice that that U.S. policymakers will confront is where to invest in fighter engine development. There are a range of options that have the potential to deliver different advantages, which array along two dimensions. The first dimension is the stage of technology. The United States must consider alternative technology stages for its investments—from foundational technologies, such as the material sciences and manufacturing technology, to improving the design of existing engines, to the design and

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<sup>7</sup> "With New Engine, Russia to Re-pitch Su-57 Stealth Fighter Jet to India," DefenseWorld.net, August 23, 2018, [https://www.defenseworld.net/news/23231/With\\_New\\_Engine\\_Russia\\_to\\_Re\\_pitch\\_Su\\_57\\_Stealth\\_Fighter\\_Jet\\_to\\_India#.XNwlOjBKipo](https://www.defenseworld.net/news/23231/With_New_Engine_Russia_to_Re_pitch_Su_57_Stealth_Fighter_Jet_to_India#.XNwlOjBKipo); and Kristin Huang, "China's New Jet Engine Suddenly Takes Air Combat in a Whole New Direction," *South China Morning Post*, November 10, 2018, <https://www.scmp.com/news/china/military/article/2172535/chinas-new-jet-engine-suddenly-takes-air-combat-whole-new>.

production of a new fighter engine. The more extensive the design effort, the greater the improvement in operational capability that is likely to be achieved. In addition, greater support is provided to fighter engine design capabilities when there is more extensive design effort. However, more limited design efforts are likely to be more affordable, making it more likely that the DoD can afford to pursue business with multiple vendors, thus supporting a broader set of capabilities in industry.

The second dimension of engine investment is generational. There are three generations of fighters in which the DoD could choose to deploy new engine capabilities. Beyond current fifth-generation fighters, upgrades to fourth-generation engines have the potential to create a “4.5 generation” fighter, deploying operational improvements to the largest part of the current tactical fighter fleet. Design improvements on the current F135 engine or development of a new advanced-cycle engine, such as the designs being prototyped under the AETP program, could deploy in the near term on the F-35, the part of the U.S. tactical fleet most likely to engage peer competitors now and for the foreseeable future. Conversely, design of a new engine optimized for the next generation of combat aircraft—the sixth generation, which is currently in earliest stages of development—would provide the greatest flexibility to design an engine for the critical needs of future missions. Engine designers would be unconstrained by the structure and power needs of the F-35, and as a result, new design approaches, such as hybrid electric engines, could even be relevant. Design and delivery of a completely new design fighter engine would likely take a number of years, however, and would also be paced by the time required to design and produce the new sixth-generation aircraft on which they would deploy.

In addition, it is important to note that design efforts on engines outside the fighter engine niche can serve to help maintain the workforce. There are mission-specific elements that are unique to the smaller engines utilized on many UAV platforms, and improved engine designs for vertical lift, such as the Army’s Improved Turbine Engine Program (ITEP), can also support the engine design workforce, even when not applied directly to fighter engines.

## Business Model

The third choice policymakers will confront is what business model to use in supporting fighter engine development. The business model (or combination of business models) selected matters because, ultimately, industry profit provides the return on investment used to justify corporate investment in developing new technology. The timing and manner of how that profit is delivered creates different incentives for industry. In choosing the business model for fighter engine development, the DoD can adjust the nature and timing of its need to invest in R&D, but it must understand and accept the incentives its approach presents to industry, as well as the resulting consequences. Business models available include the traditional defense acquisition development model, the commercial aviation development model, and the commercial aviation sustainment model.

In the traditional defense acquisition development model, the government accepts most of the risk and funding responsibility of R&D while limiting the profits it will pay to industry

in development, production, and sustainment. This approach maximizes government control of the development process. In the past, development of engines under the traditional business model has been closely paired with the development of a new generation of fighter aircraft. The combination of these two major development efforts meant that engine development was part of a broader modernization initiative so large that it shaped the DoD's entire investment approach, as with the F-35 program. In this way, the traditional business model has been tied to structural aspects of how the DoD is organized and resourced, in ways that make departing from the traditional business model a major challenge requiring significant leadership commitment.

Non-traditional business models would make significant changes to the DoD's standard approach. The commercial aviation development model involves industry developing equipment at its own expense, then recovering the investment through the sale of that equipment. This approach shifts the upfront development risk to industry—but it requires shifting significant control of the development process along with it, as well as giving industry the ability to charge larger fees to the government in production to recoup its risk and capital expenses. It would also change the way that technology development shapes the overall budget. Alternatively, the commercial aviation sustainment model involves industry developing equipment at its own expense, selling that equipment at relatively low prices, and then recouping its development and production expenses during sustainment. This business model currently predominates in the engine market for commercial aviation. It is important to note that there are differences in the military and commercial engine markets, in terms of the number of actors, their relative power, and the scale of the market, all of which will affect the extent to which commercial business models can be implemented by the DoD.

Policymakers will have to decide which business model, or which combination of investment approaches, best suits the government's needs, works in concert with its resource allocation choices, and supports sustainment of the fighter engine industrial base. Combining business models could prove an attractive option if the DoD were to select a combination of technology investments for resourcing under the second set of policy choices outlined above, although commercial business models require a degree of scale that may limit the practicality of such an option.

## Competition

The fourth decision that policymakers will have to make is how to foster competition in the military engine industrial base. This choice is closely related to the issues of priority, resource allocation, and business model, as different prioritization, investment choices, and business models relate to different modes of competition for industry. However, competition is important enough to be highlighted as an issue in its own right. Given that U.S. companies are the world leaders in the development and production of both military and commercial engines, it is pivotal that policymakers determine how many competitors they seek to keep involved in the military engine industrial base, and how they intend to do so.

Classically, the DoD has sought to keep several competitors in the military engine industrial base. The decision to cancel the F136 engine development for the F-35 aircraft brought that commitment into question; nonetheless, although in this case the DoD argued against paying the cost of developing two similar competing engines, it did not claim that competition in the engine industrial base was uneconomical more generally. It has subsequently awarded engine development contracts to multiple competitors for next-generation technologies, suggesting that it still values competition in the military engine industrial base. This has included providing funding to both General Electric and Pratt & Whitney to build new engine prototypes as part of AETP. However, prototyping programs are less expensive than developing engine designs that are ready for use on production aircraft. As a result, there remains some skepticism in the industrial base about the DoD's commitment to competition and its plans for sustaining it.

## Informing the Critical Policy Choices

This study provides a detailed analysis of the military engine industrial base and relevant trends in order to fully understand the nature of these policy choices and to inform future policy decisions. This begins with an understanding of how the changes in aircraft and engine inventories have led to changes in the development of engine technology. It then explores how revenue is flowing to the engine industrial base, establishing that the primary current area of weakness for industry is in engine development. Finally, the data analysis explores budgetary plans for future engine investment to establish the real choices available to policymakers and when they are likely to come due.

## The U.S. Engine Industrial Base

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The engine industrial base is a major asset to the U.S. economy. The United States is the world leader in a globally competitive industrial sector which successfully develops and manufactures high-technology products for export around the world. The enduring economic success of the engine industry could create the impression that there is little reason for defense policymakers to devote much attention to the issue. However, there are key features of the engine industry that explain why the DoD has taken such a deep interest in the industry, both historically and in the modern day.

### Relationship between Commercial and Military Engines

The close relationship between commercial and military aircraft engines is a critical factor in any discussion of the industrial base. U.S. firms are world leaders in both the commercial and military parts of the aircraft engine sector, and the same companies design and manufacture both kinds of engines. The integration of commercial and military engine technology within the industrial base is a tremendous asset for defense. It allows the DoD to leverage investment in manufacturing capacity and technology driven by and financed through commercial sales, thus reducing the overhead expense allocated directly to military production. At the same time, there are significant differences between commercial and military engines. As a result, the DoD cannot simply assume that commercial engine technology development will suffice to meet its needs, or that the commercial sector can sustain design and production capabilities important to the military in the absence of engine orders from the DoD. Therefore, the recent rapid growth that has been seen on the commercial side is not enough to sustain innovation on the military side. And yet, because the two sides do not operate in separate bubbles, it is important to examine their relationship more closely. A better understanding of commercial versus military technologies can help inform the defense policy choices discussed in this paper.

### Differences between Commercial and Military Engines

#### REQUIREMENTS

Commercial airline and military fighter aircraft buyers have different requirements. Airlines prioritize reliability and fuel economy. Most of the time, commercial aircraft cruise at steady speeds and consistent altitudes chosen for efficiency. Furthermore, given the number of commercial flights, a small improvement in fuel economy results in a substantial reduction in airline expenses. In 2019, fuel accounted for 24 percent of the global airline

industry's total operating cost.<sup>8</sup> Engine reliability is also a huge factor for airlines: when aircraft do not fly, the airlines are not earning revenue. More reliable engines therefore translate directly to higher airline revenues. There is thus fierce competition among engine companies to supply airlines with highly reliable engines that are focused on operating with maximum efficiency on typical commercial airline flight profiles, engendering lower fuel costs.<sup>9</sup>

The performance requirements for fighter aircraft engines are quite different from those of their commercial counterparts. Military aircraft are required to maneuver aggressively and change speeds rapidly in order to perform defense missions—including aerial combat, aerial assault, self-defense maneuvering, and close air support. While the military is not completely impervious to issues of fuel efficiency, it does not have the option to limit its operations to inherently efficient flight profiles or to optimize engines to operate in these conditions. Instead, the military must design its engine performance for the flight profiles required to fulfill its military missions, and then try to optimize engine efficiency within those parameters. So, for example, the flight envelope of a given military aircraft (i.e., the range of possible operating conditions, such as speed and altitude) will be much larger than that of commercial aircraft. Military aircraft need the capability to fly low to the ground at high speeds to evade enemy radar as well as the means to loiter at high altitudes to obtain the best possible view of a battlefield and operate above certain kinds of anti-aircraft systems. Engines on these aircraft must also be able to go from the low end to the high end of their thrust performance capabilities in a matter of seconds in order to perform combat maneuvers. In combat aircraft, engines are also located inside the aircraft fuselage for protection and lower visibility, and several other aspects of commercial engine design do not lend themselves readily to the characteristics required for stealth aircraft. As military engines have improved, this focus on pushing the technological boundary for more flexibility and performance has only increased.

#### DIVERGENT DESIGNS

Different requirements have led to divergent engine designs. One of the most recognizable differences is the size of the engine inlet. Commercial jets have high-bypass turbofan engines, while fighter engines, along with many other military aircraft, have low-bypass turbofan engines. High-bypass turbofans are much larger and derive much of their thrust from the turning of the massive bypass fans. The high-bypass ratio allows them to generate higher rates of thrust at a given fuel burn rate, making them more fuel efficient. Low-bypass turbofans derive most of their thrust from the expulsion of fuel burn exhaust. These engines are not as fuel efficient but can support supersonic speeds.

Beyond the high- and low-bypass distinction, there are less apparent but still critical design differences, including materials, engineering, engine controls, and airframe integration. First, to support higher performance, military engines require special materials. These materials can be designed with higher melting points and greater durability to withstand

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<sup>8</sup> "Fuel: Fact Sheet," IATA, November 2020, <https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---fuel/>.

<sup>9</sup> Richard Martin, "The Race for the Ultra-Efficient Jet Engine of the Future," *MIT Technology Review*, April 23, 2016, <https://www.technologyreview.com/s/601008/the-race-for-the-ultra-efficient-jet-engine-of-the-future/>.

the stress of extreme high-temperature and high-pressure conditions.<sup>10</sup> In addition to stronger materials, the parts required in military engines are often unique to military aircraft, or at least more complicated. For example, some engines need special cooling apparatuses capable of sustaining the high temperatures generated from high speeds.<sup>11</sup> Military engines are often subjected to rapid acceleration, deceleration, high-G maneuvers, and even inverted flights. All these conditions further complicate the design of oil pumps, fuel pumps, lubrication systems, engine bearings, and internal spool shafts. High-impact maneuvers require highly advanced engine controls that are capable of rapidly changing the engine's operations to deliver this flexible performance.

Airframe integration poses yet another challenge for military engine designs. A typical commercial engine is attached below the wings of an airliner and requires relatively minimal attention to integration. Due to low visibility and observability requirements, military engines are often buried deep within the body of an aircraft. This makes the task of integration more difficult—something that needs to be addressed early on in an engine's development cycle. These requirements also result in military engines having to deal with complex, high-pressure airflows that civilian engines do not.

The differences derive not only from where military aircraft fly, but also where they park. The military needs to be able to maintain its aircraft in forward-deployed locations, sometimes including areas without substantial infrastructure or aboard ships. The conditions can include extreme heat, cold, humidity, sand, and salt; furthermore, engines may need to be maintained by personnel with limited space, equipment, and tools. Military engines must be designed with these challenging maintenance environments in mind. Commercial engines, on the other hand, can be maintained in controlled settings that are accessible to high-skilled, well-equipped personnel.

#### DESIGN WORKFORCE

The differences in military engine requirements present exceptional technical challenges when designing new propulsion systems. These challenges require unique, specialized engineering skills. As a result, many engineers work exclusively on military engines and have been doing so for most of their careers. Although there are skills that transfer from working on commercial engines, many of the unique nuances of designing military engines are best acquired through experience. And while engineers with experience in military engines can sometime be retained by shifting them to commercial work, the design skills required can also erode over time if not exercised. In the past, the companies that have been able to invest in and sustain a military engine design workforce have been the ones to successfully develop next-generation propulsion technology.<sup>12</sup> Those companies that have

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<sup>10</sup> Committee on Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems, *Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems* (Washington, DC: National Research Council, 2011), <https://www.nap.edu/download/13144>.

<sup>11</sup> Ibid.

<sup>12</sup> Mark A. Lorell and Hugh P. Levaux, *The Cutting Edge: A Half Century of U.S. Fighter Aircraft R&D* (Santa Monica, CA: RAND Corporation, 1998), 155, [https://www.rand.org/pubs/monograph\\_reports/MR939.html](https://www.rand.org/pubs/monograph_reports/MR939.html).



not made this investment and have not been able to sustain an experienced, skilled design workforce are no longer military engine innovators.

Regulations are another complicating factor in building and maintaining a capable design workforce. In an effort to protect U.S. technological superiority in military propulsion technology, there are many regulations on who can work on military engine projects. Foreign nationals are not permitted to work on the design or production of military engines except in unusual circumstances. In accordance with International Traffic in Arms Regulations (ITAR) and Defense Federal Acquisition Regulation Supplement (DFARS), engine producers must segregate U.S. and non-U.S. personnel when working on military projects. These workforce-related barriers to entry (both technical and regulatory) lead to an environment where human capital takes time to develop. Military engine producers cannot easily rebuild critical workforce skills, particularly design skills, if the workforce is downsized due to gaps in work.

#### DEVELOPMENT COSTS

On average, military engine development tends to require more time and resources—sometimes upwards of four times the cost—than that of commercial engines. There are several reasons for this disparity.<sup>13</sup>

First, military engine requirements are more complex and demand a higher level of performance, which results in longer development times at a higher cost.<sup>14</sup> Military engine parts often require special materials that are expensive and challenging to manufacture and assemble, as in the case of some composite materials.<sup>15</sup>

Second, commercial engines have maintained a relatively constant set of requirements that enables developers to update existing designs incrementally. Military engine technology must often break new ground to accommodate new and more complex requirements, such as better maneuverability or increased stealth. This typically results in a lengthier, more expensive development process as the developers experiment with various designs and materials.

Finally, the commercial sector historically has leveraged technology and practices from the defense sector without having to directly fund the heavy lifting of initial development. Many design elements of the turbojet and turbofan engines—common today on large commercial aircraft—were first developed for military aircraft, then transferred to the private sector as the commercial aviation industry began to take off.<sup>16</sup> The steady state of commercial engine requirements mentioned above gives the commercial sector leeway to take a more conservative approach to development, then integrate useful engine technologies that come out of the defense world. This dynamic, however, has receded in

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<sup>13</sup> Michael S. Mutty, *A Comparison of Military and Commercial Aircraft Development* (Washington, DC: U.S. Department of Defense, April 1993) <https://apps.dtic.mil/dtic/tr/fulltext/u2/a276830.pdf>.

<sup>14</sup> Mark V. Arena et al., *Why Has the Cost of Fixed-Wing Aircraft Risen? A Macroscopic Examination of the Trends in U.S. Military Aircraft Costs over the Past Several Decades* (Santa Monica, CA: RAND Corporation, 2008), 47, <https://www.rand.org/pubs/monographs/MG696.html>.

<sup>15</sup> Jeff Sloan, "Pratt & Whitney demonstrates F135 full-life capability," *Composites World*, June 15, 2015, <https://www.compositesworld.com/news/pratt-whitney-demonstrates-f135-full-life-capability>.

<sup>16</sup> Eric Roberts, "The Development of Jet Engines During The War," personal page at Stanford University, March 16, 2004, <https://cs.stanford.edu/people/eroberts/courses/ww2/projects/jet-airplanes/planes.html>.

recent years, as the deployment of new military engine technology has fallen far behind the pace of commercial engine technology development. Arguably, the technology flow is now likely to travel in the other direction.

Overall, the military is driven to spend more time and resources on engine development due to more sophisticated requirements, more urgent incentives for technology advancement, and varying missions for the platforms for which the engines are built. The commercial sector has simpler, less varied requirements that allow for an easier and cheaper development cycle.

Critics of the military requirements process have argued that some of the sophistication and mandates for new technology should not be treated as inherently necessary, but instead that they reflect poor management of technology trade-offs. This question of whether and how military engines might pursue a development model more like commercial engines is addressed in more depth later, in the section on business models for engine development. However, research has found that the development time for aviation has been fairly steady across the past several decades, suggesting that the challenge is a consistent one, at least for those engines that are not commercial-adjacent or iterations on past designs.<sup>17</sup>

## Benefits and Challenges of a Common Engine Industrial Base

Despite the differences between civilian and military fighter engines, the two sides continue to impact each other in many ways, and the impact is mostly positive. Apart from fighter engines, many aircraft engines are bought by both commercial and military customers, and the military often buys commercial-derivative engines to power cargo and tanker aircraft. As a result, the military can benefit from economies of scale in the growing commercial market. This can help decrease costs for the commercial derivatives that the military buys and even military-unique engines that rely on some of the same materials and processes as commercial engines.

Second, the military increasingly benefits from the flow of technology developed by the commercial side. The pace of commercial engine development remains quite robust. For instance, Pratt & Whitney spent more than \$10 billion developing a new turbofan engine, the PW1100, that utilizes a gearbox that allows the bypass fan to rotate at different speed from the driveshaft for the compressor and turbine, boosting fuel efficiency.<sup>18</sup> General Electric recently delivered the highest thrust engine ever produced, the GE 9X, using advanced ceramic matrix composite components to enable high-pressure ratios that lead to increased thrust.<sup>19</sup> These new commercial engine designs advance the state of engine engineering, develop and sustain the design workforce, and demonstrate new technologies

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<sup>17</sup> David M. Tate, *Acquisition Cycle Time: Defining the Problem* (Alexandria, VA: Institute for Defense Analyses, 2016), 6, <https://www.ida.org/-/media/feature/publications/a/ac/acquisition-cycle-time-defining-the-problem-revised/d-5762.ashx>.

<sup>18</sup> Peter Coy, "The Little Gear That Could Reshape the Jet Engine," *Bloomberg Businessweek*, October 15, 2015, <https://www.bloomberg.com/news/articles/2015-10-15/pratt-s-purepower-gtf-jet-engine-innovation-took-almost-30-years>.

<sup>19</sup> Ben Sampson, "GE9X recognized as most power engine in the world," *Aerospace Testing International*, July 24, 2019, <https://www.aerospacetestinginternational.com/videos/ge9x-recognised-as-most-powerful-jet-engine-in-the-world.html>.

that can migrate to military engines. Engine producers utilize new robust lightweight materials in commercial engines to decrease weight and improve efficiency, and thus decrease fuel use.<sup>20</sup> Although developed for commercial use, these technologies have dual-use applications.

At the same time, changing demand for commercial engines can cause challenges for the industrial base. In 2017, Airbus delivered 718 commercial aircraft.<sup>21</sup> In the same year, Boeing delivered 763, a new record.<sup>22</sup> This boom in demand increased engine production and strained supply chains in 2017 and 2018. By contrast, aircraft production plunged in 2019 and 2020 due to issues with the grounding of the Boeing 737 Max and the Covid-19 crisis, which not only dramatically reduced air travel but also directly impacted aircraft production.<sup>23</sup> This decline in the commercial aircraft markets has heavily impacted engine suppliers, leading to workforce reductions of as much as 25 percent.<sup>24</sup> Just within the last five years, the commercial market has put substantial pressure on common commercial and military engine supply chains in both directions. In boom years, the strain of surging production on supply chains results in the military sector and civilian sector competing against one another for raw material, parts, and engineering talent. When the market for commercial aircraft experiences a down cycle, as it is currently, the resulting pressure on the industry can negatively affect military suppliers in the supply chain by undermining the commercial business base on which they depend for profitability.

## The Criticality of the Engine Supply Chain

Just as significant in the success of the U.S. engine industrial base as the leading engine manufacturers are the suppliers who build critical parts for these complex systems. Major U.S. companies—such as Arconic, Precision Castparts Corporation (PCC), Cobham Composites, and Allegheny Technologies Incorporated (ATI)—are among the most important producers of key parts for military engines. The U.S. advantage in engine technology depends not only on the engine manufacturers' exceptional design and production expertise but also on advanced precision manufacturing capabilities and an ability to produce parts to exceptionally high performance and quality standards in the supply chain.

Key examples of the sophistication involved in developing and manufacturing crucial engine parts with these capabilities are single crystal turbine blades and ceramic matrix composites. Single crystal turbine blades were developed in the 1970s to address issues with

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<sup>20</sup> Marcus Finley, "Composites make for greener aircraft engines," *Material Today*, January 30, 2018, <https://www.materialstoday.com/composite-applications/features/composites-make-for-greener-aircraft-engines/>.

<sup>21</sup> Robert Wall, "There's a Boom in Airline Travel, and Jet Makers Are Making the Most of It," *Wall Street Journal*, February 18, 2018, <https://www.wsj.com/articles/airbus-reaps-rewards-for-rising-plane-production-1518681047>.

<sup>22</sup> Jon Ostrower, "Boeing delivered more jetliners than ever in 2017," *CNN Money*, January 9, 2018, <http://money.cnn.com/2018/01/09/news/companies/boeing-2017-record-deliveries/index.html>.

<sup>23</sup> David Slotnick, "Boeing's move to halt 737 Max production could hurt the 600 suppliers that make parts for the plane despite its promise not to cut its own workforce," *Business Insider*, December 17, 2019, <https://www.businessinsider.com/boeing-737-max-production-halt-suppliers-components-2019-12>.

<sup>24</sup> Matt Egan, "GE is cutting up to 13,000 jobs at its jet engine division because of the pandemic," *CNN Business*, May 4, 2020, <https://www.cnn.com/2020/05/04/business/ge-aviation-job-cuts/index.html>.

the wear and tear that engine turbine blades experience in the high-pressure, high-temperature operating environment of a jet engine.<sup>25</sup> Turbine blades are made from special metal alloys to tolerate these conditions, which would quickly melt almost any normal metal part, but the complex chemical structure of these alloys can generate problems in their own right: any manufacturing variance or weakness in the turbine blade will tend to deform and break down the turbine over time, potentially leading to dangerous conditions resulting in engine failure. It is common for such weaknesses to develop at seams and other weak points in the crystalline structure. A single crystal blade is grown with an entirely uniform and consistent metallic crystalline structure, effectively eliminating these weaknesses. Ceramic matrix composites (CMCs) are a more recent addition to the supply chain.<sup>26</sup> These materials withstand heat intensities that would melt any known metal material while simultaneously being lower in weight than their metal-based counterparts. As a result, the use of CMCs increases thrust—by enabling more efficient operating temperatures and reducing the need for cooling air—and reduces weight, improving the thrust-to-weight ratio. While the engine manufacturers have promoted, helped develop, and utilized technologies such as single crystal turbine blades and CMCs, the responsibility for actually manufacturing parts with these technologies at the volumes required for production falls to the engine supply chain. Hence, the supply chain is a critical enabler for the engine performance, efficiency, and durability that are the hallmarks of the U.S. engine industrial base.

There is also substantial overlap between the supply chain for military and commercial engines. On the factory floor at Arconic, there are no separate production lines for military and commercial products. Arconic, a major supplier of parts for military and civilian engines, “overwhelmingly manufactures parts for defense applications in the same facilities where commercial products are produced.”<sup>27</sup> Indeed, the farther down the supply chain you travel, the less separation between military and civilian engines, until there is effectively no difference. Historically, military requirements have tended to drive the adoption of newer, advanced materials in the supply chain, as exemplified by single crystal turbine blades. However, CMCs have already been adopted in civilian engines, and they are only now flowing into military engines. The commonality between the military and commercial engine supply chains can be both a benefit and a challenge with respect to workforce issues. When commercial sales are going well, they can support the development and sustainment of the skilled workforce that can also support military programs. However, stresses created when the commercial market is undergoing rapid growth or decline can have a cascading, disruptive impact on military programs—either by competing for talent with military programs, when commercial business is peaking, or conversely, by reducing support to

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<sup>25</sup> Lee S. Langston, “Each Blade a Single Crystal,” *American Scientist* 103, no. 1 (January—February 2015), <https://www.americanscientist.org/article/each-blade-a-single-crystal>.

<sup>26</sup> Ginger Gardiner, “The next generation of ceramic matrix composites,” *Composites World*, April 11, 2017, <https://www.compositesworld.com/blog/post/the-next-generation-of-ceramic-matrix-composites>.

<sup>27</sup> Valerie Insinna, “How one company uses commercial tech to make larger, less expensive aircraft structures,” *DefenseNews*, September 29, 2017, <https://www.defensenews.com/smr/equipping-the-warfighter/2017/09/29/how-one-company-uses-commercial-tech-to-make-larger-less-expensive-aircraft-structures/>.

common overhead personnel expenses when commercial business declines. This is particularly true for the engine design workforce.

Domestic sourcing requirements complicate the supply chain for military engines. Demanding performance requirements often require the use of alloys covered by specialty metals restrictions, which further complicate and sometimes can differentiate the supply chain due to the statutory provision requiring certain specialty metals to be produced in the United States. Specialty metals are defined as:

- Steel with more than 1.65 percent manganese, 0.6 percent silicon or copper, or 0.25 percent aluminum, chromium, cobalt, columbium, molybdenum, nickel, titanium, tungsten, or vanadium;
- Alloys of nickel, iron-nickel, or cobalt with other alloying metals in excess of 10 percent;
- Titanium and titanium alloys; and
- Zirconium and zirconium alloys.<sup>28</sup>

Military-unique requirements for specialty metals have affected the engine industrial base for a long time, so the supply chain has developed mechanisms for meeting them. However, over the years the demand for these specialty metals to produce military fighter aircraft has increased, meaning that their potential for impact on the supply chain is growing. Titanium components constituted 8 percent and 10 percent of the structural weight on the F-16 and the F-18, respectively. In contrast, modern fifth-generation fighter aircraft, such as the F-22 and the F-35, derive approximately 25 to 30 percent of their structural weight from titanium components.<sup>29</sup> Titanium and other specialty metals, such as nickel alloys, could become even more prominent in the supply chain of some of the advanced designs that are being considered for next-generation engines. There are also countervailing trends to consider. For instance, the proliferation of unmanned aerial vehicles and smart weapons has created a demand for engines that are substantially cheaper, to the point where a jet engine is a “consumable” product rather than a durable good. In these kinds of applications, the push would be for simpler, cheaper materials. However, there are real limits to how much trends toward cheaper solutions in aviation are likely to disrupt critical elements of the military engine supply chain. Achieving the demanding requirements for high-performance engines for military-unique applications will almost certainly continue to require high-performance technologies and materials that call for specialized expertise.

As DoD leaders consider the investments needed to ensure U.S. advantage in engine technology, the supply chain should also be considered. A few issues stand out that tie into broad trends important to defense that are beyond the scope of any individual supplier. The first is digital thread. Digital thread is a process for integrating the design, manufacture, and sustainment of complex systems through use of a common digital environment that

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<sup>28</sup> “Frequently Asked Questions Regarding the Specialty Metals Restriction under 10 U.S.C. 2533b As of July 29, 2009,” U.S. Department of Defense, July 27, 2016, [https://www.acq.osd.mil/dpap/cpic/ic/docs/Updated\\_Frequently\\_Asked\\_Questions\\_Specialty\\_Metals\\_07-26-13.pdf](https://www.acq.osd.mil/dpap/cpic/ic/docs/Updated_Frequently_Asked_Questions_Specialty_Metals_07-26-13.pdf).

<sup>29</sup> Arena et al., *Why Has the Cost of Fixed-Wing Aircraft Risen?*, 60.

connects design engineers with the production floor and the maintenance system.<sup>30</sup> It also ties together firms throughout the supply chain, who thereby share a common picture of the entire system and all its parts. The benefits of digital thread are that it allows people involved in different stages of the product lifecycle and the supply chain to share information, explore alternatives, and quickly engineer solutions to issues in design, production, or maintenance. However, the ability to do digital thread is a major challenge for small firms in the supply chain, for whom the technical capacity required to engage in a digital thread environment can represent a prohibitively expensive investment.

Additive manufacturing is having a growing impact on the engine industrial base and offers the potential to reduce manufacturing costs and simplify maintenance through reductions in part complexity.<sup>31</sup> However, the process of qualifying additive manufacturing parts for use in critical engine applications is expensive, and it may be beyond the capacity of small firms seeking to innovate using only their own resources. Another major issue confronting the supply chain is cybersecurity. It is challenging for small firms in the supply chain to invest in the level of cybersecurity needed to protect sensitive engine designs and manufacturing technologies that are being aggressively pursued by competitors, including in many cases by nation-state actors that are targeting the U.S. engine industrial base. Because key expertise is resident in the supply chain, small, specialized firms can be high-priority targets.

Issues such as digital thread, additive manufacturing, and cybersecurity may lend themselves to solutions that allow for cooperative industry efforts, such as industry consortia working with the DoD through Other Transaction Authority (OTA) agreements. These structures let industry competitors work together, legally, on common issues and do so cooperatively with the government.

## Understanding the Military Aircraft Engine Market

There is a wide range of markets within the engine industrial base. Many of these markets are currently or potentially relevant to the military, and it is worthwhile to situate the fighter engine market—which is described in detail in Chapter 3 of this report—within the broader ecosystem of engine applications that it inhabits.

### TRANSPORTS AND TANKERS

There is significant crossover between commercial airliners and military transports. The C-5M Super Galaxy and the C-17A Globemaster III are two of the most common turbofan-powered transports in the Air Force's inventory. The C-5M is powered by General Electric's CF6 engine. Derivatives of the CF6 also power Airbus's A300, A310, and A330 airliners as well as Boeing's 747 and 767 airliners. The C-17A is powered by Pratt & Whitney's F117 engine. Like the CF6, derivatives of the F117 also power a range of commercial airliners, such as Boeing's 757.

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<sup>30</sup> Conrad Leiva, "Demystifying the Digital Thread and Digital Twin Concepts," Industry Week, August 1, 2016, <https://www.industryweek.com/systems-integration/demystifying-digital-thread-and-digital-twin-concepts>.

<sup>31</sup> Brent Donaldson, "Mission Critical: An additive manufacturing breakthrough in commercial aviation," Composites World, June 1, 2019, [https://www.compositesworld.com/blog/post/mission-critical-an-additive-manufacturing-breakthrough-in-commercial-aviation\(2\)](https://www.compositesworld.com/blog/post/mission-critical-an-additive-manufacturing-breakthrough-in-commercial-aviation(2)).

This crossover also extends to tankers, the military's aerial refueling aircraft. The KC-10 Extender, a derivative of the DC-10 airliner, retains 88 percent commonality with its commercial counterpart. The three CF6 engines that power the KC-10A represent one aspect of this commonality.<sup>8</sup> The older, but more common, KC-135 Stratotanker is powered by CFM56 engines, which are also widely used on Airbus's A320 and A340 airliners as well as Boeing's 737 airliner—not to mention the Air Force's newest tanker, the KC-46 Pegasus.

The reason for this crossover is that flight profiles for these military aircraft are much closer to those of commercial flights than to those of fighter aircraft. As a result, the engine requirements for transports and tankers resemble those of their commercial counterparts. Budgetary constraints also provide an incentive to rely on commercially developed engines where military mission profiles can be supported by commercial derivatives.

#### HELICOPTERS AND TILTROTORS

Helicopters are relatively new to the scene, compared to fixed-wing aircraft. However, their quick rise in military use has impacted the engine business and could further impact the industrial base. Today, there are almost as many helicopters and tiltrotors in the U.S. military as there are all other manned military aircraft.

Helicopters were first used for military purposes during the late days of World War II, but mostly as novelties that provided little tactical or strategic utility. Their use picked up during the Korean War, where they provided increased assistance to troops in combat.<sup>32</sup> However, their utility remained limited because helicopters were still in the early stages of development, underpowered, and unfamiliar to military planners.<sup>33</sup> During the Vietnam War, their utility increased dramatically.

Helicopters became ubiquitous in Vietnam. Driven by operational requirements, the military invested in rapid improvements to helicopter engine technology. The UH-1D (an early variant of the H-1 Huey) was first delivered to the Army in 1963, powered by a Lycoming T-53-L-11 engine capable of providing up to 1,100 shaft horsepower.<sup>34</sup> This improvement almost doubled the power of the helicopters used during the Korean War.<sup>35</sup> Since then, helicopter engine technology has continued to improve.

Modern military helicopters are powered by turboshaft engines. These engines are similar to turbofan engines, except they are optimized to produce shaft power to turn a rotor instead of producing thrust power to propel the aircraft. Turboshaft engines are also similar to turboprop engines, which are used to power fixed-wing propeller aircraft, such as the C-130 Hercules. Turboshaft engines can, therefore, be modified and scaled to power quite different aircraft. For example, General Electric's T700 engine powers military helicopters such as the AH-1 SuperCobra, the AH-64 Apache, and the UH-60 Blackhawk. The T700 also powers fixed-wing aircraft such as the Sukhoi SU-80 and the Saab 340.<sup>36</sup>

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<sup>32</sup> Otto Kreisher, "The Rise of the Helicopter During the Korean War," HistoryNet, January 16, 2011, <http://www.historynet.com/the-rise-of-the-helicopter-during-the-korean-war.htm>.

<sup>33</sup> Ibid.

<sup>34</sup> "UH-1 Huey Helicopter," Federation of American Scientists Military Analysis Network, <https://fas.org/man/dod-101/sys/ac/uh-1.htm>.

<sup>35</sup> "Sikorsky H-19 Chickasaw: Multi-Purpose / Multi-Role Transport Utility Helicopter," Military Factory, [https://www.militaryfactory.com/aircraft/detail.asp?aircraft\\_id=128](https://www.militaryfactory.com/aircraft/detail.asp?aircraft_id=128).

<sup>36</sup> "The T700 Engine," General Electric Corporation, <https://www.geaviation.com/military/engines/t700-engine>.

In terms of comparability to commercial engines, military helicopter engines lie somewhere in between fighters and transports. Relative to fighters, the performance requirements for military helicopters are not substantially different from the commercial side. However, military helicopters need to operate in vastly different conditions. This includes extreme conditions, forward-deployed contested locations where quick ingress and egress is required, or even operating off of aircraft carriers. Consequently, commercial derivatives for military helicopters often require more modifications than transports do.

#### UNMANNED VEHICLES

Unmanned aerial systems (UAS) have become ubiquitous in recent years and will represent a growing share of airborne systems. UASs use a wide variety of propulsion systems, but the largest use engines derived from manned aircraft: for example, jet engines are used on the MQ-9 Reaper (turboprop engine) and the RQ-4 Global Hawk (engine developed for business and regional jets). The propulsion capabilities required for both current and future UASs differ significantly from the capabilities required for current and future fighter jet aircraft. However, as unmanned systems develop and take on more complex mission requirements that require more sophisticated maneuvering capabilities, their engines may need to take on more fighter-like performance characteristics. In interviews, experts told the study team that the most important capabilities that engines for future UASs will need to provide are greater endurance and greater range, while being small, reliable, and low-maintenance. The demands placed upon UAS engines by their payloads may also increase. Andrew Metrick of CSIS argues that UASs could be utilized as “long dwell electronic warfare platforms operating outside of or at the edge of enemy air defenses [and as ideal platforms] to carry standoff jammers or expendable stand-in jamming munitions.”<sup>37</sup> For UASs to effectively carry out these kinds of missions, they must have enough electric power and thermal management capability for payloads such as directed energy weapons, electronic warfare, and electronic attack mission systems.

Furthermore, increased endurance of unmanned systems would enable new capabilities to be leveraged. Endurance in UASs refers to the amount of time that the systems can remain airborne. *Unmanned Systems Integrated Roadmap FY2013-2038* emphasizes that the DoD wants to develop systems that have endurance capabilities measured in days, not hours.<sup>38</sup> According to Daniel Gouré of the Lexington institute, a UAS with far greater endurance could provide critical “medium altitude ISR in a region as vast as the Western Pacific [that] would be beyond the capability of any proposed fleet of presently deployed UASs.”<sup>39</sup> In a step toward developing these ultra-high endurance UASs, in January of 2018 the USAF made a \$48 million investment in Aurora Flight Sciences to create a certified version of the Orion.<sup>40</sup> The Orion is a medium-altitude long-endurance UAS that in December of 2014 completed a flight of more than 80 hours without landing or being refueled—a world record.<sup>41</sup> Another

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<sup>37</sup> Andrew Metrick, “Bad Idea: UAVs Aren’t Usable in Contested Environments,” CSIS, December 2017, [http://defense360.csis.org/wp-content/uploads/2017/12/Metrick\\_UAVs-Contested-Environments\\_Bad-Idea-1.pdf](http://defense360.csis.org/wp-content/uploads/2017/12/Metrick_UAVs-Contested-Environments_Bad-Idea-1.pdf).

<sup>38</sup> U.S. Department of Defense, *Unmanned Systems Integrated Roadmap, FY2013-FY2038* (Washington, DC: January 2014), <http://www.dtic.mil/dtic/tr/fulltext/u2/a592015.pdf>.

<sup>39</sup> Daniel Gouré, “Need For An Ultra-Endurance UAS Is Becoming Urgent,” Lexington Institute, December 2016, <http://www.lexingtoninstitute.org/need-for-an-ultra-endurance-uas-is-becoming-urgent/>.

<sup>40</sup> Valerie Insinna, “Is the Air Force changing its mind on long-endurance drones?,” *DefenseNews*, January 8, 2018, <https://www.defensenews.com/air/2018/01/08/aurora-ceo-optimistic-about-future-of-long-endurance-drones/>.

<sup>41</sup> *Ibid.*



capability likely to be of increasing importance to future unmanned systems is stealth. This can be accomplished through improvements to existing engine designs or incorporated upfront in a new engine design effort.

While the historical pattern of UAS development has been to leverage engines built primarily for commercial use, industry experts stated that since UASs do not require life support systems, radically different engine designs could be explored to most efficiently advance their unique capabilities. However, industry experts also stated that this type of experimentation has not been widespread due to DoD underinvestment in UAS engine technology. One industry source told the study team that “investments in small military engines and medium thrust class engines (the class of engines that UASs typically utilize) are incurring the brunt of the historic funding cuts.” At the same time, there is a significant gap between what current UAS engine propulsion systems can do and the UAS capabilities the military envisions in the future. Thus, to develop new UAS propulsion technology that would enable the DoD to best leverage the capabilities of UASs, sustained S&T programs on small engines similar to those of the S&T programs on the largest class of engines are required.

#### HYPERSONIC SYSTEMS

In recent years, the United States, Russia, and China have made efforts to develop combat-useable hypersonic weapons.<sup>42</sup> Hypersonic weapons are commonly defined as weapons capable of traveling at speeds of Mach 5 or faster. Current missile defense systems could be rendered ineffective by hypersonic weapons due to their speed and maneuverability.<sup>43</sup> According to Richard Speier of the RAND corporation, “hypersonic missiles require a reconsideration of traditional second-strike calculations, as they have the potential to decapitate a nation's leadership before it has the opportunity to launch a counter attack,” thus inviting “trigger-happy state behavior.”<sup>44</sup> Hypersonic missiles could be one of the new, game-changing weapon systems of the twenty-first century.

There are two categories of hypersonic missiles: hypersonic glide vehicles (HGVs) and hypersonic cruise missiles (HCMs). HGVs are launched via rockets to the upper level of the atmosphere, at which point they are released and “glide” at hypersonic speeds to their targets. In contrast, HCMs are powered by rockets or scramjet engines all the way to their targets—they are essentially advanced cruise missiles. HCMs could potentially be fired from current fighter jets. According to a RAND corporation analysis, both types of hypersonic weapon systems may be combat-ready in a decade or less.<sup>45</sup>

However, before a hypersonic weapon is ready for combat, there are significant engineering hurdles that need to be overcome—particularly for HCMs. First, the aerodynamic environment at hypersonic speeds makes controllability quite difficult. Second, traveling at hypersonic speeds generates immensely high temperatures. The missile would need to be able to withstand these temperatures for extended periods of time. Third, igniting a

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<sup>42</sup> Richard Speier et al., *Hypersonic Missile Nonproliferation* (Santa Monica, CA: RAND Corporation, 2017), xii, [https://www.rand.org/pubs/research\\_reports/RR2137.html](https://www.rand.org/pubs/research_reports/RR2137.html).

<sup>43</sup> *Ibid.*, xi.

<sup>44</sup> Richard Speier, “Hypersonic Missiles: A New Proliferation Challenge,” RAND Corporation, March 20, 2018, <https://www.rand.org/blog/2018/03/hypersonic-missiles-a-new-proliferation-challenge.html>.

<sup>45</sup> Speier et al., *Hypersonic Missile Nonproliferation*, xii.

scramjet engine at hypersonic speed “has been compared to lighting a match in a 5,000 km/hr wind.”<sup>46</sup> To overcome these challenges, significant investment would be needed.

Russia has reportedly had success in developing an HCM. In March of 2018, the Russian Air Force reportedly tested an operational, hypersonic cruise missile called the “Dagger.”<sup>47</sup> The Dagger was launched from MiG-31, and President Putin boasted that the missile was capable of reaching speeds up to Mach 10.<sup>48</sup> However, U.S. Secretary of Defense Jim Mattis categorized President Putin’s claims as “election rhetoric,” adding that the capabilities the Russians claimed to possess were “still years away.”<sup>49</sup>

China has also made progress in the field of hypersonic systems. Under Secretary of Defense for Research and Engineering Michael Griffin spoke to the Senate Armed Services Subcommittee on Emerging Threats and Capabilities in April of 2018 regarding hypersonic weapons. Griffin stated that “China has fielded or can field . . . hypersonic delivery systems for conventional prompt strike than can reach out thousands of kilometers from the Chinese shore and hold our carrier battle groups or our forward deployed forces . . . at risk.”<sup>50</sup> Reportedly, China’s hypersonic achievements have been in regard to HGVs.<sup>51</sup>

Investment in hypersonic weapon development in the United States was given a significant boost in April 2018, when Lockheed Martin was awarded a \$928 million indefinite-delivery/indefinite-quantity contract to develop a conventional strike hypersonic weapon.<sup>52</sup> This recent and substantial investment in hypersonic technology is due to a fear that the United States has fallen behind China and Russia in the development of hypersonic weapons. However, experts in industry have expressed a worry that heavy investment in hypersonic systems will divert funds away from other propulsion development efforts, such as small engines, three stream adaptive engines, and engines for next-generation UASs. These industry experts emphasize that future investment and development strategies must promote the health of the entire engine industrial base.

## ELECTRIC

Since the advent of heavier-than-air flight, aircraft have, for the most part, been powered by fossil fuels. However, in recent years, due to significant improvements in battery technology, electrically-powered aircraft have become genuinely feasible. For instance, a team at the University of Stuttgart developed the E-Genius in May of 2011. This two-seater electric powered aircraft reached a speed of 142 miles an hour and flew nonstop for 300 miles.<sup>53</sup> More recently, in late 2017, Slovenia-based manufacturer Pipistrel received

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<sup>46</sup> Ibid., 38.

<sup>47</sup> Tamir Eshel, “Hypersonic Weapons Enter Service with Russian Aviation,” Defense Update, March 2, 2018, [http://defense-update.com/20180302\\_new\\_russian\\_strategic\\_weapons.html](http://defense-update.com/20180302_new_russian_strategic_weapons.html).

<sup>48</sup> Radio Free Europe Radio Liberty, “Russia Test-Fires ‘Hypersonic’ Missile, U.S. Sees No Change In Capability,” RFE/RL, March 11, 2018, <https://www.rferl.org/a/russia-test-fires-hypersonic-kinzhal-missile-dagger/29091423.html>.

<sup>49</sup> Ibid.

<sup>50</sup> Ben Brimelow, “Pentagon warns that the US is falling behind to China in hypersonic missile race,” Business Insider, April 20, 2018, <http://www.businessinsider.com/us-falling-behind-to-china-hypersonic-missile-race-2018-4>.

<sup>51</sup> Ibid.

<sup>52</sup> “Contracts for April 18, 2018,” U.S. Department of Defense, <https://www.defense.gov/News/Contracts/Contract-View/Article/1497461/>.

<sup>53</sup> “Why 2025 Matters: Fly Electric, the Aircraft of the Future Takes Flight,” *The Atlantic*, <https://www.theatlantic.com/sponsored/thomson-reuters-why-2025-matters/electric-flight/208/>.

certification from the Australian Civil Aviation Safety Authority for its Alpha Electro—a two-seater, single propeller, electric-powered light aircraft.<sup>54</sup> The Alpha Electro is capable of staying in the air for an hour. Furthermore, the Alpha Electro costs as little as 3 dollars to operate per hour, and thus Pipistrel is currently marketing it as a low-cost training aircraft.<sup>55</sup> Electric-powered aircraft are not theoretical R&D projects—they are already here.

Electric-powered engines do provide some unique advantages when compared to airbreathing, fossil-fuel-burning engines. Electric engines do not need air and thus do not lose performance at higher altitudes in the same way that traditional engines do.<sup>56</sup> Electric engines also do not require provisions for features such as cooling lines, gas lines, and air intakes and thus can be mounted to an airframe in new, untried ways.<sup>57</sup> This could allow for experimentation with new airframes that could potentially reduce the power needed for flight, thus making electric aircraft even more viable.<sup>58</sup> Furthermore, electric engines have significantly fewer moving parts than traditional engines.<sup>59</sup> This reduces the maintenance needs of electric engines and makes them theoretically more reliable than their traditional counterparts.<sup>60</sup> Finally, electric engines also have lower per-hour operating costs and are significantly quieter. These characteristics of electric engines open new doors for aviation, including potentially for military aviation.

While some of the wished-for applications for electric aviation attempt to use existing infrastructure, others, such as Uber's "Uber Elevate," proposed constructing an entirely new component of civilian transportation infrastructure to take advantage of the unique capabilities of electric aviation. Uber wanted the aerospace industry to design and produce lightweight electric aircraft that can cruise at between 150 and 200 miles per hour, reach up to 2,000 feet altitude, have a range of around 60 miles, and carry four people plus a pilot.<sup>61</sup> These aircraft then would be flown from the tops of buildings in urban centers and create a sort of "sky taxi" service.<sup>62</sup> Uber had the ambitious goal of beginning demonstration flights of these types of vehicles by 2020 with commercial flights starting in 2023.<sup>63</sup> In late 2020, though, Uber sold off its Uber Elevate business to industrial partner Joby Aviation.<sup>64</sup>

Before electric-powered aviation can become commonplace there are two large hurdles to overcome: battery technology and regulatory barriers. Even with significant recent advances

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<sup>54</sup> Rich Haridy, "Battery-powered electric plane quietly takes to Australian skies for the first time," *New Atlas*, January 7, 2018, <https://newatlas.com/electric-aircraft-test-flight-australia/52846/>.

<sup>55</sup> Nicolas Zart, "The Pipistrel Alpha Electro, An Awesome 2-Seat Electric Trainer," *Clean Technica*, November 13, 2017, <https://cleantechnica.com/2017/11/13/pipistrel-alpha-electro-awesome-2-seat-electric-trainer/>.

<sup>56</sup> George C. Larson, "Electrical Power Will Change the Look of Aviation," *Air & Space Magazine*, December 2015, <https://www.airspacemag.com/flight-today/NASA-electric-propulsion-180957302/>.

<sup>57</sup> Ibid.

<sup>58</sup> Rob Mark, "Electric Aircraft Might Become an Industry Standard Sooner than Expected," *Flying Magazine*, April 3, 2018, <https://www.flyingmag.com/electric-aircraft-might-become-an-industry-standard-sooner-than-expected/>.

<sup>59</sup> Ibid.

<sup>60</sup> Ibid.

<sup>61</sup> Jack Stewart, "Uber Unveils the Flying Taxi It Wants to Rule the Skies," *Wired*, May 8, 2018, <https://www.wired.com/story/uber-unveils-flying-taxi/>.

<sup>62</sup> Ibid.

<sup>63</sup> "Joby Aviation Welcomes New \$75M Investment from Uber as it Acquires Uber Elevate and Expands Partnership," Joby Aviation, Dec 8, 2020, <https://www.jobyaviation.com/news/joby-aviation-welcomes-new-75m-investment-from-uber-as-it-acquires-uber-elevate-and-expands-partnership/>.

<sup>64</sup> Andrew J. Hawkins, "Uber reportedly will sell its flying taxi business to secretive startup Joby Aviation," *The Verge*, December 2, 2020. <https://www.theverge.com/2020/12/2/22086597/uber-sells-flying-taxi-elevate-joby-aviation>.

in battery technology, batteries still yield significantly less power than jet fuel. Currently, 1,000 pounds of jet fuel yields about 14 times more energy than a 1,000-pound battery.<sup>65</sup> For example, a Boeing 787 carries about 223,000 pounds of jet fuel. A battery pack with the same amount of energy as 223,000 pounds of jet fuel would weigh approximately 4.5 million pounds.<sup>66</sup> The comparatively heavy weight of batteries is particularly problematic for aviation, where it is crucial to keep unnecessary weight down. To produce a fully electric aircraft capable of anything but short flights would require investment in, and development of, new battery technologies.

Electric-powered aircraft could have various military applications if the technology continues to mature. As noted, electric aircraft are significantly quieter and thus would be ideal for special operations insertions where stealth is highly valued. Electric aircraft could also be used to quickly move troops around an area of operations. In addition, electric engines could have applications for UASs. However, regardless of how the military ends up utilizing electric aircraft, industry experts have stated that the actual development of the technology will most likely be carried out by commercial players.

## Major Military Engine Competitors

The United States has been a leader in the production of military engines since the dawn of the jet age. High-performance engines are designed and produced in only a few countries, and the main U.S. fighter engine companies, General Electric and Pratt & Whitney, are generally acknowledged to have the world's leading engine designs and manufacturing capabilities. While Pratt & Whitney is the prime contractor for the biggest fighter engine acquisition program currently underway, the F135, GE is the prime contractor for the Army's Improved Turbine Engine Program (ITEP). Other U.S. engine manufacturers, such as Honeywell, Williams, and Rolls Royce North America, produce high-quality engines used on a range of other U.S. defense systems, such as missiles, UAVs, and cargo aircraft. Capable fighter engines are also produced in Europe, for example the EJ200 Eurojet engine used on the Typhoon Eurofighter and the M88 used on the Dassault Rafale, with technology developed by Rolls Royce and Safran. While Europe-based engine manufacturers dominate the production of engines for European fighter designs, these systems and the technology that powers them are generally restricted to use by U.S. allies and partners and do not represent a threat to U.S. military interests. Rather, the primary threat to the U.S. technological advantage in engine technology comes from Russia and China.

U.S. and Western technological advantage in fighter engines could erode substantially if U.S. engine technology development were to stand still. Given the significantly slowing pace of U.S. deployment of engine technology since the 1990s, the conditions necessary for such an erosion are certainly present, but they are not foreordained. Russia and China are currently

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<sup>65</sup> Eric Adams, "The Age of Electric Aviation Is Just 30 Years Away," *Wired*, May 31, 2017, <https://www.wired.com/2017/05/electric-airplanes-2/>.

<sup>66</sup> Samantha Masunaga, "No flying Tesla? That's because electric planes are a steeper challenge than electric cars," *Los Angeles Times*, September 9, 2016, <http://www.latimes.com/business/la-fi-electric-aircraft-20160830-snap-story.html>.

investing aggressively in fighter engine development.<sup>67</sup> While the engines currently produced by these nations can deliver engine performance similar to U.S. engines in individual flights and engagements, there is a critical difference in the reliability of U.S. engines and their ability to perform over time. This difference translates into a major advantage over the course of an air campaign, resulting in dramatic increases in U.S. aerial capability due to superior sortie generation, performance margin, and reliability in critical engagements. The U.S. advantage is built on both design expertise and manufacturing sophistication.

## RUSSIA

While Russian fighter jet capabilities were close to or on par with that of U.S. fighter jets during the Cold War, Russian engine technology often lagged behind that of the United States.<sup>68</sup> Russia consistently relied on foreign engines to support its fighter jet fleets but was unable to fully master those designs—for example, during the Korean War, Russia reverse-engineered Rolls-Royce’s Nene engine onto MiG-15s and surprised the West with their speed and range, but ultimately faced problems with performance due to use of substandard materials and less precise engineering.<sup>69</sup> However, Russia has more recently devoted significant energy and capital to bringing up its engine development capabilities closer to U.S. standards.

After the Cold War, the Russian aviation companies underwent a period of instability with limited resources and declining manufacturing capabilities. To counter these losses, President Vladimir Putin mandated an industry-wide consolidation in 2006 that rolled up various companies into the United Aircraft Corporation (UAC), including companies in both commercial and military aviation.<sup>70</sup> This vertical integration was intended to expedite the development process and increase competitiveness, a goal it has largely managed to accomplish. Today, all Russian fighter jets operate with Russian-made engines, and Russia has had success exporting its jet engines abroad (as in the case of China’s J-20, which relies on the AL-31F turbofan developed by NPO Saturn).<sup>71</sup> While Russian jet engines may still not perform at the level of their U.S. counterparts, UAC continues to invest significant resources toward closing that gap.

Today, Russia is in the process of developing its first fifth-generation fighter, the Su-57 (also known as the PAK FA or T-50). The aircraft is expected to use the new Izdeliye-30

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<sup>67</sup> “With New Engine, Russia to Re-Pitch Su-57 Stealth Fighter Jet to India,” *Defense World.net*, August 23, 2018, [https://www.defenseworld.net/news/23231/With\\_New\\_Engine\\_Russia\\_to\\_Re\\_pitch\\_Su\\_57\\_Stealth\\_Fighter\\_Jet\\_to\\_India#.XNwlQjBKipo](https://www.defenseworld.net/news/23231/With_New_Engine_Russia_to_Re_pitch_Su_57_Stealth_Fighter_Jet_to_India#.XNwlQjBKipo); and Huang, “China’s new jet engine.”

<sup>68</sup> Aneli Bongers and Jose Torres, “Measuring technological trends: A comparison between U.S. and U.S.S.R./Russian jet fighter aircraft,” *Technological Forecasting and Social Change* 87 (September 2014), 132, <https://www.sciencedirect.com/science/article/pii/S0040162513003144?via%3Dihub>.

<sup>69</sup> Stephen Joiner, “The Jet that Shocked the West,” *Air & Space Magazine*, December 2013, <https://www.airspacemag.com/military-aviation/the-jet-that-shocked-the-west-180947758/>.

<sup>70</sup> “History,” United Aircraft Corporation, accessed September 12, 2018, <http://www.uacrussia.ru/en/corporation/history/>.

<sup>71</sup> Kyle Mizokami, “China’s Super Fighter Comes Online – With Inferior Engines,” *Popular Mechanics*, February 13, 2018, <https://www.popularmechanics.com/military/aviation/a17763845/chinas-super-fighter-comes-online-with-inferior-engines/>.

turbofan engine, and a Su-57 prototype had its first successful test flight in December of 2017.<sup>72</sup> While the Izdeliye-30 development has faced its challenges, UAC is clearly making progress in increasing the thrust capacity of its jet engines and continues to invest in new materials and methods, including additive manufacturing and composites.<sup>73</sup>

However, there are risks to this growth trajectory. The Izdeliye-30 likely will not be ready for production until 2025, which suggests that it may have encountered some snags in development.<sup>74</sup> Meanwhile, Russia may lose some of its core engine export customers—China has begun to invest in its own jet engine industrial base after years of depending on Russian designs, such as the AL-31.<sup>75</sup> Without that core market, Russia will be less able to buy quality materials and fund its own engine development.

## CHINA

During the Cold War, China's domestic capacity to design and produce military engines was almost nonexistent. China largely relied on imported jet engines from the Soviet Union, with some technology imported from Western countries until the arms export embargo following the 1989 Tiananmen Square massacre cut off the flow of information.<sup>76</sup>

However, in recent times, China has devoted itself to building out its own internal fighter jet capability, including variants such as the J-10 and J-20. However, most of these homegrown fighters still rely on Russian engines; although efforts have been made to install the Chinese-made WS-10 onto various aircraft.<sup>77</sup>

Like Russia, China has developed its own fifth-generation fighter, the J-20. Also like Russia, the program has encountered many problems. The Chinese-made WS-15 engine was intended to power the J-20; this would have enabled the J-20 to cruise at supersonic speeds without utilizing afterburners.<sup>78</sup> However, the WS-15 has been plagued with development

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<sup>72</sup> Tom Demerly, "Russia's Su-57 Stealth Fighter Completes Engine Upgrade and Continues Development Amid Business Concerns," *The Aviationist*, December 22, 2017, <https://theaviationist.com/2017/12/22/russias-su-57-stealth-fighter-completes-engine-upgrade-and-continues-development-amid-business-concerns/>.

<sup>73</sup> David Cenciotti, "Guess what's worse than a flameout on take off? A flameout on catapult launch from an aircraft carrier," *The Aviationist*, August 22, 2011, <https://theaviationist.com/2011/08/22/flameout/>; and Maxim Pyadushkin, "Russia Launches PD-35 Heavy Engine Development," *Aviation Week*, February 7, 2018, <http://aviationweek.com/singapore-airshow-2018/russia-launches-pd-35-heavy-engine-development>.

<sup>74</sup> Daniel Brown, "Russia has begun testing its new Su-57 stealth fighter engine – but there's a snag," *Business Insider*, December 15, 2017, <https://www.businessinsider.com/su-57-russia-testing-new-stealth-fighter-engine-2017-12>.

<sup>75</sup> David Lague and Charlie Zhu, "Unable to copy it, China tries building own jet engine," *Reuters*, October 30, 2012, <https://www.reuters.com/article/uk-china-engine/unable-to-copy-it-china-tries-building-own-jet-engine-idUSLNE89TooW20121030>.

<sup>76</sup> Mizokami, "China's Super Fighter Comes Online."

<sup>77</sup> Jeffrey Lin and P.W. Singer, "The Next Generation of China's Carrier-Borne Fighter, The Flying Shark, Takes to the Skies," *Popular Science*, September 20, 2016, <https://www.popsci.com/he-next-generation-chinas-carrier-borne-fighter-flying-shark-takes-to-skies>; and Minnie Chan, "Why China's first stealth fighter was rushed into service with inferior engines," *South China Morning Post*, August 30, 2018, <https://www.scmp.com/news/china/diplomacy-defence/article/2130718/why-chinas-first-stealth-fighter-was-rushed-service>.

<sup>78</sup> "Chinese Military Aviation Overcomes its Engine Woes; Has the PLA Surpassed the Greatest Obstacle in its Military Modernisation Program?," *Military Watch Magazine*, January 22, 2018, [http://militarywatchmagazine.com/read.php?my\\_data=60271](http://militarywatchmagazine.com/read.php?my_data=60271).

problems; in 2015, reports surfaced that a WS-15 exploded on the ground during a test.<sup>79</sup> Due to these issues, less-powerful WS-10B engines have had to be used. Until China can perfect its engine production process, it will be incapable of fielding a true fifth-generation fighter aircraft.

China has taken several approaches to improving its internal engine development capabilities. First, it centralized its efforts to aircraft technology development by consolidating the aviation industry into the state-owned Aviation Industry Corporation of China (AVIC), similar to Russia's approach with UAC.<sup>80</sup> China then pushed significant funding toward jet engine development, with some reports citing as much as \$22 billion invested in that effort between 2010 and 2015.<sup>81</sup> Finally, AVIC and other parts of the Chinese aviation industry have made strategic investments into Western engine technologies, in many cases acquiring Western companies, such as Germany's Thielert Aircraft Engines.<sup>82</sup> In some cases, they have also conducted corporate espionage to obtain information.<sup>83</sup>

There is evidence that China's efforts to improve its engine development are paying off. Earlier this year, China began talks with Germany to sell jet engine technology for turbine blades, which suggests that China is beginning to close the gap with the West in certain areas of engine materials, components, and development.<sup>84</sup> While China's fifth-generation fighter, the J-31, is slated to use the Russian-made RD-93 engine, there have been discussions about replacing it with the Chinese-made WS-13, which could theoretically match the capabilities of the RD-93.<sup>85</sup> While current Chinese jet engine technology might lag the United States, the effort and funding being applied to the problem suggests that the United States should keep an eye on China's progress.

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<sup>79</sup> Mizokami, "China's Super Fighter Comes Online."

<sup>80</sup> "Overview," Aviation Industry Corporation of China, <http://www.avic.com/en/aboutus/overview/>.

<sup>81</sup> Minnie Chan, "Engine boost for China's J-15 fighter jets as Beijing tries to build up navy," *South China Morning Post*, September 7, 2018, <https://www.scmp.com/news/china/diplomacy/article/2163126/engine-boost-chinas-j-15-fighter-jets-it-tries-build-navy>.

<sup>82</sup> Eugene Chow, "China May have Solved the One Thing That Was Poised to Stop Its Military Rise," *National Interest*, January 20, 2018, <https://nationalinterest.org/blog/the-buzz/chinas-may-have-solved-the-one-thing-was-poised-stop-its-24149>.

<sup>83</sup> Sophia Yan, "Why China wants U.S. military jet engines," CNN Money, June 10, 2016, <https://money.cnn.com/2016/06/10/news/us-china-military-jet-engine-espionage/index.html>.

<sup>84</sup> Stephen Chen, "China in talks for sale of jet engine technology to Germany," *South China Morning Post*, January 14, 2018, <https://www.scmp.com/news/china/society/article/2127796/china-talks-sale-jet-engine-technology-germany>.

<sup>85</sup> Jeffrey Lin and P.W. Singer, "China's J-31 stealth fighter gets an improved prototype – and a potential future on a carrier," *Popular Science*, May 1, 2017, <https://www.popsoci.com/j-31-stealth-fighter-improved-prototype>.

## Military Aircraft and Engine Trends

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To understand the nature and importance of the competitive advantage in military aircraft engines that the United States has today, it is important to understand how this advantage was developed. Assessing historical trends in U.S. military engines will help answer several questions: What factors helped the United States develop and sustain its advantage? Which of these factors still exist and which are no longer relevant? And which factors are gone but may be possible to bring back?

### Aircraft Trends

To begin assessing historical aircraft trends relevant to military engines, this study analyzes the pace of generational change in fighter/attack engines based on a data set of Air Force aircraft on which they are deployed.<sup>86</sup> We focus this part of our analysis on the Air Force for two reasons:

- 1) Air Force data is more accessible and organized. Combining Air Force variables that were easy to collect, such as inventory numbers and performance specifications, allowed us to do data analysis that had not been done or made publicly available before.
- 2) The Air Force has always been at the forefront of engine development (except for helicopter engines, which the Army has led). The Navy has, at times, been alongside the Air Force but typically follows the Air Force in engine development, especially in the past three decades.

There are two broad trends within Air Force aircraft inventories that are immediately apparent and that have a profound impact on the engine industrial base: first, the Air Force is flying substantially older aircraft, and second, they are flying substantially fewer aircraft overall. The next two figures show just how significant these two trends are.

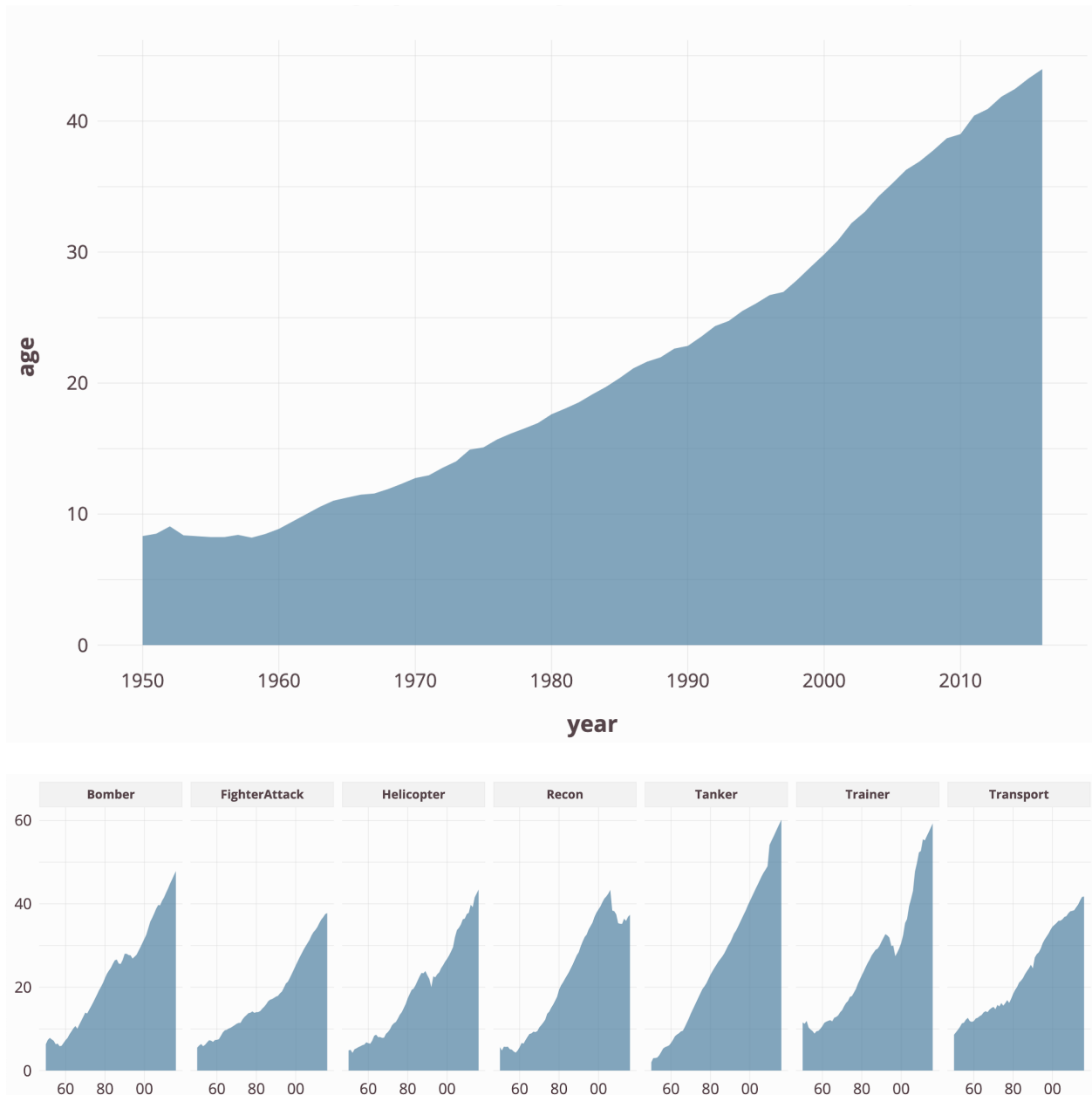
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<sup>86</sup> The study team built this data set by updating and expanding an existing data set created by the Air Force Association's Mitchell Institute. See our methodology for a detailed description of the data sets used in this analysis.



## AGING FLEET

Figure 1: Average Platform Age of the USAF Inventory



The first figure tracks the average platform age of the U.S. Air Force inventory.<sup>87</sup> In 2011, the average age for all platforms surpassed 40 years. The last time that the average age

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<sup>87</sup> This figure takes the entire USAF inventory and calculates the average platform age. The study team determined the age for each aircraft in a given year by calculating the first year that each platform entered the active USAF inventory, and then weighting the age by its inventory relative to the inventory of the total force in a given year. For example, according to our sources, the F-16 was introduced in 1975 and the F-35 was introduced in 2010. In

decreased was in the late-1950s. Fighter Attack platforms, the category with the most aircraft, will reach an average age of 40 years within the next two years (based on the current pace of retirements and F-35 procurement).<sup>88</sup> Air Force aircraft platform age is only a proxy for the aging of the engine fleet, but a useful one because the trend is clear. Although a similar level of specificity for Army and Navy aircraft age is lacking, the trends are similar. A single platform may go through different engines throughout its lifetime, whether it is a replacement engine or an upgrade. For example, the F-16 (introduced in 1975) had four distinct engines, which means that average engine age will vary from the F-16 platform age. However, the trend lines are similar. Even when new engines are installed on older aircraft, the platform imposes design limitations on engine technology and constrains the scope and scale of upgrades. Platform age is therefore a useful indicator for evaluating the trade-offs that the U.S. military has had to make in engine development.

To defense experts, the fact that Air Force aircraft are aging is nothing new. But the degree of this trend is marked, especially within certain categories. There are several consequences that concern this report. As aircraft age, sustainment costs increase to keep aircraft flying beyond their expected service life. This is especially true for engines, which do not have the same lifespan as airframes and need substantial maintenance as they age. Often engines need to be replaced before the aircraft completes its service life. This provides revenue for the military engine industrial base; however, it tends to focus the work of the industrial base on sustaining existing engine fleets rather than on designing new ones.

Many of the aircraft in the Air Force fleet have not only flown well beyond their expected service life but have also flown more frequently than expected. Operations in Afghanistan, Iraq, and beyond have put enormous stress on engines. This trend further compounds the need to raise sustainment costs, constraining the level of government resources for engine development.

As aircraft age, the need to replace older platforms with newer ones increases. If the Air Force, Navy, and Army follow through on their plans to do just this, aircraft procurement costs will increase in the next few decades. Furthermore, in most aircraft categories, there is only one platform that will be procured for the foreseeable future to replace those currently in the fleet.<sup>89</sup> So, while procurement numbers may increase, there will only be a handful of new platforms that will enter into the inventory. This dynamic has progressively limited the pace of military engine development over time. With fewer new aircraft being procured and given the long timelines for new aircraft being introduced into the inventory, there has been a significant slowdown in the tempo of engine development to support aircraft development.

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2015, the platform age is 40 for the F-16 and 5 for the F-35. So, if the entire USAF inventory consisted of 80% F-16s and 20% F-35s, we would calculate the 'Average platform age of the USAF inventory' to be 33 years (calculation:  $40 * .8 + 5 * .2 = 33$ ).

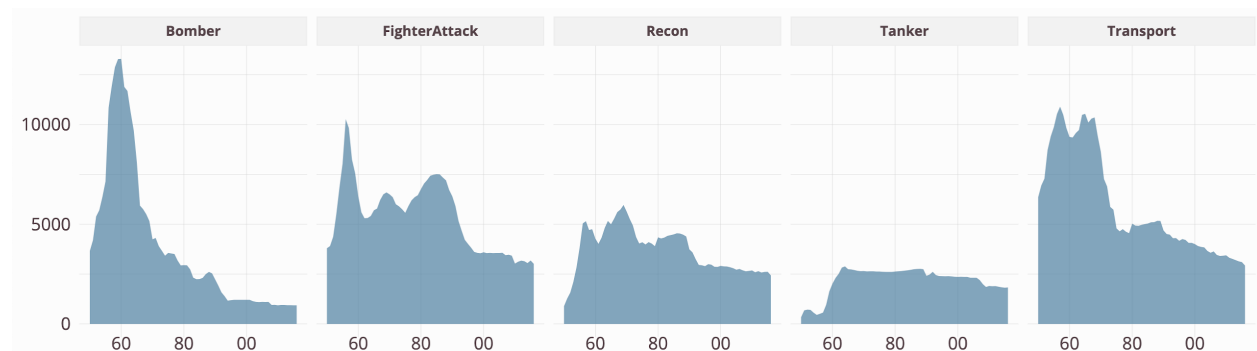
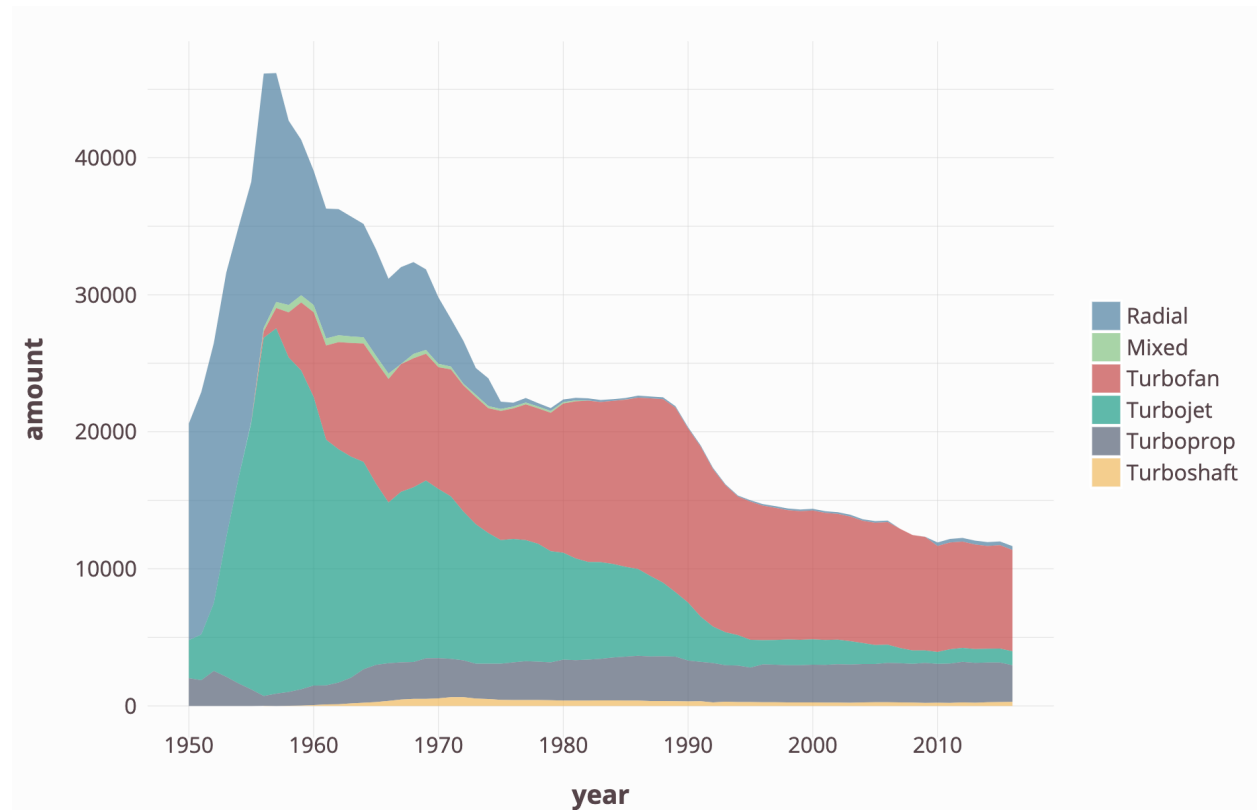
<sup>88</sup> This assumes that the trend will continue based on current retirement and procurement plans.

<sup>89</sup> In the case of Bombers, the B-21; Fighter/Attack, the F-35; Helicopter, the Combat Rescue Helicopter; and Tanker, the KC-46.

With higher sustainment costs and the rising need for additional procurements that comes with an aging fleet, R&D funding is at risk of being squeezed. Therefore, while DoD senior leadership emphasizes the need to adapt quickly to new threats with agile innovation, there is a substantial competition for resources which limits this ability. And since Operation and Sustainment (O&S) and procurement are immediate pressing needs, R&D for engine development can often be found on the chopping block.

### SHRINKING ENGINE AND AIRCRAFT FLEETS

**Figure 2: USAF Engine Inventory on Active Aircraft**



Note: This number is calculated by taking the number of aircraft and multiplying it by the number of engines on each type of platform. This, therefore, excludes extra engines that are stored on airbases, but not the aircraft itself. This also excludes rare aircraft with variable engine counts, such as the KC-97 and NT-29.

The second broad trend is that the number of aircraft and engines in the inventory is much lower than past levels. Figure 2 shows the number of engines on active Air Force aircraft each year. There are several factors that explain this trend.

For one, the relative size of the defense budget has dropped since the end of the Cold War. Changes in the security environment after the fall of the Soviet Union led the U.S. military to decrease the number of aircraft in its active inventory. This, of course, does not explain the entire decrease because the larger drop began well before the end of the Cold War. However, an important reason for decreasing inventory has been the increasing capabilities of aircraft. So even if the relative size of the defense budget had remained stable in the second half of the twentieth century, the military would likely have decreased the number of aircraft in its inventory.

These two decisions—to decrease the relative size of the defense budget after the Cold War and to lower the number of aircraft as capabilities improve—have had several important consequences for the military engine industrial base.

## JET ENGINE TYPES

**Turbojet:** These engines were the first jet engines. With turbojets, all air entering the engine passes through its core. As air enters, the compressor increases the pressure of the air. The high-pressure air then enters the combustor where fuel is injected. This fuel-air mixture ignites and passes through turbines, which extract energy from the hot gas to power the compressor. The hot gas that is produced from the ignition also provides the thrust to propel the aircraft.<sup>90</sup>

**Turbofan:** These engines are the modern version of jet engines. Most fixed-wing aircraft, both commercial and military, use these engines because of their high thrust and better fuel efficiency. Unlike turbojets, not all the inlet air passes through the core. Turbofans also have a fan in the front of the engine that is powered by the turbines. Some of the air that enters the fan is bypassed around the engine. The fan then acts as a propeller for this air. As a result, a turbofan gets power from the thrust of the core (like a turbojet) and from the fan (like a propeller).<sup>91</sup>

Many turbofan engines (and turbojets) are equipped with afterburners. Afterburners are located at the rear of the engine and inject fuel into the hot exhaust. As the fuel burns, it produces additional thrust. However, this process is inefficient and burns a lot of fuel. Use of afterburners only when extra speed is required allows the aircraft to cruise relatively efficiently but still achieve high thrust when necessary.<sup>92</sup>

**Turboprop:** These engines use a gas turbine core to power a propeller. Since the efficiency of propellers becomes less efficient when the speed of the aircraft increases, turboprops are used to power lower-speed aircraft, such as some U.S. military transports.<sup>93</sup>

**Turboshaft:** These engines are variants of a jet engine that are designed to generate shaft power instead of thrust. Shaft power is the mechanical power that drives machinery, such as helicopter blades. They are similar to turboprop engines. Turboshaft engines are used to power the U.S. military's helicopters.<sup>94</sup>

**Adaptive Turbofan:** The Air Force is currently investing in this new type of engine. The goal of this investment is to develop engines which can change the way air flows through the engine during flight to maximize efficiency in different flight regimes. Adaptive turbofans accomplish this by adding a third stream of air in the engine—turbojets have one air stream, turbofans have two air streams, and adaptive turbofans would have three. By varying the amount of air passing through the outer two airstreams, the engine can better task its resources to optimize efficiency in flight regimes such as high-altitude flight or to increase performance in other flight regimes such as take-off or during combat maneuvers.

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<sup>90</sup> "History," NASA, <https://history.nasa.gov/SP-468/ch10-3.htm>.

<sup>91</sup> Ibid.

<sup>92</sup> "Afterburning Turbojet," NASA Glenn Research Center, NASA, <https://www.grc.nasa.gov/www/k-12/airplane/Animation/turbtyp/etar.html>.

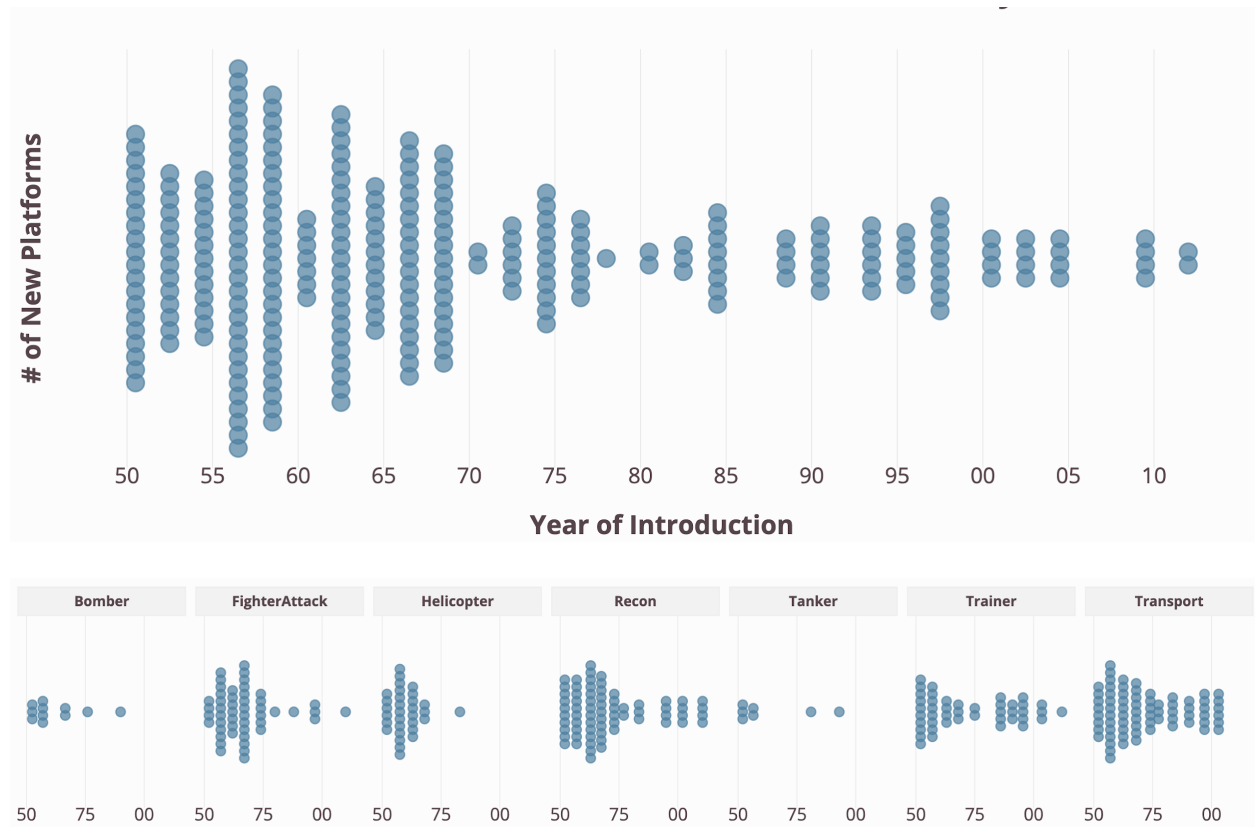
<sup>93</sup> "Turboprop Engine," NASA Glenn Research Center, NASA, <https://www.grc.nasa.gov/www/k-12/airplane/aturbp.html>.

<sup>94</sup> "Turboshaft Engine," Skybrary, [https://www.skybrary.aero/index.php/Turboshaft\\_Engine](https://www.skybrary.aero/index.php/Turboshaft_Engine).

### SLOWING RATE OF INTRODUCTION

To identify the consequences of a reduced defense budget and decreased number of aircraft, it helps to dive deeper into inventory trends and examine the rate of introduction of new platforms. One major factor that has led to a reduction in inventory levels has been the slowing introduction rate of aircraft.

Figure 3: Introduction Rate for the USAF Inventory



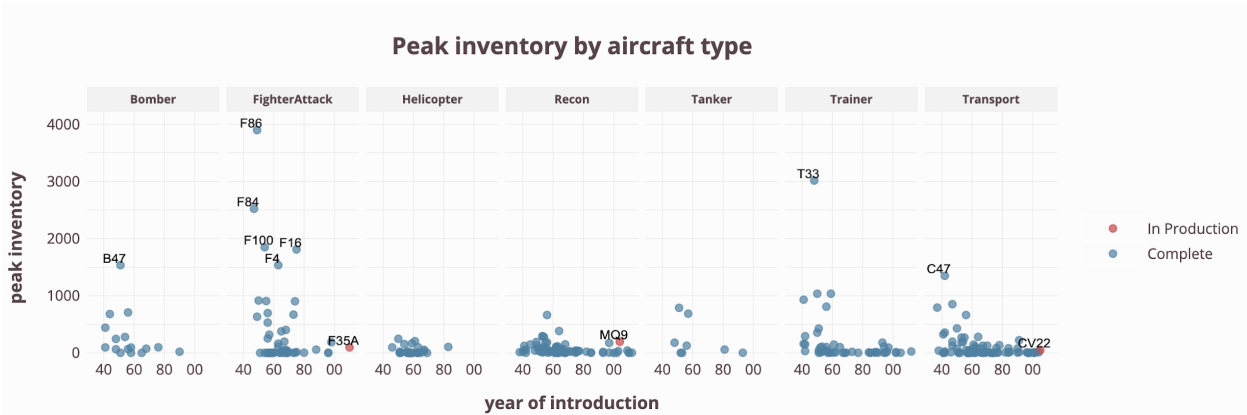
In this figure, each dot represents a distinct aircraft (e.g., B-52, F-15) and is located along the x-axis based on the aircraft's year of introduction. For the Air Force overall, and for each category, there has been a notable decrease in the introduction rate. For example, with fighter/attack aircraft (1950–present), there were five years when at least four new platforms were introduced. All five of these years were before 1980. Moreover, in the past three decades, the Air Force has only introduced four new fighter/attack platforms.

This has several implications on military engines. First, most aircraft have one type of engine during their lifetime and most new engines are designed for new aircraft. Therefore, jumps in the state of engine technology often accompany new aircraft. So, as the drumbeat of aircraft introduction slows, the pace of new engine development slows with it. While the engine industrial base may be developing technology at a more robust pace, only a portion of this technology can be employed in each new design, and fewer new designs means that the deployment of new engine technology is inherently constrained.

Second, there are also cases when new engines are built for existing aircraft, such as with the F-16, where an additional engine design was built for the platform after its initial deployment. Similarly, large numbers of the KC-135 aircraft were reengined with a new, more modern engine after a few decades of operation. Upgrading engines for active aircraft also allows for incremental improvements while waiting for new aircraft, but there are two major constraints here as well. The improvements are limited because the engine upgrades must conform to the initial airframe design. So, if the goal is to increase power but the airframe is quite small or has structural limitations, then the scope of the upgrade will be limited by constraints imposed in the initial airframe design. Moreover, the case for upgrading engines for active aircraft is most compelling when the quantity of aircraft is high enough to justify a significant investment in the capability. Lower inventory levels reduce the impact that such an investment can have on fleet operations.

LOWER INVENTORY LEVELS

Figure 4: Peak Inventory by Aircraft Type



This figure shows the decline in peak inventory levels for each aircraft type. Once again, each dot represents a distinct aircraft, with the position along the x-axis determined by the year of introduction. This time, the dot is also placed on the y-axis based on the aircraft’s peak inventory during its lifetime. There have been 27 aircraft that reached a peak inventory above 500. All 27 were introduced before 1980. Of those, only four were introduced after 1960—and all four were fighter aircraft.

Producing fewer aircraft of each type has several implications for the military engine industrial base. First, there is simply much less revenue, both from the production of engines for smaller fleets of aircraft and from sustainment because there are simply fewer engines to maintain. Second, there is heightened operational risk to taking aircraft offline to apply engine upgrades and fixes. This is because a lower quantity means that a greater percentage of the fleet is temporarily removed from active duty. Third, there are fewer economies of scale to producing upgrades and alternative engine designs for smaller fleets, reducing the potential return on investment in terms of added capability from investing in engine improvements.

These military aircraft trends—a slower rate of new aircraft introduction and substantially lower inventories of aircraft that are introduced—dramatically slowed the rate of military engine technology deployment. There has been no similar slowing of aircraft introduction on the commercial side, which has led to the reversal in engine technology flow. Where military engines used to drive much engine technology development and supplied technology advances to the commercial side, in recent years technology is increasingly developed for commercial aircraft first and then applied to military applications.

## Fighter/Attack Aircraft Trends

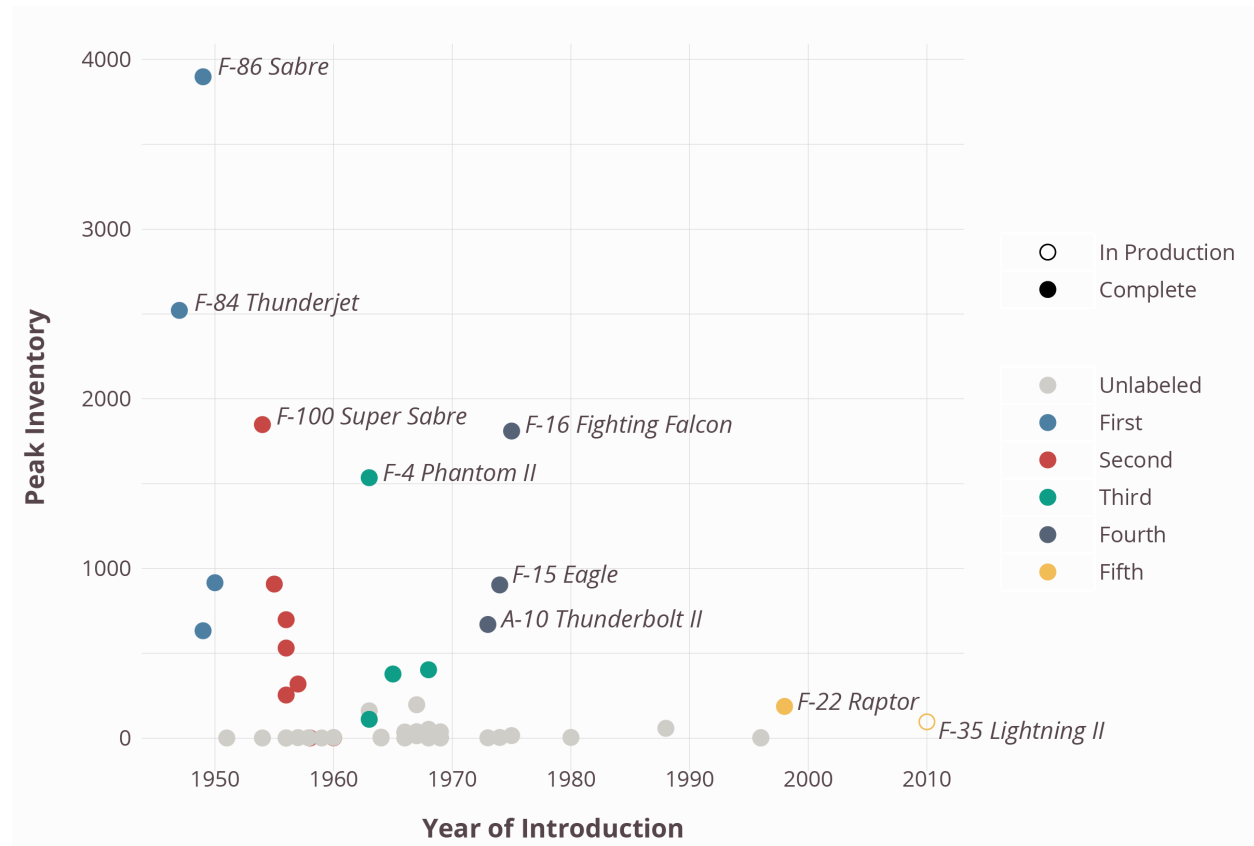
Aircraft engines come in a variety of forms. These forms are related to one another and align around the performance characteristics of aircraft missions. Much of the Air Force's larger aircraft, such as the KC-135 and C-17, use engines that are basically indistinguishable from the engines found on commercial airliners. Many large unmanned aerial vehicles and cruise missiles use engines that are similar in most respects to the engines used by business jets. Engines used for helicopters are specialized to power a rotating shaft but are closely related to commercial turboprop engines. Fighter aircraft engines, however, are unique. They have challenging performance requirements for characteristics such as thrust-to-weight ratio and the ability to rapidly and repeatedly spool power up and down in support of combat maneuvers. In part because of the extraordinary performance demands of the fighter mission, fighter engine development has historically been where the cutting edge of engine technology has been defined. For this reason, a closer examination of trends in the fighter/attack aircraft category is warranted.

Fighter/attack aircraft offer some of the clearest evidence of an aging and smaller fleet, with a slowing rate of introduction and lower procurement levels. Fighters have also been the center of investments made by the DoD in the Air Force and where most innovation in military-specific engine technology has occurred. So, not only is the evidence clearer, but the effect of these trends has an even more profound impact on the engine industrial base.



## AIRCRAFT INTRODUCTION TRENDS

**Figure 5: Fighter/Attack Inventory by Generation**



This figure represents the relationship between peak inventory and year of introduction by generation of fighter in the Air Force inventory. This is especially relevant to engines because fighter generations have been defined, in large part, by leaps in engine technology.

During the first four decades of the Air Force's existence, a new generation entered into service each decade: the first in the late-1940s, the second in the 1950s, the third in the 1960s, and the fourth in the 1970s. Then this pattern ceased. In the past four decades, only one generation was introduced: the fifth, which included the F-22 in the late-1990s and then the F-35 when it was introduced into the fleet in 2010. Based on current plans, this trend will continue: sixth-generation aircraft are only in the early stages of R&D and likely will not be fielded until the 2030s at the earliest. Meanwhile, peak inventory levels for each aircraft, which had declined slowly during the first four decades, dropped during the last two. The peak inventory for the F-35 is likely to be similar to that of the F-16, however, if production proceeds under current plans. As a result, the transition from fourth- to fifth-generation aircraft in the Air Force fleet is markedly different from those that came before.

#### GENERATION OVERVIEW

**First Generation:** These fighters had subsonic capabilities with limited sensors and basic armament. Engine capacity was limited, but first-generation fighters did transition from piston engines to turbojet engines to increase speed and maneuverability.

**Second Generation:** These fighters had limited supersonic capabilities, enabled by afterburning turbojet engines. Sensor capabilities also increased, enabling the use of a broader range of weapons in the air.

**Third Generation:** These fighters had relatively limited upgrades to the engine, improving maneuverability through a series of airframe adjustments instead. Upgraded radar and missile capabilities allowed fighting to occur outside of visual range, changing the airborne battlespace.

**Fourth Generation:** These fighters began to transition from turbojet to turbofan engines, gaining fuel efficiency, all while improving avionics and aerodynamics that allowed aircraft to serve multiple roles.

**Fifth Generation:** In recent times, a handful of countries have developed fifth-generation aircraft, characterized by stealth capabilities, sophisticated avionics and sensor suites, and networked ability to rapidly share data and information with other platforms and systems.<sup>95</sup>

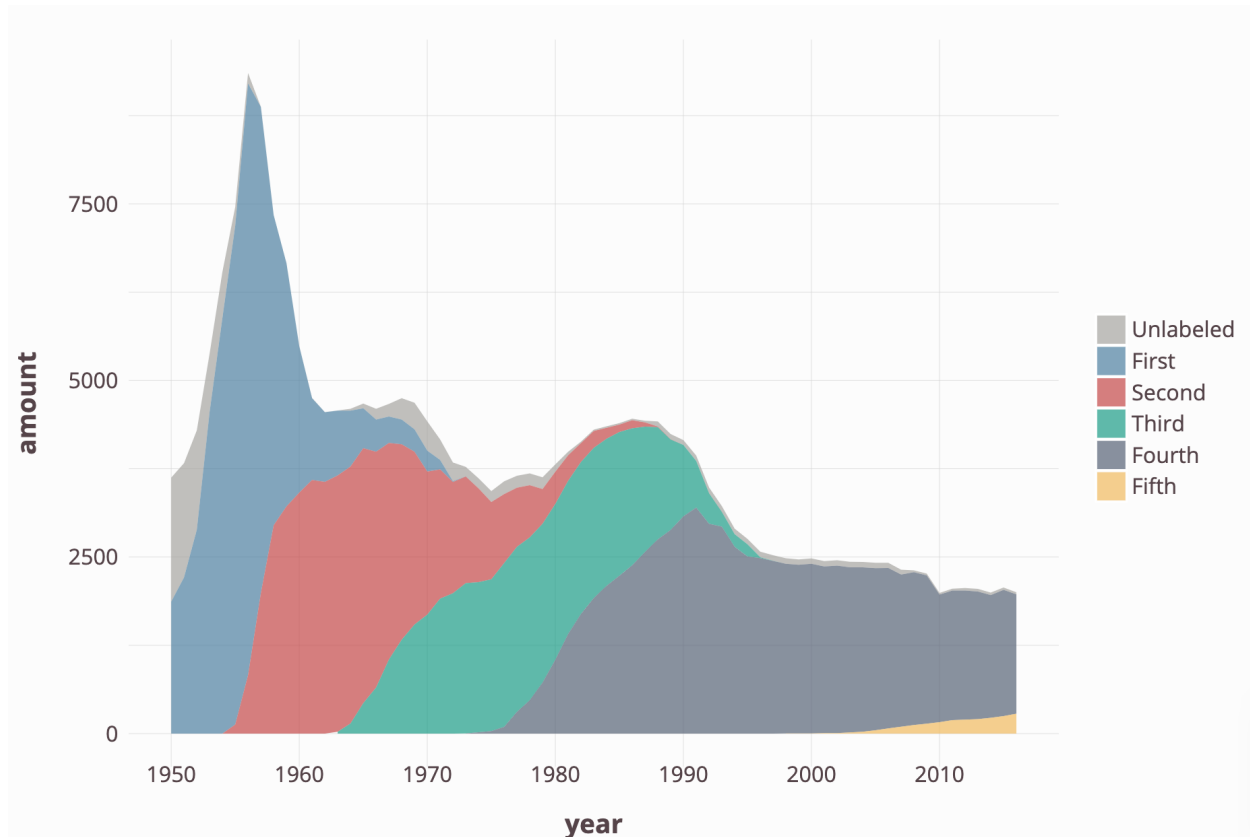
**Sixth Generation:** The U.S. Air Force and Navy currently have research and development programs for sixth-generation fighters. Although the designs are still in their early stages, capability options include improved pilot helmets, optional-manning, and sensor fusion. Next-generation engine upgrade plans currently focus on efficiency, with preliminary options for adaptive cycle engines begin considered.<sup>96</sup> This will be discussed in more detail later in the report.

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<sup>95</sup> "Five Generations of Jets," Fighterworld, <http://www.fighterworld.com.au/az-of-fighter-aircraft/five-generations-of-jets>.

<sup>96</sup> Sebastien Roblin, "Beyond the F-22 or F-35: What Will the Sixth Generation Jet Fighter Look Like?," *National Interest*, July 21, 2018, <https://nationalinterest.org/blog/buzz/beyond-f-22-or-f-35-what-will-sixth-generation-jet-fighter-look-26451>.

**Figure 6: Fighter Inventory by Generation**



This figure shows the sharp contrast in the transition from the fourth to the fifth generation compared to past transitions. With first-, second-, and third-generation fighters, the subsequent generation arrived close to when the past generation reached its peak level. Gradually, these older generations of aircraft were then phased out.

Conversely, when the fourth generation hit its peak, the fifth generation was still a decade away from entering service. Moreover, when the fifth generation was introduced, the slow rate of deployment did not come close to the rapid rate of deployment for past aircraft.

As a result, fourth-generation fighters also have made up most of the U.S. fighter/attack fleet for more than three decades, pushing many aircraft well beyond their expected lifetimes. In fact, even with procurement plans for the F-35, fourth-generation fighters will continue to make up the majority of both U.S. Air Force and U.S. Navy fleets well into the 2020s.

#### PERFORMANCE TRENDS

The trends in aircraft age, inventory, introduction rate, and peak inventory translate into related trends in fleet performance. This section assesses the impact of these trends on commonly noted engine performance measures by taking the performance specifications for each aircraft and its main engine and weighting that performance by each aircraft's

inventory levels. This has allowed us to track the performance characteristics of the entire Air Force fighter/attack fleet from 1950 to present by these key metrics. The key metrics were selected based on the relevancy to military engines and the availability of data for all aircraft.

#### KEY METRICS OBSERVED

**Thrust:** Mechanical force generated by the engines to move aircraft through the air. The more powerful the engine, the more thrust.

**Thrust-to-Weight Ratio:** Thrust divided by the weight of the engine or aircraft. For combat aircraft, this ratio is a good indicator of aircraft maneuverability.<sup>97</sup>

**Overall Pressure Ratio:** A measure of the pressure of air being released from the compressor relative to the pressure of air as it enters the engine.<sup>98</sup> A higher ratio means higher levels of efficiency.

**Speed:** The rate at which the aircraft can move.

**Takeoff Weight:** The maximum weight for an aircraft to safely takeoff.

**Climb Rate:** The rate at which the aircraft can increase its altitude.

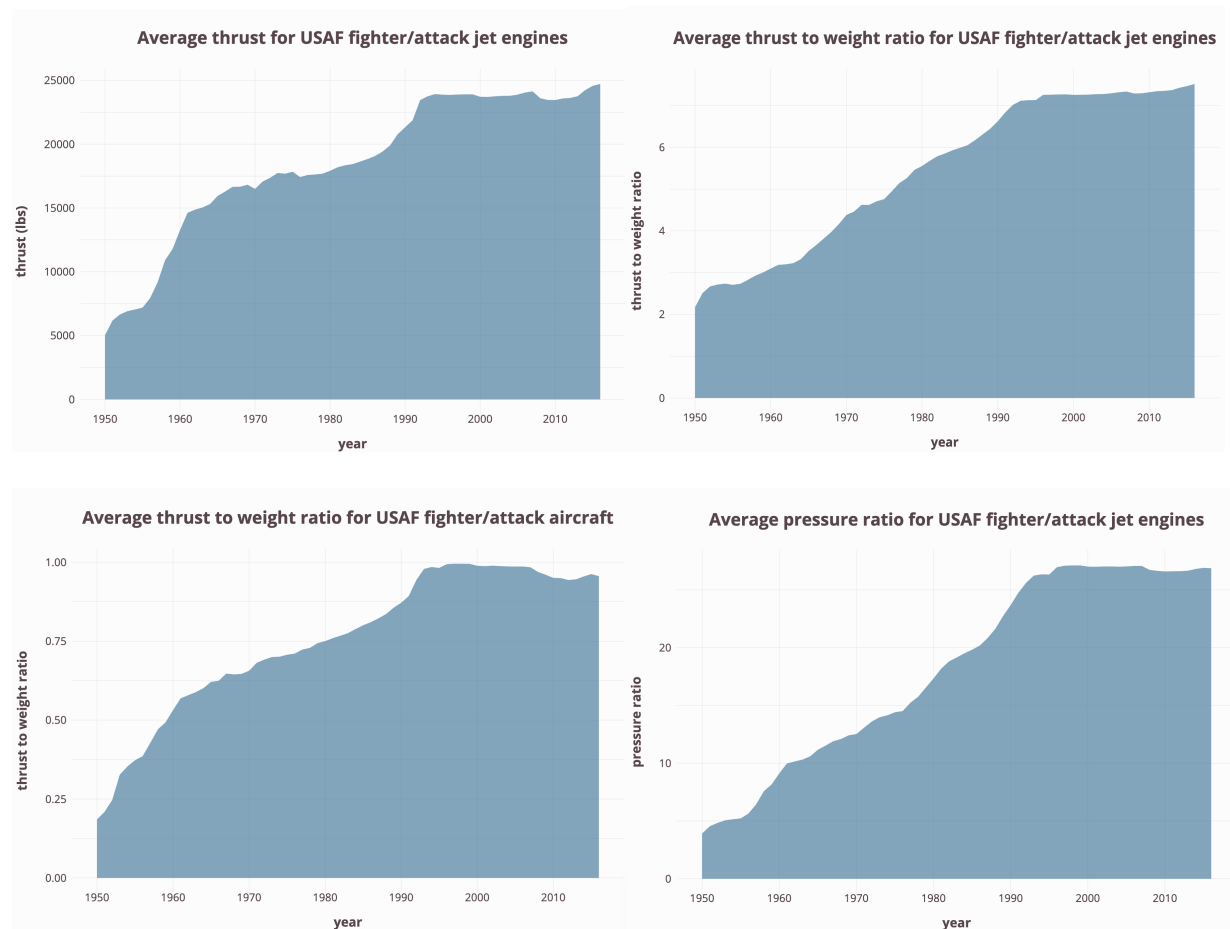
**Range:** The maximum distance that an aircraft can fly between takeoff and landing (without refueling in the air).

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<sup>97</sup> Obaid Younossi et al., *Military Jet Engine Acquisition: Technology Basics and Cost-Estimating Methodology* (Santa Monica, CA: RAND, 2002), 14–20, [https://www.rand.org/content/dam/rand/pubs/monograph\\_reports/2005/MR1596.pdf](https://www.rand.org/content/dam/rand/pubs/monograph_reports/2005/MR1596.pdf).

<sup>98</sup> Ibid.

**Figure 7: Air Force Fleet Engine Performance Metrics**



This figure shows the history of some of the most commonly-used metrics for engine performance as measured for the entire Air Force inventory of fighter/attack aircraft. Thrust and pressure ratio are two of the main metrics that the Air Force has sought to improve in its engines as engine technology has developed.

Average thrust (which does not account for the weight of the engine or the aircraft) rose steeply from the mid-1950s to the early-1960s, rising by roughly 150 percent. Then, once average thrust reached 15,000 lb., the rate of increase slowed, rising by roughly 25 percent from the early-1960s to the late-1980s. Subsequently, average thrust increased another 30 percent in the late-1980s and early-1990s before plateauing for the next two and a half decades. Average thrust has started to increase slowly again since 2010, as greater numbers of F-35s enter the fleet.

The average thrust-to-weight ratio for jet engines started around two in 1950 and increased steadily until reaching seven just after 1990, following the end of the Cold War. Then, for

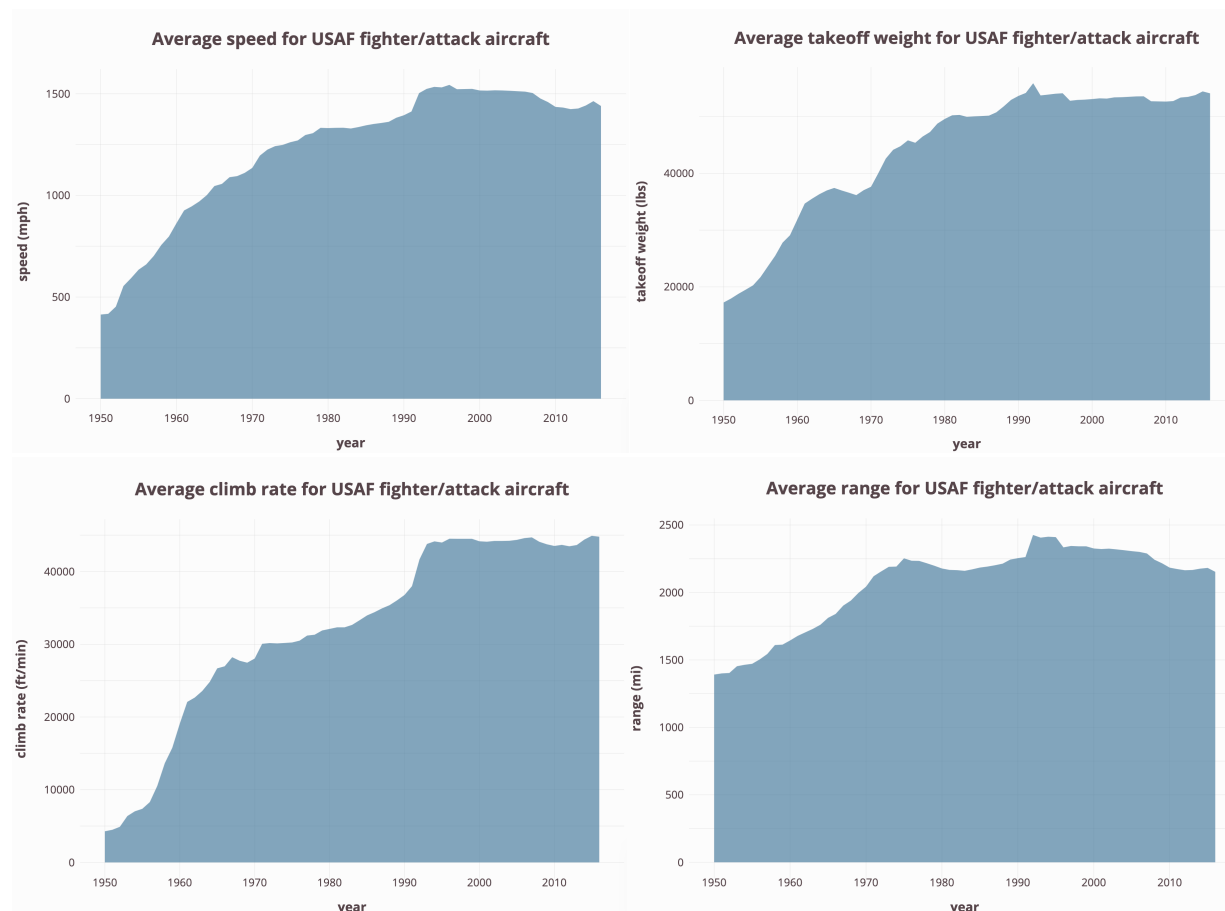
the past two and a half decades, average thrust-to-weight for engines plateaued, rising less than 10 percent from 1992 to present.

Average thrust-to-weight for the aircraft (which accounts for the weight of the entire aircraft) is a key performance parameter when understanding the mission implications of advances in engine technology. Between 1950 and 1960, this ratio increased roughly 200 percent (from about 0.2 to 0.6). After this sharp rise the rate slowed, rising only around 33 percent (from about 0.6 to 0.8) over the next three decades. In the early-1990s, there was a quick increase to an average thrust-to-weight ratio of almost one. However, this ratio plateaued and even decreased slightly in the mid-2000s, as aircraft grew heavier without comparable increases in thrust.

Engine pressure ratio is another widely used method for measuring engine performance, which compares the pressure of air at the engine intake to the pressure of air leaving the engine. A higher engine pressure ratio is closely associated with higher engine thrust. Average engine pressure ratio followed a similar trend to thrust-to-weight for engines, increasing steadily from 1950 to 1990. During this time, the ratio increased from approximately 4 to 27, more than a sixfold increase. Then, in the early-1990s, the ratio plateaued.

The story across these four engine performance metrics (which are closely related) shows that the slowdown in the deployment of new engine technology in military engines led to a stagnation in engine performance across the Air Force's fighter/attack fleet.

**Figure 8: Air Force Fleet Aircraft Performance Metrics**



Engine performance metrics tell part of the story, but ultimately it is aircraft performance metrics that bear most directly on warfighting outcomes. There is a wide variety of potential aircraft performance metrics, many of which are entirely unrelated to engines, and as indicated earlier in this report, investments in other technologies such as stealth and avionics have led to significant increases in warfighting capability. However, it remains important to understand how the reduction in engine technology deployment has affected aircraft performance on related metrics by focusing on four aspects: speed, takeoff weight, climb rate, and range.

The aircraft metrics follow a similar progression to the engine metrics: a sharp increase, then a slower but continued increase, and then a plateau (or even a decrease). For example, the average speed for Air Force fighter aircraft in 1950 was under 500 mph. It quickly rose above 500 mph in the early-1950s and increased until the early-1990s. During these 40 years, the rate of increase slowed. It took less than a decade for average speed to double from 500 to 1,000 mph. Then it took about three decades to increase only 50 percent further, from 1,000 to 1,500 mph. And, from the mid-1990s to present, the average speed, based on reported data, has actually dropped below 1,500 mph.

Of the aircraft fleet performance metrics, one of the most notable is average range, which increased steadily from 1950 until the mid-1970s but has been stagnant since and has declined in recent years.<sup>99</sup> While no single performance metric can capture the capability of the U.S. fleet, aircraft range is an increasingly important characteristic as the DoD has increased its focus on operations in the Indo-Pacific region. More broadly, the leveling out of both engine and engine-related aircraft performance metrics in the 1990s came at the same time that U.S. competitors were investing to catch up.

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<sup>99</sup> Note that the aircraft range values provided here are maximums and are not reflective of combat mission profiles, which would generally cover smaller ranges due to weapons carriage and combat radius issues.



## Defense Investment in Military Engines

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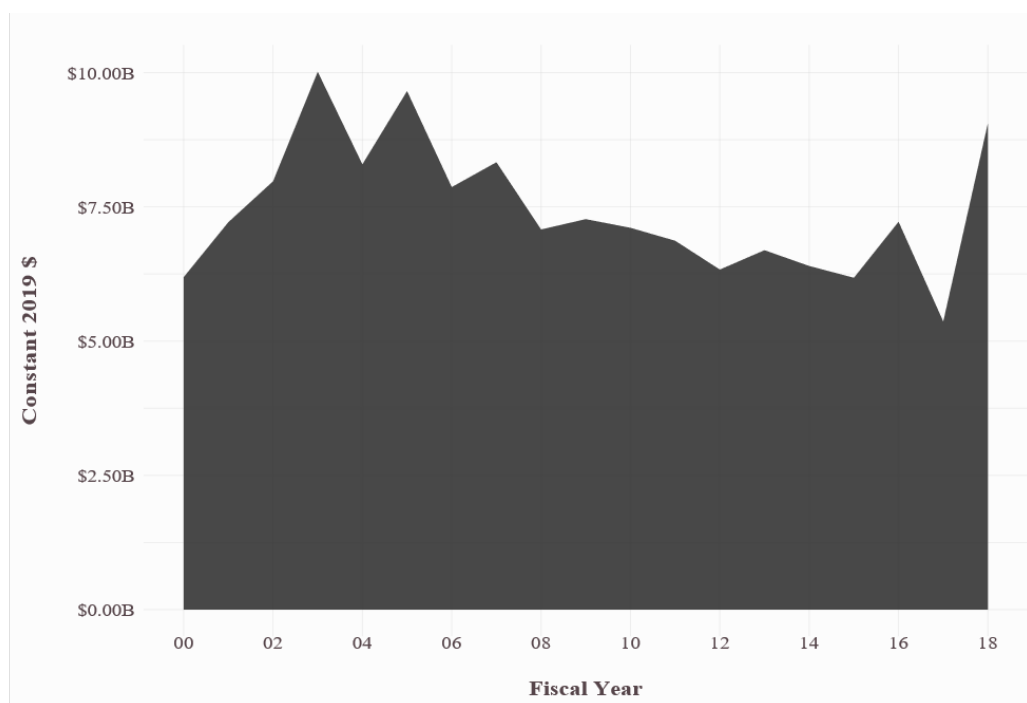
The Department of Defense is a major source of revenue for the engine industrial base across the entire product life cycle of the engine. The DoD pays to develop new materials and research basic engine technologies, pays to develop new engine designs, funds new engine production lines in industry, buys engines from industry, pays to maintain engines in operation, and buys spare parts to keep its engines running. All this activity produces revenue for the engine industrial base, and much of it does—or at least can—support the ability of industry to invest in advanced military engine technology.

### Engine-Related Acquisition Trends

To assess the health and structure of the engine industrial base, it is important to look at the money going from government to industry for engine-related activity. DoD contract obligations, available through the Federal Procurement Data System (FPDS), are the best source to analyze these expenditures. This data makes it possible not only to evaluate financial trends for the engine industry but also to determine where in the DoD the money is coming from, what type of work it is funding, how much competition there is, what type of contracts there are, and how the industry is structured.

## TOPLINE TRENDS

Figure 9: DoD Aircraft Engine Contract Obligations



DoD contract obligations for engines totaled \$9.01 billion in 2018, the highest contract obligations for engines in the previous 10 years. While DoD contract obligations for engines had decreased in the 2000 to 2017 window by 13.3 percent, as seen in Figure 9, they showed an increase of 68.9 percent from 2017 to 2018. Due to this increase, contract obligations for engines in 2018 are up by 46.4 percent from 2000's total of \$6.19 billion. From 2002 to 2007, obligations remained above \$7.50 billion. Spending declined after that, but it did so relatively modestly during a time when topline defense spending was highly volatile, as will be shown in the next section. From 2008 to 2016, obligations remained above \$6.25 billion, except for one year (in 2015, the level dropped slightly below this threshold to around \$6.18 billion). The dramatic rebound in engine spending in 2018 comes closest to the peak engine spending years of 2003 (total of \$10.02 billion) and 2005 (total of \$9.66 billion), although it does not surpass those years.

While there is a sawtooth pattern for several years, as observed in Figure 9 above, this irregularity is likely due to how F-35 contracts were recorded. This state of relative stability for such an expensive category of the military's portfolio sharply contrasts with the trends for other major categories. The next section will draw comparisons between engine contract obligations and total defense contract obligations.

**Figure 10: Change in Aircraft Engine vs. Overall Contract Obligations by Category**

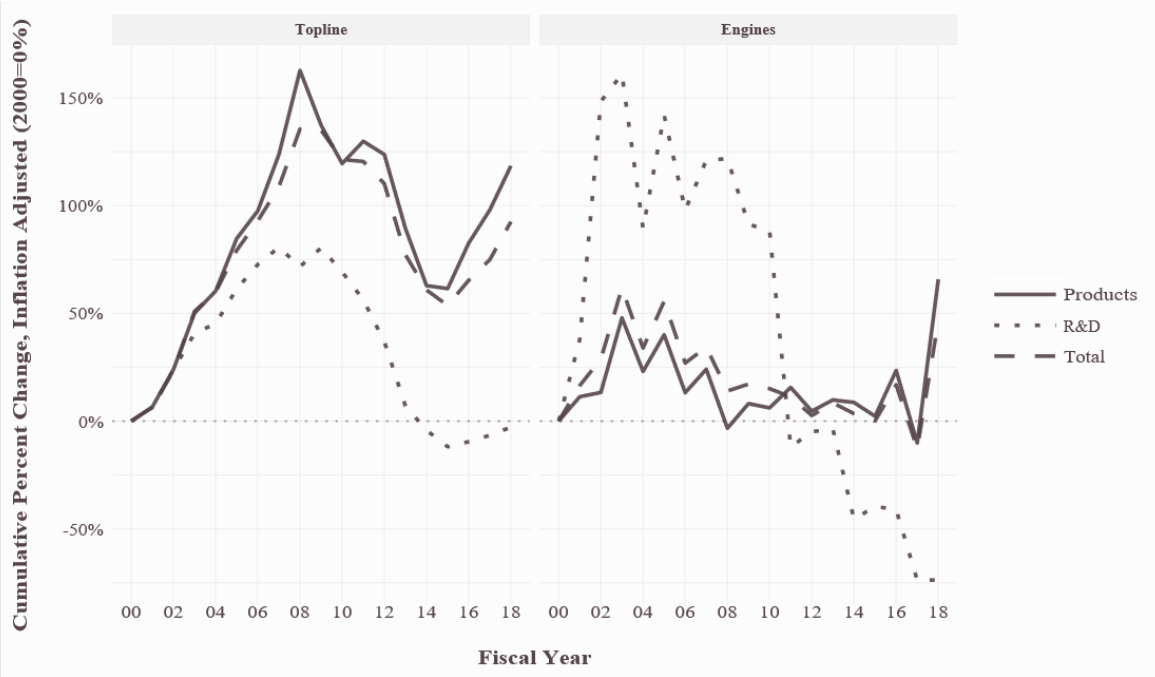


Figure 10 highlights the topline defense contract obligations—and, specifically, engine contract obligations—in terms of percent change since 2000. For example, when looking at the topline category, overall defense contract obligations totaled \$189.31 billion in 2000 and \$364.51 billion in 2018, as an increase of 92.6 percent. This is compared to engine contract obligations, which totaled \$6.19 billion in 2000 and \$9.06 billion in 2018—an increase of 46.5 percent in the same window of time. Within those two categories, Figure 10 also breaks the data out by category, including R&D, products, and the total amounts in percent change terms. For example, Figure 10 shows that, for engine obligations, there was a noticeable drop in R&D spending over the years observed. R&D spending in engines saw a steep decline of 73.7 percent across the total years observed and an even steeper decline of 86 percent from 2010 to 2018, compared to a 2.8 percent drop in R&D spending across topline defense contract obligations.

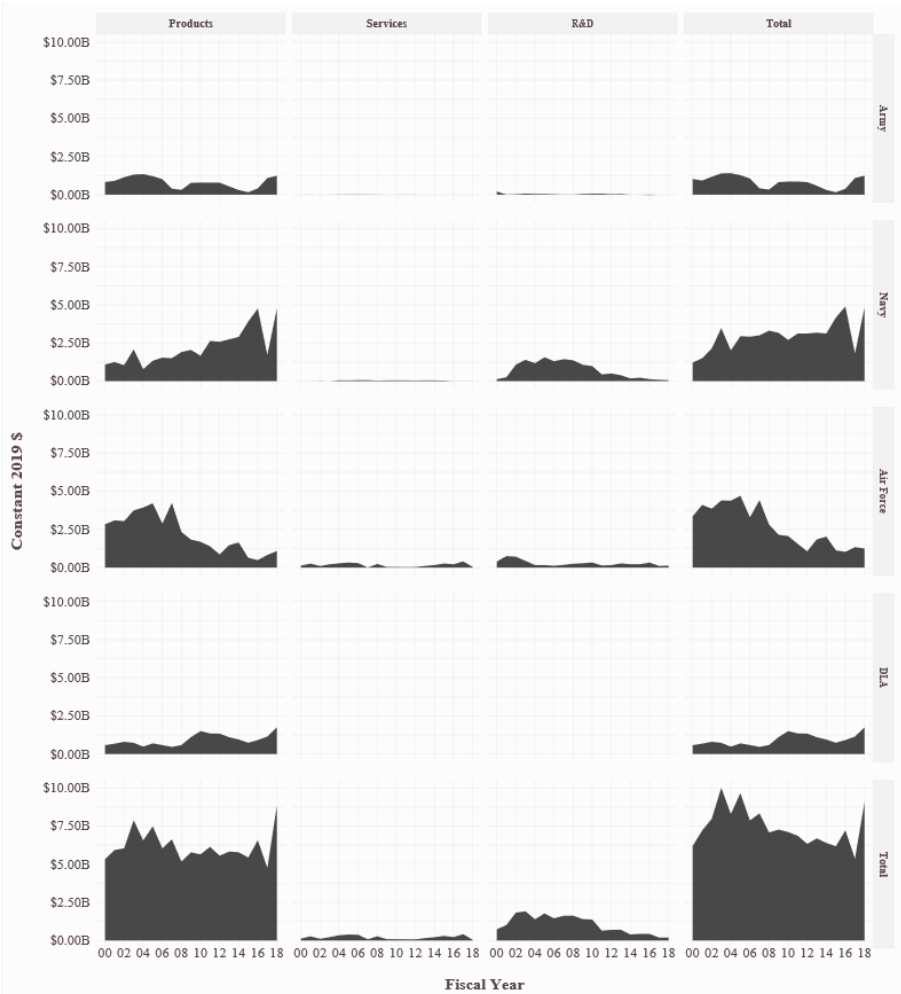
This comparison of overall defense contract obligations to engine obligations shows just how different the two paths were in the observed time. While both the topline and engine contract obligation categories ultimately grew in the 2000 to 2018 window, each showcased different patterns of growth and loss during that time, with the top trendline showing more frequent and sharp changes. When looking at this period for topline defense contract obligations, as shown in Figure 10, the trend shows a rapid rise, at a 135.5 percent rate from 2000 to 2008. This rapid rate of growth is then followed by a drop after 2008, which starts slow and then falls sharply after 2010, until 2016. This trend occurred for DoD contract obligations overall, as well as other industrial bases such as land vehicles, as a result of reductions in war spending in the Overseas Contingency Operations account, the Budget Control Act of 2011, and sequestration. Revenues to the engine industrial base are quite

notable for their failure to follow this general trend. While engines did not demonstrate exponential growth over the years observed, their revenue declined much less sharply despite the apparent falloff observed in the topline trends.

Stability helps companies plan with more certainty and maintain expertise. As a result, this relatively stable and healthy level in contract obligations for engines has been helpful to engine companies over the past two decades. However, the story is not entirely one of financial health and stability relative to other defense spending. For one, engine contract obligations saw a steady decrease over many of the years observed, until a sizable bump from 2017 to 2018. Many of the challenges, however, lie beneath the topline level. Therefore, it is important to dive deeper into these trends to identify the specific strengths and weaknesses of the engine industrial base.

SERVICE AND CATEGORY TRENDS

Figure 11: DoD Aircraft Engine Contract Obligations by Service and Category



Note: Navy includes all F-35 contracts because F-35 contracting office is done by the Navy. Obligations for the remainder of DoD and those with an unlabeled customer are excluded from the graph.

Figure 11 shows a breakdown in contract trends by service and category. Panels for category (including products, services, and R&D) are arranged horizontally, with totals of all categories on the far right. Panels for services (including Army, Navy, Air Force, and the Defense Logistics Agency) are arranged vertically, with totals of all services on the bottom.

This figure tells several stories. First, products spending has always been larger than R&D spending. However, since 2000, procurement spending in engine contracts has increased by 65.7 percent, going from \$5.33 billion to \$8.83 billion by 2018. Procurement spending has remained strong across the 19-year window, staying above \$5.00 billion (except for 2017, where it fell to \$4.76 billion). Meanwhile, research, testing, development, and evaluation (RDT&E) spending in engine contracts has dropped 73.7 percent from 2000 to 2018. While it was largely above \$1.25 billion from 2002 to 2010 (with its peak in 2002, at \$1.82 billion), it dropped by 86 percent from 2010 to 2018, and in 2018 the total was only \$192.35 million. Ultimately, products accounted for 83.2 percent of engines spending over the entire period observed, compared to 14 percent spent on R&D.

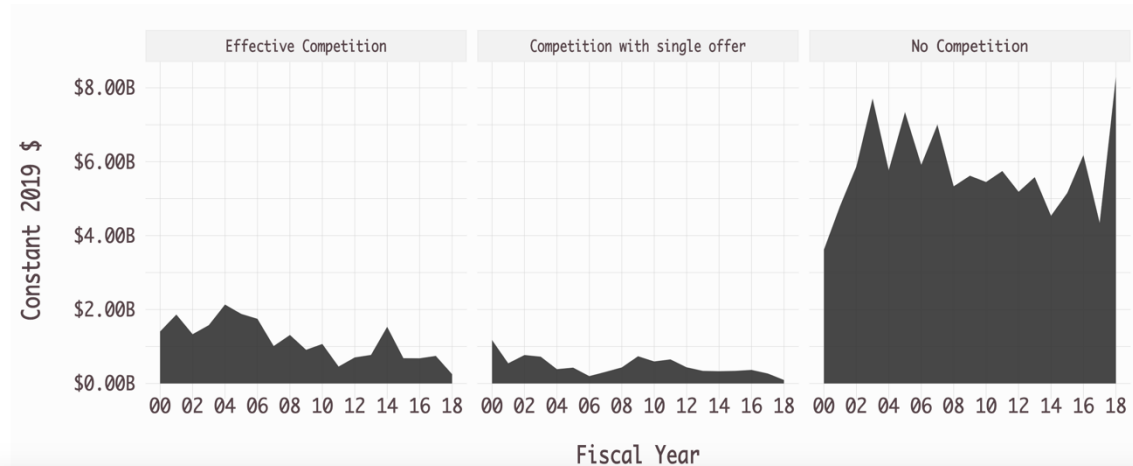
Compared to products and R&D, spending on services in the past 19 years was negligible. This is because military users primarily maintain aircraft engines organically, by using military and defense civilian personnel to perform the maintenance; any external spending on engines that does occur during the sustainment phase of the product life cycle shows up in contract data as products spending. It consists largely of spare parts purchases. Spending on engine-related services had increased by 377.1 percent between 2009 and 2017, where it totaled \$415 million; however, it dropped down to a low of \$38 million in 2018.

The relationship between products and R&D expenditures for engines is greatly shaped by the biggest defense acquisition program, the F-35. As the F-35 entered full-rate production, production spending for its engine, the F135, increased. R&D spending for the F135 (and an alternate F-35 engine, the F136, that was cancelled) used to make up most of the engine R&D spending. However, as the F-35 shifted from development to production, contract obligations shifted along with it. This effect was partially offset by the DoD's decision to support engine design activities through AETP and its precursor efforts. However, even these partially-offsetting R&D efforts are scheduled to complete in 2021. The decline in R&D spending has created significant challenges for the design workforce in the engine industrial base, and if no new design effort follows after AETP, these issues will become critical.

While overall trends show that the engine industrial base has benefited from more revenue reliability than other military contractors, a closer look shows that this has been limited to products. This is because engine-related products made up such a large share of overall engine contracts and did not experience wild swings. The stability of production revenue has helped sustain the industrial base, but it leaves key areas of the industrial base, namely the engine design workforce, more precariously supported. Looking into the future, the decline in defense R&D revenue to industry is likely to steepen further as existing R&D programs finish, creating a major gap in support to the design workforce specialized in military engines.

## COMPETITION TRENDS

Figure 12: DoD Aircraft Engine Contract Obligations by Competition



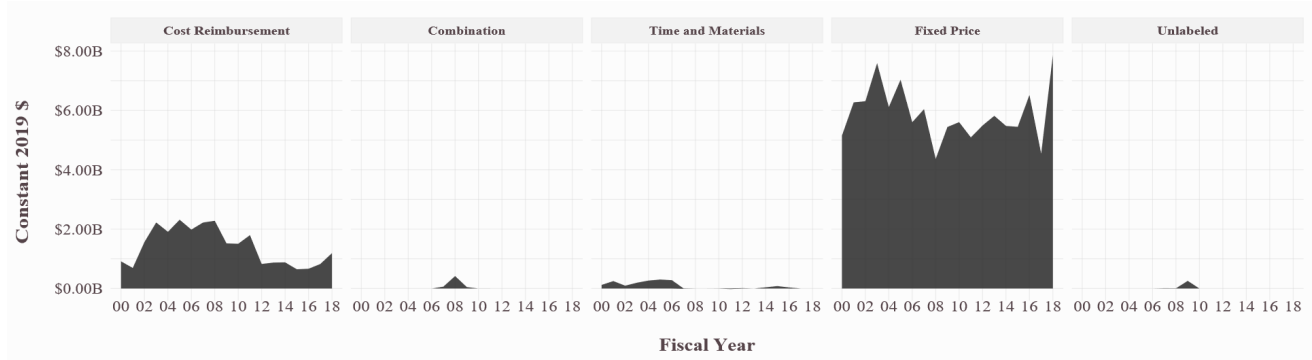
A breakdown of obligations, presented in Figure 12, shows that most engine contracts have no competition. Throughout the 19-year window observed, 77.8 percent of engine contracts had no competition, 15.7 percent had effective competition (defined as receiving two or more offers), and 6.5 percent had competition with only a single offer. Contracts with effective competition represent only a small fraction of obligations and tend to be tied to R&D expenditures. Competed contracts with only a single offer rank even lower. Both single-offer competition and effective competition numbers dropped from 2000 to 2018, by 92 percent and 82 percent, respectively. During this same period, engine contracts with no competition increased 39.3 percent.

It is worth recognizing that the lack of competition within FPDS does not suggest that there is minimal competition throughout the acquisition process; there is intense competition during the early stages of most engine development programs, as demonstrated by ITEP and AETP. However, from a broad perspective, competition is minimal. This is partly due to most contract obligations over the past two decades being product contracts. The winners of engine design R&D programs often maintain their hold on these engine contracts without the threat of further competition. The major exception to this is the “Great Engine War” of the 1980s, but since then the DoD has demonstrated limited interest in carrying competition beyond the early stages of engine development. This fact has implications for possible alternative business models for engine development, as discussed later in this report.

## CONTRACT TYPE TRENDS

Contract type is important because it relates directly to the industry business model. Cost-reimbursable contracts are usually found in a business model where the DoD assumes the cost risk of technology development; these are often utilized on R&D contracts in the traditional defense business model. Conversely, fixed-price contracts predominate in the middle and later stages of production, as well as the sustainment phase. This contract type puts more risk on the contractor, but it also opens the opportunity for greater profitability for the contractor if they can keep costs under control.

**Figure 13: DoD Aircraft Engine Contract Obligations by Contract Type**



A breakdown of engine-related contract obligations by contract type, as shown in Figure 13, suggests that the vast majority of engine contracts are fixed-price contracts, consistent with the dominance of contracts for products shown earlier. For example, in 2018, fixed-price contracts made up 86.8 percent of all contracts. Furthermore, the volume of fixed-price contracts has been steady. This consistency in revenue to the production sector of the industrial base provides stability not only for manufacturers but also for the supply chain. On the other hand, cost-reimbursable contracts come in a distant second, making up only 13.2 percent of all contracts in 2018. Unlike their fixed-price counterparts, cost-reimbursable contracts have experienced a sharp drop over the years, surpassing \$2 billion in 2005 and falling below \$1 billion from 2012 to 2017. This decline is consistent with the decline in obligations for R&D and highlights a slowdown in engine design activities. Other types of contract types, such as combination or time and materials, are negligible.

**VENDOR SIZE TRENDS**

**Figure 14: DoD Aircraft Engine Contract Obligations by Vendor Size**

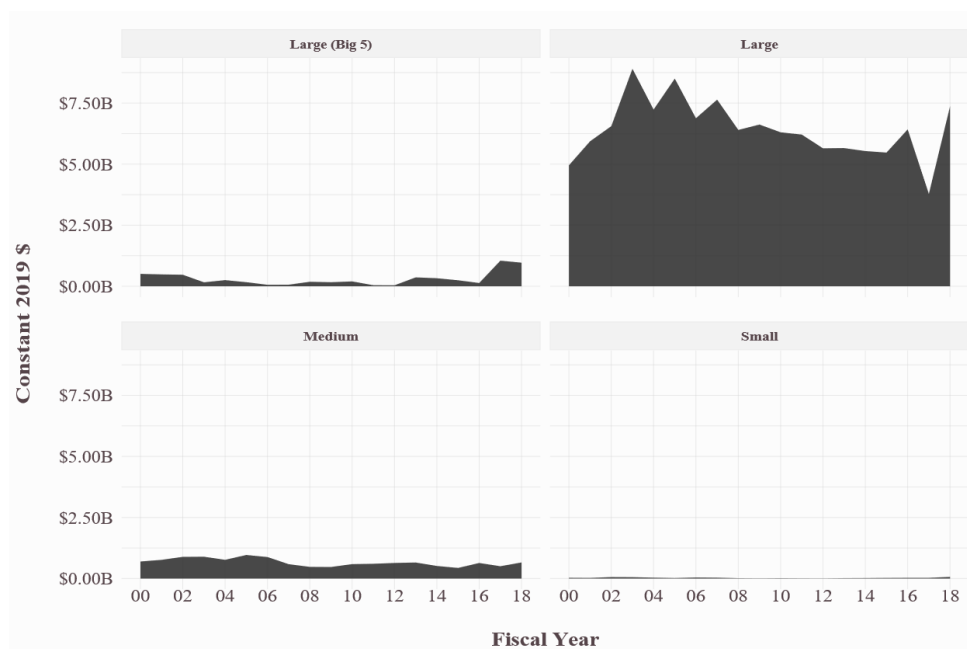


Figure 14 presents a breakdown in contract obligations by vendor size, showing that the vast majority of engine-related prime contracts are with large vendors. Across all the years observed, large vendors made up 86.5 percent of all vendors for engines contracts, compared to 8.9 percent for medium vendors and 4.2 percent for the largest (Big 5) vendors.<sup>100</sup> It makes sense that large vendors make up so much of engine-related contracts; General Electric and Pratt & Whitney, for example, dominate military engine sales, and both companies fall into the large category. However, while large vendors take on the majority of contracts, this category has also seen the most notable decrease in contracts over the past 19 years.

## Engine-Related Research and Development in the Future Years Defense Program

In addition to understanding how DoD revenue has flowed to industry in the form of contract obligations, it is also important to examine how the DoD's strategy for investing in engines has informed budgets over time. The FYDP, the DoD's five-year budget projections, is a useful tool for understanding this dynamic. The FYDP reveals not only the current plans for U.S. defense investments but also how reliable recent plans have been. This analysis focuses on key RDT&E projects within the defense budget (for the Army, Navy, and Air Force) that are focused on aircraft engines. In examining budget, RDT&E is the only category that lends itself to a clear focus on engine-related spending; in other budget categories, such as Procurement and Operation and Maintenance, engine spending is buried in much larger funding lines.

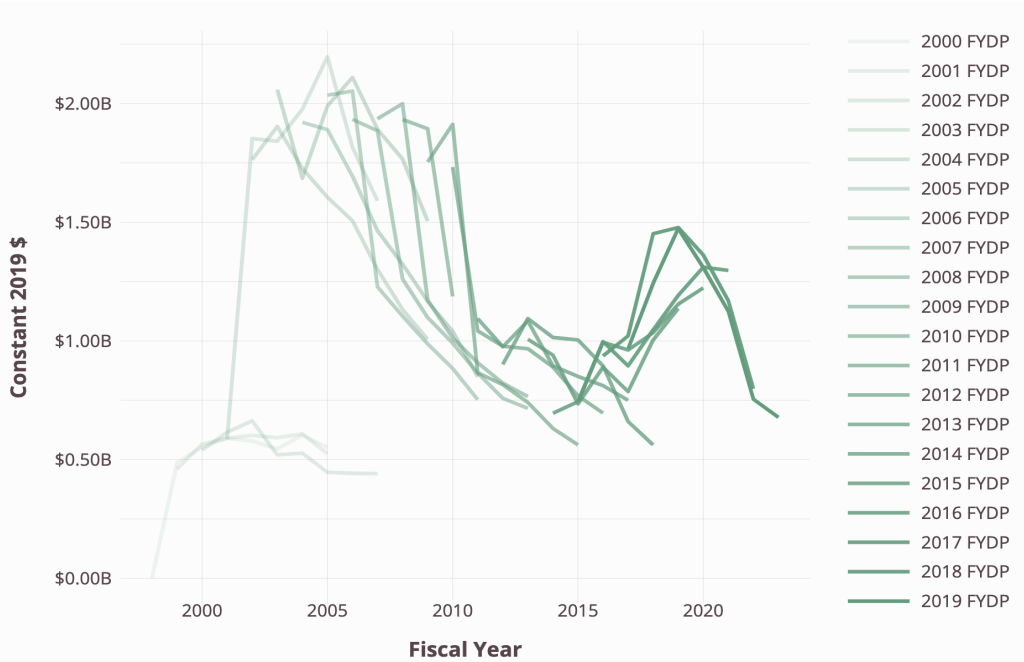
The figures below reflect FYDP trends for these engine-related projects. Each line is one year's FYDP, which specifies the president's budget request submitted in that year. Each line includes actual and projected spending for seven years. For example, "2019 FYDP" includes spending for 2017 through 2023 (2017: amount spent; 2018: enacted spending; 2019: proposed spending; 2020–2023: projected spending).

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<sup>100</sup> In CSIS's categorization of defense contractor vendor categories, the Big 5 defense contractors are Lockheed Martin, Boeing, Raytheon, Northrop Grumman, and General Dynamics.

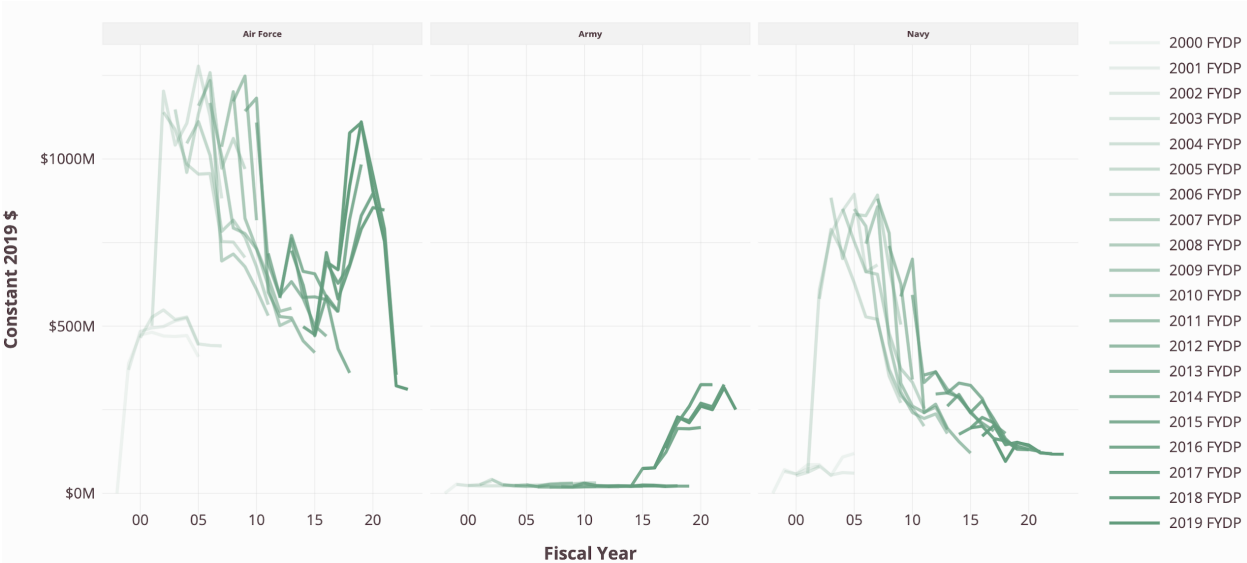


**Figure 15: DoD RDT&E Spending Projections for Aircraft Engine Technology**



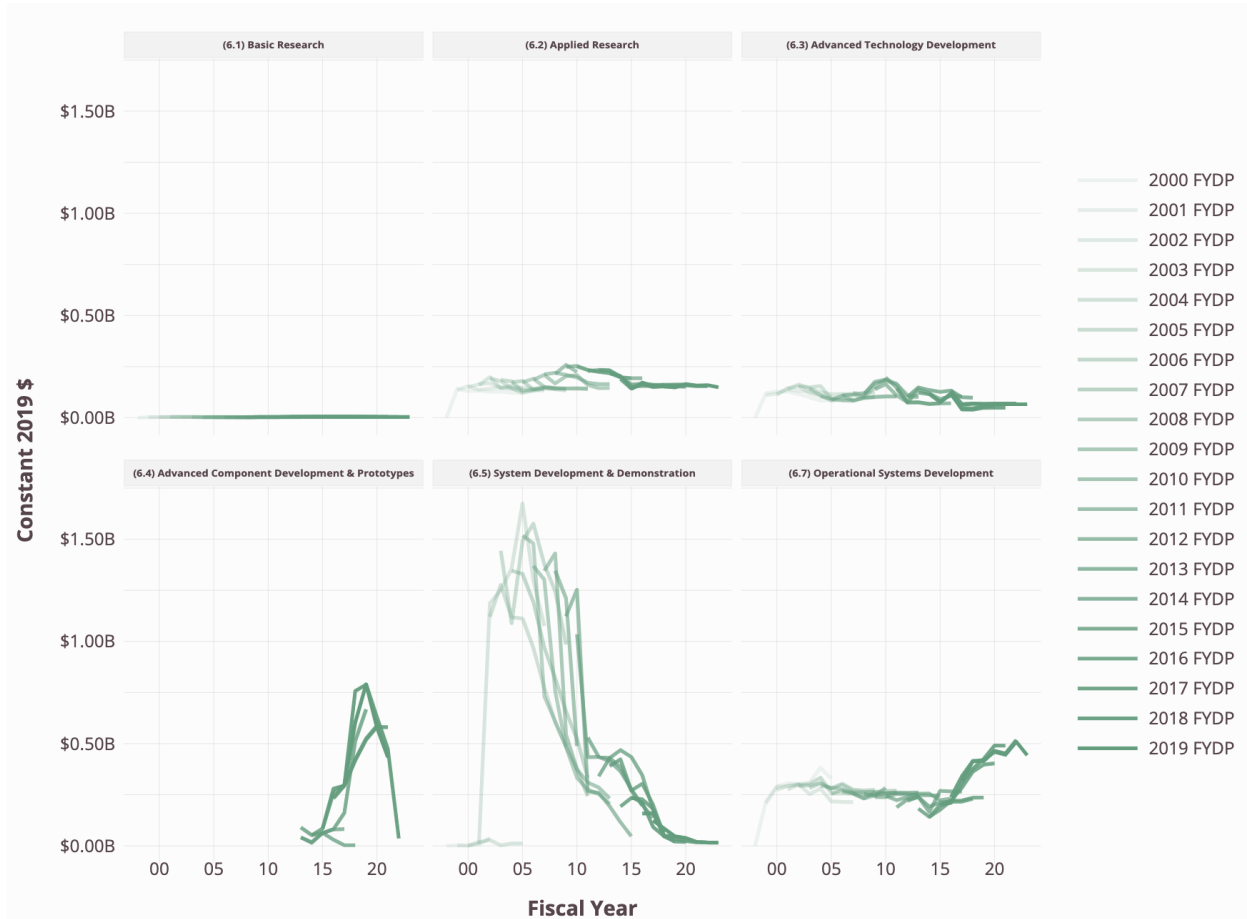
The FYDP data reflects a rise in RDT&E in the FYDP in the early-2000s, as the F-35 program entered development and design of the F135 engine began in earnest. During the period from 2000 to 2010, when RDT&E funding was strongest, each successive FYDP projected a rapid decline in RDT&E funding set to occur one year later than in the previous year’s projection. The long-projected decline in RDT&E funding was continuously deferred through the 2000s, as F-35 development ran over schedule and as Congress regularly added funding for the F136 engine. However, in 2011, this decline was finally realized when work on the F136 engine was halted. A recovery in RDT&E funding started in 2016 with the start of AETP and acceleration of ITEP. Recent FYDP data projects another major drop after the AETP program completes in 2021. While there are differences between the data on contract obligations in FPDS (seen earlier in this chapter) and budget authority depicted in the FYDP, in terms of total dollar value the trend is the same.

**Figure 16: DoD RDT&E Spending Projections for Aircraft Engine Technology by Service**

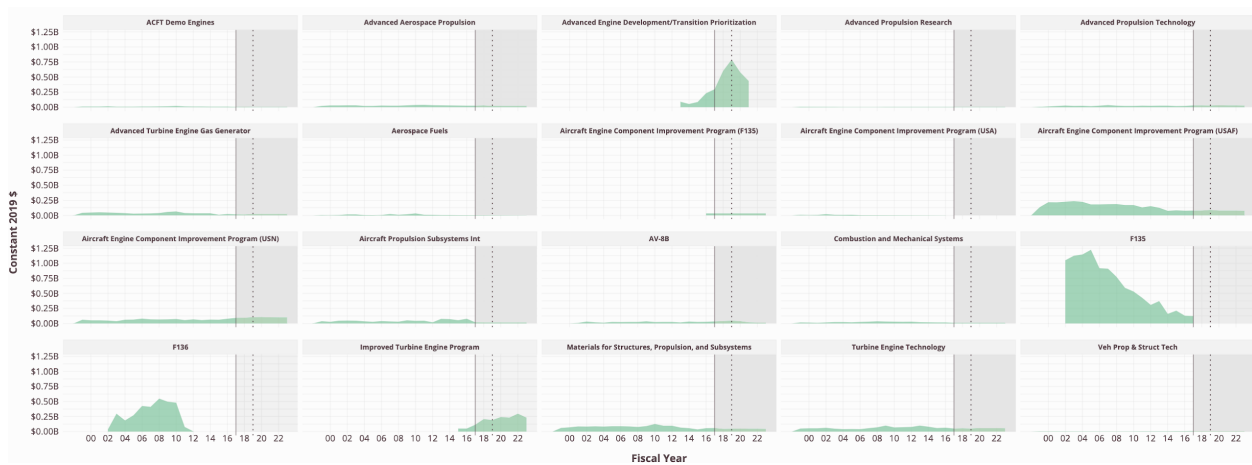


The FYDP data presents a more accurate depiction of the importance of engine-related RDT&E across the services. While contract data classifies all F-35-related contract obligations under the Navy (since the Navy leads F-35 contracting), the FYDP data shows that the Air Force has long been, and remains, the primary source of engine-related development funding. Air Force RDT&E funding surpassed \$1 billion in 2010, did so again in 2018, and is projected to do the same in 2019. The Air Force’s funding, however, is projected to decline steeply when AETP ends. Army resources for engine related RDT&E become significant with the award of two competitive design contracts in 2016 under the ITEP program. Navy support for engine-related RDT&E remains on a slow downward trend after plunging sharply in 2010.

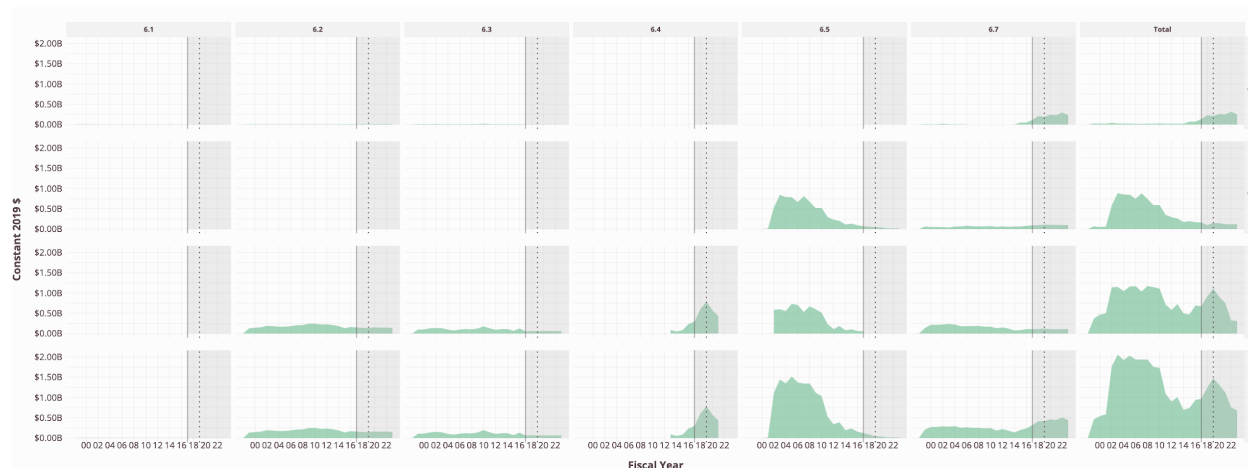
**Figure 17: DoD RDT&E Spending Projections for Aircraft Engine Technology by Stage**



**Figure 18: DoD RDT&E Spending Projections for Aircraft Engine Technology by Project**



**Figure 19: DoD RDT&E Spending Projections for Aircraft Engine Technology by Service and Stage**



Looking at R&D budgets by stage shows how the dramatic decline in system design and development funding (6.5) has been partially offset by increases in both prototyping funding (6.4)—in the Air Force budget associated with AETP—and operational systems development funding (6.7)—in the Army budget associated with ITEP. However, the gap in system design and development is currently projected to continue indefinitely. This budget activity is where major engine design activity would traditionally be funded. Thus, a review of FYDP data reveals a similar gap to that identified by the review of contract data, namely an absence of design work associated with new engine development. However, because the FYDP data is forward looking, it adds to the issue identified in reviewing contract data because it shows that this gap has no remedy in the DoD’s current plans.

## Recent Engine-Related Research and Development Programs

The overall trend of engine-related R&D spending highlights the gap in funding for next-generation engine design, but it is also useful to examine the individual engine-related R&D programs directly. The U.S. military has spearheaded many programs with the goal to increase the capabilities and affordability of military propulsion technology. In the last three decades, the Air Force was the primary funder for these efforts. Major efforts include the Integrated High-Performance Turbine Engine Technology (IHPTET) and the Versatile Affordable Advanced Turbine Engine (VAATE).

IHPTET ran from 1987 to 2005. VAATE formally began in 2005 and is still ongoing. Under the auspices of VAATE, Adaptive Versatile Engine Technology (ADVENT) was initiated in 2008. This was followed by Adaptive Engine Technology Development (AETD) in 2012 and Adaptive Engine Transition Program (AETP) in 2016. To the U.S. military, these programs are the primary mechanism to develop new propulsion technologies and get them into the fleet. For the industrial base, they are the funding mechanism meant to push the boundaries of turbine engines and to compete for lucrative next-generation contracts. At times, these programs are even lifelines to the military industrial base.

## INTEGRATED HIGH-PERFORMANCE TURBINE ENGINE (IHPTET)

IHPTET was a government–industry partnership with two main goals:

1. Double the thrust–to–weight ratio of the initial F119 engine (the engine for the F–22)<sup>101</sup>; and
2. Reduce the maintenance costs of military engines by 35 percent.<sup>102</sup>

The government side included the Army, Navy, and Air Force, as well as NASA and the Defense Advanced Research Programs Agency (DARPA). The industry side included General Electric, Pratt & Whitney, Rolls–Royce’s Allison Advanced Development Company, Honeywell, Teledyne Continental Motors, and Williams International.<sup>103</sup>

IHPTET had separate goals for three engine types: turbofan/turbojet, turboprop/turboshaft, and expendable engines. But its primary focus was on the first type, specifically low–bypass–ratio fighter engines. By the end of the program, IHPTET had largely met its technical goals.<sup>104</sup>

Moreover, in addition to its technical successes, the program was well regarded for strong coordination and teamwork among its participants (including communication between government and industry). This formed a strong foundation for follow–on research and development programs.

## VERSATILE AFFORDABLE ADVANCED TURBINE ENGINE (VAATE)

VAATE was the primary engine development effort that followed IHPTET and was scheduled to run from 2005 to 2017. But according to the first VAATE program manager, Larry Burns, the program almost never existed. Burns stated in 2007 that “after the success of IHPTET, we faced an uphill battle bringing VAATE on board. People believed turbine technology had peaked and asked why we needed another multi–year program. It was a fierce battle to convince military planners to put research and development money into technology for next–generation turbine engines.”<sup>105</sup> However, by broadening the research agenda, VAATE received funding and began.

Similar to IHPTET, VAATE had tangible goals in terms of technological improvement.<sup>106</sup> However, while the primary goal of IHPTET was an increase in thrust–to–weight ratio, the primary goal of VAATE was to increase fuel efficiency.<sup>107</sup> Furthermore, VAATE had two major sub–component demonstrator programs: ADVENT and Highly Efficient Embedded Turbine

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<sup>101</sup> Younossi et al., *Military Jet Engine Acquisition*, 26.

<sup>102</sup> *Ibid.*

<sup>103</sup> *Ibid.*

<sup>104</sup> Air Force Studies Board, *Improving the Efficiency of Engines for Large Nonfighter Aircraft* (Washington, DC: National Academies Press, 2007), 96–105, <https://www.nap.edu/read/11837/chapter/10#97>.

<sup>105</sup> Rebecca Grant, “Adaptive Engines,” *Air Force Magazine*, September, 2012, <http://www.airforcemag.com/MagazineArchive/Pages/2012/September%202012/0912engines.aspx>.

<sup>106</sup> Committee on Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems, *Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems* (Washington, DC: National Academies Press, 2011), 42–44, <https://www.nap.edu/catalog/13144/materials-needs-and-rd-strategy-for-future-military-aerospace-propulsion-systems>.

<sup>107</sup> *Ibid.*

Engine (HEETE). Despite these two subprograms, the total number of demonstrator engines produced under VAATE is significantly fewer than the number produced under IHPTET.<sup>108</sup>

#### ADAPTIVE VERSATILE ENGINE TECHNOLOGY (ADVENT)

ADVENT began in 2007 under VAATE as a five-year effort to develop adaptive engines.<sup>109</sup> Adaptive engines allow for the airflow through the engine to be significantly modified based on the desired engine performance in different flight regimes. A primary mechanism for adapting air flow to different flight regimes is adding a third airstream to the two airstreams in standard turbofan engines (the core airstream and the bypass airstream). Under ADVENT, the Air Force funded General Electric and Rolls-Royce to develop adaptive engines. However, the program was focused on the technologies behind adaptive engines, and it was less concerned with developing flight-rated hardware or confronting production issues.<sup>110</sup>

The stated goal of ADVENT was to reduce the fuel consumption of combat engines by 25 percent compared to the fuel consumption of early-2000s fighter engines.<sup>111</sup>

Throughout this program, engineers confronted new challenges presented by adaptive engines, such as maintaining constant engine flow with variable-fan engine design and maintaining operational stability with higher temperatures. Significant progress was made in developing ways to modulate cooling air and design simpler exhaust systems. Such advancements were critical in bringing three-stream adaptive engines closer to operational feasibility.<sup>112</sup>

In 2013, near the end of the program, General Electric tested its ADVENT-funded engine core. The test concluded that the engine core could generate the power required to implement three-stream engine architecture. Furthermore, the engine core achieved the 25 percent fuel consumption reduction goal.<sup>113</sup>

#### ADAPTIVE ENGINE TECHNOLOGY DEVELOPMENT (AETD)

AETD began in 2012 as a follow-on program to ADVENT.<sup>114</sup> The goal of AETD was to transition from an early technology program to the development of a useable engine design.<sup>115</sup> This incremental approach to developing three-stream adaptive engines was taken to reduce costs and the risk of eventually maturing the technology.<sup>116</sup> Pratt & Whitney and General Electric were selected by the Air Force to participate in the program, with initial Air Force funding for the program set at \$213.6 million, augmented by cost-sharing

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<sup>108</sup> Ibid.

<sup>109</sup> Jim Mathews, "Engines of Innovation," *Air Force Magazine*, August 2017, <http://www.airforcemag.com/MagazineArchive/Pages/2017/August%202017/Engines-of-Innovation.aspx>.

<sup>110</sup> Ibid.

<sup>111</sup> Guy Norris, "GE Details Sixth-Generation Adaptive Fighter Engine Plan," *Aviation Week*, January 29, 2015, <http://aviationweek.com/defense/ge-details-sixth-generation-adaptive-fighter-engine-plan>.

<sup>112</sup> Ibid.

<sup>113</sup> Ibid.

<sup>114</sup> "GE Aviation Awarded \$1B Adaptive Engine Transition Program Contract From US Air Force," *Aviation Pros*, June 20, 2016, [http://www.aviationpros.com/press\\_release/12227521/ge-aviation-awarded-1b-adaptive-engine-transition-program-contract-from-us-air-force](http://www.aviationpros.com/press_release/12227521/ge-aviation-awarded-1b-adaptive-engine-transition-program-contract-from-us-air-force).

<sup>115</sup> Jim Mathews, "Engines of Innovation," *Air Force Magazine*, June 26, 2017,

<http://www.airforcemag.com/MagazineArchive/Pages/2017/August%202017/Engines-of-Innovation.aspx>.

<sup>116</sup> Ibid.

contributions from industry.<sup>117</sup> Both General Electric and Pratt & Whitney were able to separately develop and successfully test adaptive-cycle fan technologies as a result of the AETD program.

#### ADAPTIVE ENGINE TRANSITION PROGRAM (AETP)

In July 2016, the Air Force awarded \$1.01 billion contracts to both General Electric and Pratt & Whitney to continue both companies' efforts to further refine and develop adaptive engine technology.<sup>118</sup> The program is anticipated to be five years long, with a period of performance concluding in September 2021.<sup>119</sup> The stated goal of the program is to "design, develop, fabricate, and test complete, flight-weight, centerline, 45,000-pound thrust-class adaptive engines."<sup>120</sup> More specifically, the technical objective is to produce an engine that cuts fuel consumption by 25 percent and improves thrust by at least 10 percent, compared to the baseline of current fifth-generation engines.<sup>121</sup>

#### IMPROVED TURBINE ENGINE PROGRAM (ITEP)

The size of the U.S. vertical lift fleet and the unique requirements of these aircraft have made turboshaft engines one of the few major priorities for military engine investments, beyond fighter engines. Funding for programs such as AETD and AETP remain far more significant, but ITEP demonstrates that fighter engines are not a singular priority in engine development.

Most of the U.S. vertical lift fleet consists of helicopter designs that were first introduced in the 1980s, such as the UH-60 Blackhawk and the AH-64 Apache. While upgrades have improved these older designs, they have also resulted in heavier aircraft, which puts more stress on the engines. For example, during the wars in Afghanistan and Iraq, many helicopters experienced problems operating at high altitudes and hot temperatures.<sup>122</sup> Engine improvements can address most of these issues.

In 2009, the Army launched ITEP with the goal of developing a new turboshaft engine that is "25 percent more fuel efficient; 50 percent more powerful; 35 percent less costly to produce and maintain; and that offers 20 percent more engine life than the T700."<sup>123</sup> The engine would replace the T700, which powers the Blackhawk and Apache helicopters.<sup>124</sup> The

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<sup>117</sup> Rebecca Grant, "Adaptive Engines" *Air Force Magazine*, August 31, 2012, <https://www.airforcemag.com/article/0912engines/>.

<sup>118</sup> Aaron Mehta, "US Air Force Funds Next Advanced Engine Stage," *DefenseNews*, July 1, 2016, <https://www.defensenews.com/training-sim/2016/07/01/us-air-force-funds-next-advanced-engine-stage/>.

<sup>119</sup> Matthews, "Engines of Innovation."

<sup>120</sup> Bryan Ripple, "Air Force awards Adaptive Engine Transition Program contracts," *Wright-Patterson AFB*, July 6, 2016, <http://www.wpafb.af.mil/News/Article-Display/Article/847976/air-force-awards-adaptive-engine-transition-program-contracts/>.

<sup>121</sup> Valerie Insinna, "Eyeing the future fighter, Pratt & Whitney hits milestone with new adaptive engine," *DefenseNews*, September 18, 2017, <https://www.defensenews.com/digital-show-dailies/air-force-association/2017/09/18/pratt-whitney-completes-tests-for-new-adaptive-engine-that-could-power-future-fighter/>.

<sup>122</sup> Mike Hirschber, "Why America Really Needs ITEP Engines," *Breaking Defense*, September 30, 2016, <https://breakingdefense.com/2016/09/why-america-really-needs-itep-engines/>.

<sup>123</sup> Chris Kjelgaard, "HE Achieves Testing Milestones for US Army FATE and ITEP Turboshaft Programs," *AINonline*, October 11, 2017, <https://www.ainonline.com/aviation-news/defense/2017-10-11/ge-achieves-testing-milestones-us-army-fate-and-itep-turboshaft-programs>.

<sup>124</sup> *Ibid.*

Army anticipated that the total cost of development would be \$750 million and hoped to have an engine that was operational by 2027.<sup>125</sup>

In 2016, the Army awarded competing contracts to Advanced Turbine Engine Company (ATEC)—a Honeywell and Pratt & Whitney partnership—and General Electric to develop the new engine. ATEC was awarded a \$152 million contract and General Electric was awarded a \$102 million contract.<sup>126</sup> ATEC developed the T900, a dual-spool engine, and General Electric developed the T901, a single-spool engine. While both engines were viewed as meeting the Army's requirements, the competitors' marketing strategy centered around the dual-spool and single-spool distinction. In 2019, the Army selected General Electric's T901 engine as the winner for ITEP.<sup>127</sup>

### ENGINE DEVELOPMENT AFTER AETP

One of the biggest questions is: what follows AETP? The FY 2021 budget request represents the first time the Air Force has programmed funding for engine development efforts extending beyond the end of AETP, identifying a successor line of effort known as the Next Generation Adaptive Propulsion program, described as supporting design and component risk reduction for flight weight engine prototypes of next-generation fighter aircraft. This approach might indicate a policy choice to focus engine development on next-generation aircraft. However, the program is very leanly funded, allocating \$112 million in FY 2022, ramping up to \$218 million in FY 2024, and then ending the funding. This suggests that the successor program to AETP will not carry forward the significant prototyping efforts invested in AETP. If the program does terminate in FY 2025, it is not clear what it would deliver. For this reason, it remains unclear how and when adaptive engine technology will transition into a procurement program and into the Air Force's fleet. Answering this question requires addressing the four key policy choices articulated in Chapter 1 of this paper.

## Business Model for Engine Development

As the Air Force develops its plans for engine investment after the AETP program concludes, it has options to consider the business models it will use for engine development. The business model defines who funds and controls the engine development process, and it determines how industry is provided with a return on investment if they are using their own funds for this development. The recent effort by the federal government to develop vaccines effective against Covid-19 has demonstrated that multiple business models can be applied to even expensive development efforts, including using different business models

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<sup>125</sup> Jen Judson, "GE, ATEC Win Contracts To Design Army's Future Helo Engine," DefenseNews, August 22, 2016, <https://www.defensenews.com/land/2016/08/22/ge-atec-win-contracts-to-design-army-s-future-helo-engine/>.

<sup>126</sup> Jen Judson, "US Army on track to award future helicopter engine contract late next year," DefenseNews, September 11, 2017, <https://www.defensenews.com/digital-show-dailies/dsei/2017/09/11/us-army-on-track-to-award-future-helicopter-engine-contract-late-next-year/>.

<sup>127</sup> Garrett Reim, "GE wins \$517m ITEP contract for US Army helicopters," Flight Global, February 1, 2019, <https://www.flightglobal.com/helicopters/ge-wins-517m-itep-contract-for-us-army-helicopters/131233.article>.



with different competitors. The decision on business model should support and reinforce the national priority placed on engine development and the investment mix chosen.

The classic business model used for fighter engine development has been a government-led, government-funded design. In this business model, engine development is funded exclusively by government R&D investment, often on a cost-plus basis, with a transition to fixed-price contracts for procuring engines at some point in production. Industry profit in this approach tends to be greatest during engine production. This is especially true as manufacturers gain experience with production and begin to produce in volume, allowing them to increase their profit by identifying manufacturing efficiencies. Margins in the development phase are low, and while engine sustainment provides a long-term source of revenue to OEMs, it usually generates modest profit margins in supplying parts and engineering expertise. The DoD typically performs most engine maintenance and support itself using military personnel and defense civilians working at government-run depots.

This approach also maximizes government control. As the primary funder of R&D, government directly controls the technologies chosen for development, obtains ownership in the intellectual property developed, and has enormous direct and indirect control over how that technology is shared throughout the industry, especially internationally. There is a strong appeal in this approach to many in government, particularly given that China has worked assiduously to obtain commercial engine technology through joint ventures and other means. Government-funded development is seen as a more secure and sustainable way to increase or maintain U.S. technological advantage. A focus on ensuring security is also consistent with the historical importance of engine development in establishing aerial combat advantage, where fighter engine technology has been treated as a “crown jewel” technology. However, the classic business model also puts a high demand on government resources, maximizing the need to trade off engine investment against other technologies considered critical to future warfighting. As demonstrated by the cancellation of the F136 engine development, the scale of the resources required for government-funded development can also be a challenge to competition, since the cost of developing two unique engine designs is roughly double that of developing one.

The classic defense business model contrasts with the business model that U.S. engine manufacturers use to finance their commercial engine development. In the commercial market, engine companies self-finance their engine design and development efforts and recoup these investments as they sell and maintain these engines in the international market. R&D generates no immediate profit, as it is almost entirely a cost to be recovered later. Production also tends to be relatively low-margin work, as engine sales to airlines are highly competitive. In the commercial model, the highest returns come through engine sustainment. Engine companies are closely involved in the engine maintenance business as well as providing the parts and engineering support required to keep engines operating profitably for the airlines.

Using a commercial business model would potentially offer some advantages to the government. If industry could be persuaded to self-finance fighter engine development,

that would reduce the need for government resources in the near term, especially if the government were able to offer an attractive business case to both the major engine suppliers. The use of a business model that is consistent with the model used for commercial engine development could allow for even greater leveraging of commercially-funded R&D in fighter engines. However, it is not clear that this business model is truly viable for something as expensive as developing an entirely new military engine design.

Because the DoD is the primary buyer for military engines (with foreign military sales providing a significant part of the market, but one that is inherently linked to the DoD share), the military engine market differs from the commercial one in scope, number of engines, and in the market power that the DoD has. Commercial engine providers can spread the recoupment of their R&D costs over many thousands more engines than exist in the DoD inventory and spread their risk across multiple customers. The engine providers certainly have to be responsive to individual customer needs and preferences, but they can, to a certain extent, dictate many terms to the marketplace, which gives them a degree of predictability on their ability to recapture R&D investments that the DoD market would have to be carefully managed to provide. The inherent uncertainty of defense budgeting is a significant challenge in this regard. Engines tied to a new aircraft type would be subject to the significant deviation between aircraft inventory projections and actual purchases. The F119, for example, was developed for an F-22 fighter inventory initially projected for 750 aircraft (each with two engines), but F-22 production was terminated after 187 aircraft. Engine companies would need an iron-clad guarantee that the government would purchase their engines when they reach production to ensure a return on investment. Such a guarantee is procedurally challenging to implement in the federal government context and presents potential budget scoring challenges that could undermine its appeal. If, for example, budget scorekeepers required the DoD to register an engine purchase guarantee as a mandatory obligation, the near-term budgetary advantages of the commercial business model could be nullified. Company-financed development would also offer government substantially less control of the technology development process and of how that technology was used, and potentially shared, in the commercial engine market.

However, many of the disadvantages of a company-financed approach may be substantially mitigated if the development being financed involves improvements to existing engines rather than new development. This approach would put significantly less capital, and less sensitive technology, at risk. Here the market scope would be well understood, allowing for a carefully calibrated investment approach with a high likelihood of delivering return on investment without use of extraordinary mechanisms. Traditionally, government has funded some design improvements in existing engine fleets or provided incentives for industry to be reimbursed for these investments. In the commercial marketplace, industry frequently will self-finance design improvements that can be recouped through revenues from performance-based sustainment contracts, often known as “power by the hour” contracts.

While engine sales to airlines today operate with relatively low margins in production, another possible business model for engine development would look more like commercial

industries where R&D is company-funded but profitability centers in production—as is the case in the commercial airliner market. Commercial airplane manufacturers self-fund their aircraft development but obtain most of their return on investment during aircraft production. Only recently have aircraft manufacturers sought to become major players in the aircraft maintenance and services businesses.<sup>128</sup> This business model is reasonably common in commercial product development generally, and thus could be a viable business model to consider for engine development. It is largely similar to the current commercial engine business model, but it would have the advantage of requiring less change to the way the DoD currently approaches aircraft sustainment, as it does not rely on the ability to obtain significant profits in sustainment.

## Competition in the U.S. Fighter Engine Market

In the past 40 years, there have been three major stages of fighter engine competition for the Air Force. The first stage took place primarily during the 1980s, with the procurement of engines to power the F-16 and F-15. This stage is commonly referred to as the “Great Engine War.” The second stage took place primarily during the 1990s, with the procurement of engines to power the F-22. The third took place primarily during the 2000s, with the procurement of engines to power the F-35. With each stage, the Air Force took a notably different approach.

### THE GREAT ENGINE WAR: F100 AND F110

The single-engine F-16 was the last U.S. fighter to be produced over 4,000 times. No other fourth- or fifth-generation fighter has come close to surpassing its production level. The F-16 remains the most common fighter in the Air Force; in fact, in 2016, there were still more than twice as many F-16s in the Air Force’s stated inventory as there were F-15s, the second most common fighter.

Despite being smaller and cheaper than other fighters, the scale of the F-16 program made it a critical national security investment. This program began in the 1970s and ramped up in the 1980s. The challenges that emerged during this program led to a major engine competition, often referred to as the Great Engine War.

In the 1980s, Pratt & Whitney and General Electric competed in an unprecedented series of yearly competitions. Initially, the Pratt & Whitney F100 engine was selected to power the F-16, although it was originally developed to power the twin-engine F-15.<sup>129</sup> While the F100 met the initial and primary design goal of doubling thrust-to-weight ratio, Air Force pilots quickly began pushing the F-16 to its limits, given the increased maneuverability of the airframe.<sup>130</sup> This led to engine problems and compelled the Air Force to consider alternatives.

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<sup>128</sup> “Boeing Global Services Begins Operations,” Boeing Company, press release, June 30, 2017, <https://boeing.mediaroom.com/2017-06-30-Boeing-Global-Services-Begins-Operations>.

<sup>129</sup> Jeremiah Gertler, *F-35 Alternate Engine Program: Background and Issues for Congress*, CRS Report No. R41131 (Washington, DC: Congressional Research Service, January 10, 2012), <https://fas.org/sgp/crs/weapons/R41131.pdf>.

<sup>130</sup> Frank Camm and Thomas K. Glennan, Jr., *The Development of the F100-PW-220 and F110-GE-100 Engines: A Case Study of Risk Assessment and Risk Management* (Santa Monica, CA: RAND Corporation, 1993), <https://www.rand.org/pubs/notes/N3618.html>.

Like most military engine competitions, the F-16 program began with a competition before the aircraft reached full-scale production. However, unlike others, this competition not only continued well into the procurement life cycle, but even escalated.

In 1979, due to emerging challenges, Congress funded the Engine Model Derivative Program (EMDP). EMDP was an effort for General Electric to develop its F101 engine for the F-16. The goal was to fly this alternative engine in the F-16 within 30 months.<sup>131</sup> The result was the F110 engine. The DoD also spent more than \$376 million to develop the F110 to compete with the F100 and \$600 million to improve the F100's durability and reliability.<sup>132</sup>

With an alternative engine ready to use, the Air Force was able to institute head-to-head competition between Pratt & Whitney and General Electric. To maximize the competition between the two companies, the Air Force awarded a percentage split of the total contract to both firms on a year-to-year basis. In the first year of competition, 1984, General Electric was awarded 75 percent of the contract and Pratt & Whitney was awarded the remaining 25 percent.<sup>133</sup> The Air Force also reserved the right to change this split on a year-to-year basis to reward lower costs and better performance. The figure below summarizes the yearly contract splits.<sup>134</sup>

Figure 20: "Great Engine War" Engine Procurement Quantities

**Table B-I. "Great Engine War" Procurement Quantities**

FY	Pratt & Whitney F100-PW-220	General Electric F110-GE-100	Pratt %	GE %
85 <sup>a</sup>	40	120	25%	75%
86	159	184	46%	54%
87	160	205	44%	56%
88	181	147	55%	45%
89	159	100	61%	39%
90	70	39	64%	36%
<b>Total</b>	<b>769</b>	<b>795</b>	<b>49%</b>	<b>51%</b>

While these annual engine competitions were "unprecedented and controversial," they were also viewed as successful.<sup>135</sup> Proponents argued that the Air Force received a better result than it would otherwise have received from a single company facing no competition.<sup>136</sup> These perceived benefits included lower costs and improved contractor responsiveness.<sup>137</sup>

<sup>131</sup> Karl G. Amick, *The Next Great Engine War Analysis and Recommendations for Managing the Joint Strike Fighter Engine Competition* (Monterey, CA: Naval Postgraduate School, December 2005), [https://calhoun.nps.edu/bitstream/handle/10945/1854/05Dec\\_Amick.pdf?sequence=1&isAllowed=y](https://calhoun.nps.edu/bitstream/handle/10945/1854/05Dec_Amick.pdf?sequence=1&isAllowed=y).

<sup>132</sup> Camm and Glennan, *The Development of the F100-PW-220 and F110-GE-100 Engines*.

<sup>133</sup> New York Times Editorial Board, "The Lesson of the Great Engine War," *New York Times*, February 13, 1984, 20.

<sup>134</sup> Gertler, *F-35 Alternate Engine Program*.

<sup>135</sup> *Ibid.*

<sup>136</sup> *Ibid.*

<sup>137</sup> *Ibid.*

Many continued to advocate this style of competition for future acquisition programs. However, since the Great Engine War, no comparable competition has taken place.

#### ADVANCED TACTICAL FIGHTER: YF119 AND YF120

The Advanced Tactical Fighter (ATF) program began in 1981, but the outcome of this competition was not determined until 1991. The program began with ambitious goals, including to build the first fifth-generation fighter. Initially, the plan was to procure 750 new aircraft.<sup>138</sup> However these ambitious goals were scaled back because of changing strategic considerations as the Cold War ended.

While Lockheed and Northrop competed to build the fighter, Pratt & Whitney and General Electric competed to build its engine. In the early-1980s, both engine companies were awarded contracts to deliver prototypes.

Pratt & Whitney and General Electric offered radically different designs for this competition. Pratt & Whitney proposed the YF119, a turbofan with 35,000 lb. of thrust. Even without using its afterburner, the engine could power the fighter to reach supersonic speed. The main benefit of this feature was to increase fuel savings and combat radius while maintaining performance.<sup>139</sup>

General Electric proposed the YF120, which was also a turbofan in the 35,000 lb. thrust range. It incorporated a variable cycle turbine, allowing the engine to operate like a conventional turbojet at supersonic speeds while preserving the fuel-saving capabilities of a turbofan at subsonic speeds.<sup>140</sup> Consequently, the YF120 had the edge on power, but it also had more complexity.

Both engine prototypes were tested in the YF-22 (Lockheed's fighter) and the YF-23 (Northrop's fighter). In April 1991, the Air Force selected Pratt & Whitney's engine, the YF119, to power Lockheed's fighter, the YF-22. Despite the major victory for Pratt & Whitney, the contract ended up being less lucrative than initially anticipated. The planned procurement levels for the F-22 dropped sharply in 1990 and then again in the 2000s, from 750 to 187. Meanwhile, General Electric had to wait until the next major fighter engine competition to see a new engine enter the landscape.

#### JOINT STRIKE FIGHTER: F135 AND F136

The Joint Strike Fighter (JSF) program originated from a series of programs in the late-1980s and early-1990s. JSF effectively began in 1997, after the DoD awarded contracts to develop demonstrators for a multi-role fifth-generation fighter to replace several existing fighter aircraft.<sup>141</sup> Similar to ATF, the program began with ambitious goals. This time,

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<sup>138</sup> Robert Farley, "The Real F-22 Raptor Question No One Dares Ask," *National Interest*, December 12, 2018, <https://nationalinterest.org/blog/buzz/real-f-22-raptor-question-no-one-dares-ask-38562>.

<sup>139</sup> "Pratt & Whitney YF119-PW-100L Augmented Turbofan," National Museum of the United States Air Force, May 15, 2015, <https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/196077/pratt-whitney-yf119-pw-100l-augmented-turbofan/>.

<sup>140</sup> "General Electric YF120," National Museum of the United States Air Force, November 9, 2015, <https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/195682/general-electric-yf120/>.

<sup>141</sup> Christopher Bolkcom, *F-35 Lightning II Joint Strike Fighter (JSF) Program: Background, Status, and Issues*, CRS Report No. RL30563, (Washington, DC: Congressional Research Service, February 17, 2009), <https://apps.dtic.mil/dtic/tr/fulltext/u2/a494859.pdf>.

however, the program not only included the Air Force but also the Navy, Marine Corps, and a range of U.S. allies. As a result, there were three required variants: a conventional takeoff and landing (CTOL) fighter, a carrier-capable (CV) fighter, and a short take-off vertical landing (STOVL) fighter.

Lockheed Martin, with its X-35, and Boeing, with its X-32, competed to build the fighter. However, while Pratt & Whitney and General Electric (in partnership with Rolls-Royce) once again competed to build the new engine, the situation was different from ATF, in that the engine competitors were teamed with aircraft designers. Lockheed Martin, Boeing, and McDonnell Douglas were all involved in the early concept stages of this new multi-role fighter. The McDonnell Douglas team used a General Electric/Rolls-Royce engine for their concept design. Both Lockheed Martin and Boeing used a Pratt & Whitney engine. In 1997, the DoD only awarded contracts to Lockheed Martin and Boeing. This left Pratt & Whitney as the only engine company in the competition. There was no separate engine competition.<sup>142</sup>

However, Congress, in seeking to ensure that the program “provides for adequate engine competition,” directed the DoD to invest in the development of an alternative engine. As a result, Pratt & Whitney, with its F135 engine (a derivative of its F119 engine), and General Electric/Rolls-Royce, with its F136 engine, both set out developing engines for the F-35, with Pratt & Whitney receiving more funding earlier as the main engine design.<sup>143</sup> In 2001, the DoD selected Lockheed Martin’s X-35, which used Pratt & Whitney’s F135 engine, as the winner of the JSF competition. Under the alternate engine program, General Electric/Rolls-Royce continued to receive funding for the F136 as an alternative design. However, the DoD stopped requesting funding for the F136 in 2007. Congress continued to add the funding for the F136 in succeeding years. However, in 2011, the F136 program was formally terminated by the DoD.

In formulating a strategy for engine investment, the DoD will have to choose an approach to generate and sustain competition in the engine industrial base. If the DoD chooses to invest in multiple engine investment programs, the opportunity for competition will be greater. Likewise, selecting a business model that puts more responsibility for engine development on the manufacturers would reduce the government’s upfront expense for engine development, potentially allowing industry to compete head-to-head during engine design as well as engine production. The experience of the Great Engine War showed that competition can work to control prices and improve engine performance. The experience of JSF showed that it can be difficult to sustain government funding streams for designing two competing engines for the same aircraft over more than a decade of time. The decisions the DoD makes with respect to its first three policy choices (the priority of engine technology, the focus of technology investment, and the business model for engine development) will establish constraints around its approach to competition. However, the DoD will then be able to establish the smartest approach to competition possible within those constraints.

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<sup>142</sup> Gertler, *F-35 Alternate Engine Program*.

<sup>143</sup> *Ibid.*

## Conclusion

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The story of U.S. fighter engine development is intimately bound to the story of U.S. airpower and its preeminence in the Cold War and post-Cold War eras. Fighter engine development also greatly contributed to the development of U.S. commercial aerospace and its robust global competitiveness. However, since the 1980s there has been a dramatic slowdown in the deployment of new fighter engine technology. The importance of fighter engine development has receded in relative terms, as fighter engine development has slowed, commercial engine development has risen to the fore, and other investment areas—such as stealth and electronics—have become significant alternatives for military aviation resources. Competitors such as Russia and China are investing to catch up to U.S. engine technology and have made some progress in this effort. Engine development still offers opportunities for critical improvements in air capability, such as significantly extended range, to counter advances in anti-access/area denial capabilities, and improved power generation and thermal management, to power the ever-expanding list of sensors and weapons developed for use by aircraft. While the U.S. advantage in engine technology is eroding, it can clearly be maintained with sufficient investment.

There is an important choice to be made on engine development in the near term, one that is really a series of closely-related choices. U.S. fighter engine development is at a crossroads. With the imminent end of the AETP development program and likely extended timelines for fielding of next-generation fighters, there is the potential for a gap in engine development, particularly in engine design, that would significantly impact the U.S. engine industrial base and continue the erosion of a current U.S. technological advantage. In determining how to fill this gap, the DoD faces four significant policy choices on how much to prioritize engine development, what investment path or paths to choose, how to finance investment, and how to sustain key capabilities in the industrial base through competition. The DoD's choices should be informed and determined by its strategic needs and the urgency with which it sees the need to field new capabilities to its aircraft fleets. Although the Air Force has begun to plan for investment after the AETP finishes, the DoD has not fully evaluated these choices, and the implications of the decisions may extend well beyond the impacts on the Air Force's fleet. It is therefore incumbent on the DoD to approach these choices as an enterprise decision and to develop an investment approach that best meets U.S. national objectives.

# Appendix | Methodology

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For this study, the study team interviewed and met with over 25 experts in the field of military engines. These experts included past and current government officials, military leaders, executives at engine companies, top engineers, academics, and congressional staffers.

The study team hosted two workshops to discuss the findings and conclusions of the project and potential areas of further exploration. They also identified common concerns about the industry from a group with wide-ranging perspectives. The workshops included participants from the same areas as the experts mentioned above, and, in some instances, included the same experts.

The team also conducted several site visits, including to Pratt & Whitney headquarters (East Hartford, CT), General Electric Aviation headquarters (Evendale, OH), and Wright-Patterson Air Force Base (Dayton, OH).

To help ensure transparency and objectivity, the study was advised by a Senior Review Board that reviewed the project plan, methodology, and study findings while in progress and then reviewed and commented on this report.

The following section describes the methodology behind the data sets utilized in this project. There are three main data sets:

1. Inventory: total Air Force aircraft inventory, engines, and performance specifications
2. Contracts: engine-related contracts from the Federal Procurement Data System (FPDS)
3. Budget: engine-related budget projections from the Future Years Defense Program (FYDP)

## Inventory

The purpose of the inventory data set is to map out the history of USAF engine trends from 1950 to present, in order to understand the pace of engine development. This includes the number of aircraft, the number of engines, the age of the fleet, and performance specs of the entire fleet.



## AIRCRAFT INVENTORY

The inventory data set began with a 2010 Air Force Association report, *Arsenal of Airpower: USAF Aircraft Inventory 1950-2009*.<sup>144</sup> This report provides a data set with the number of each platform that makes up the USAF Total Aircraft Inventory. Updated data from the USAF Almanacs from 2010 to 2017 was added by the study team to complete the inventory numbers. This data set includes four variables: aircraft, type, year, and amount.

## ENGINE INVENTORY

The study team then added a new variable, engine, which identifies the engine for every platform. For instance, the F-35 has the F135 and the F-22 has the F119. Furthermore, the team determined the number of engines for each platform and created the variable *engine\_amount*. For instance, the F-35 only has one engine and the F-22 has two.

## AIRCRAFT PERFORMANCE SPECS

The study team identified the most relevant and consistently available aircraft performance specs for fighter/attack aircraft. These variables included takeoff weight, speed, range, ceiling, climb rate, and thrust-to-weight ratio of the aircraft.

## ENGINE PERFORMANCE SPECS

The study team identified the most relevant and consistently available engine performance specs for fighter/attack aircraft that had turbojet or turbofan engines. These variables included maximum thrust, overall pressure ratio, engine weight, and thrust-to-weight ratio of the engine.

## LIMITATIONS

This data set has two main limitations. First, while it is more comprehensive than any other publicly available data set on aircraft and engines, it lacks data for some major categories. For example, the team did not assign performance specs for other categories beyond fighter/attack aircraft and did not assign engine inventory data to Helicopter or Trainer aircraft. This is due to the limited scope of this project and to the limited sources for this information. Second, for performance specs, the team relied heavily on internet sources. The primary sources referenced on these pages were generally reputable (e.g., Jane's All the World's Aircraft), especially for heavily produced aircraft. And when the sources were not listed or the numbers were unclear, the study team found secondary sources or made assumptions based on analysis of other platforms. Despite these shortcomings, this data set is a valuable resource for this project because of a high degree of confidence in the numbers for heavily produced aircraft and the focus on overall trend analysis.

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<sup>144</sup> James C. Ruehrmund, Jr., and Christopher Bowie, *Arsenal of Airpower: USAF Aircraft Inventory 1950-2009* (Arlington, VA: Mitchell Institute Press, November 2010), [http://secure.afa.org/Mitchell/reports/MS\\_TAI\\_1110.pdf](http://secure.afa.org/Mitchell/reports/MS_TAI_1110.pdf).

## INVENTORY VARIABLES

aircraft: the name of each platform

type: the type of aircraft. Includes: Bomber, Fighter/Attack, Helicopter, Recon, Tanker, Trainer, and Transport

year: the fiscal year

amount: the number for each platform in the USAF Total Active Inventory

engine: the name of each engine

engine\_type: the type of engine. Includes: Radial, Turbofan, Turbojet, Turboprop, and Turboshaft

engine\_number: the number of engines on the specific aircraft

engine\_company: the main manufacturer for each engine

takeoff\_weight: max listed takeoff weight in pounds

speed: max listed speed in mph

range: max listed range in mi

ceiling: max listed service ceiling in ft

climb\_rate: listed rate of climb in ft/min

thrust\_weight\_aircraft: listed thrust/weight ratio of the aircraft

thrust: max listed thrust of the engine in lb.

pressure\_ratio: listed overall pressure ratio

engine\_weight: listed engine weight in lb.

thrust\_weight\_engine: listed thrust/weight ratio of the engine

intro\_year: the first year that the aircraft appeared in the USAF Total Active Inventory

peak\_amount: the max amount for each aircraft between 1950–present

generation: the fighter generation for fighter/attack aircraft

## Contracts

The purpose of the contract data set is to identify important trends in contract obligations that are directly relevant to military aircraft engines. Contracts are the mechanism through which the U.S. government works with industry to develop and procure military engines, so this data set is particularly important for understanding how engine trends directly impact industry.

### FEDERAL PROCUREMENT DATA SYSTEM METHODOLOGY

For nearly a decade, the CSIS Defense–Industrial Initiatives Group (DIIG) has issued a series of analytical reports on federal contract spending for national security across the government. These reports are built on FPDS data, presently downloaded in bulk from USAspending.gov. DIIG now maintains its own database of federal spending, including for the years 1990–2017, that is a combination of data download from FPDS and legacy DD350 data. For this report, however, the study team primarily relied on FY 2000 to FY 2017. Data before FY 2000 require mixing sources and incur limitations.

### INHERENT RESTRICTIONS OF FPDS

Since the contract analysis presented in this report relies on FPDS data, it incurs four notable restrictions. First, contracts awarded as part of overseas contingency operations are not separately classified in FPDS. As a result, the study team did not distinguish between contracts funded by base budgets and those funded by supplemental appropriations. This limitation is of little relevance to the analysis of engine development but may come into play in other sources of engine industry revenue. Second, FPDS includes only prime contracts, and the separate subcontract database (Federal Subaward Reporting System, or FSRS) has historically been radically incomplete; only in the last few years have the subcontract data started to approach required levels of quality and comprehensiveness. Therefore, only prime contract data are included in this report. This limits the teams understanding of engine industry revenues, since engines are subsystems within aircraft. However, there is a strong pattern of the U.S. government contracting directly for aircraft engines—particularly for fighter/attack aircraft—which substantially mitigates this limitation. Third, reporting regulations require that only unclassified contracts be included in FPDS. The study team interprets this to mean that few, if any, classified contracts are in the database. For the DoD, this omits a substantial amount of total contract spending, perhaps as much as 10 percent. Such omissions are probably most noticeable in R&D contracts. Finally, classifications of contracts differ between FPDS and individual vendors. For example, some contracts that a vendor may consider as services are labeled as products in FPDS, and vice versa. This may cause some discrepancies between vendors' reports and those of the federal government.

### CONSTANT DOLLARS AND FISCAL YEARS

All dollar amounts in this data analysis section are reported as constant FY 2016 dollars unless specifically noted otherwise. Dollar amounts for all years are deflated by the implicit GDP deflator calculated by the U.S. Bureau of Economic Analysis, with FY 2016 as the base

year, allowing the CSIS team to more accurately compare and analyze changes in spending across time. Similarly, all compound annual growth values and percentage growth comparisons are based on constant dollars and thus adjusted for inflation. Due to the native format of FPDS and the ease of comparison with government databases, all references to years conform to the federal fiscal year. FY 2017, the most recent complete year in the database, spans from October 1, 2016, to September 30, 2017.

#### DATA QUALITY

Any analysis based on FPDS information is naturally limited by the quality of the underlying data. Several Government Accountability Office (GAO) studies have highlighted the problems of FPDS (for example, William T. Woods' 2003 report *Reliability of Federal Procurement Data* and Katherine V. Schinasi's 2005 report *Improvements Needed for the Federal Procurement Data System—Next Generation*).<sup>145</sup>

In addition, FPDS data from past years are continuously updated over time. While FY 2007 was long closed, over \$100 billion worth of entries for that year were modified in 2010. This explains any discrepancies between the data presented in this report and those in previous editions. The study team changes over prior-year data when a significant change in topline spending is observed in the updates. Tracking these changes does reduce ease of comparison to past years, but the revisions also enable the report to use the best available data and monitor for abuse of updates.

Despite its flaws, FPDS is the only comprehensive data source of government contracting activity, and it is more than adequate for any analysis focused on trends and order-of-magnitude comparisons. To be transparent about weaknesses in the data, this report consistently describes data that could not be classified due to missing entries or contradictory information as “unlabeled” rather than including it in an “other” category.

The 2016 data used in this report were downloaded in January 2017. The 2017 data used in this report were downloaded in January 2018; a full re-download of all back-year data was performed simultaneously.

#### CONTRACT VARIABLES

The contract variables analyzed for this study include:

fy: the fiscal year for the contract obligation

customer: the military customer, which includes Army, Air Force, Navy, DLA, and Other DoD

category: the type of contract obligation, which includes products, services, and R&D

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<sup>145</sup> William T. Woods, *Reliability of Federal Procurement Data* (Washington, DC: Government Accountability Office, December 2003), <https://www.gao.gov/products/GAO-04-295R>; and Katherine V. Schinasi, *Improvements Needed for the Federal Procurement Data system—Next Generation* (Washington, DC: Government Accountability Office, September 2005), <https://www.gao.gov/products/GAO-05-960R>.

project: the name of the project for the contract obligation

parent: the company receiving the contract

vendor\_size: the size of the company receiving the contract

competition: the way that the contract was competed

contract\_type: the type of contract

amount: the dollar value of the contract

## Budget

The purpose of the budget data set is to identify important RDT&E investments in military aircraft engines as well as to compare the DoD's spending plans to its actual spending.

### FUTURE YEARS DEFENSE PROGRAM METHODOLOGY

Most years, the DoD releases its FYDP, a five-year spending plan for each program, in a set of budget documents. These documents, known as justification books, are available on the DoD comptroller website. The study team analyzed the justification books from 1999 to 2019 for Army, Navy, and Air Force to identify spending that was directly related to military aircraft engines.

The team began with R-2s (RDT&E documents) and identified relevant program elements based on "Mission Description and Budget Item Justification." The team looked at program elements that mentioned turbine engines or more advanced aerospace technologies such as ramjets or hypersonic systems. They then identified relevant projects within each program. Each program element is broken down into separate projects. For example, *Aerospace Propulsion and Power Technology* had six projects in the 2019 President's Budget request: *Aerospace Fuels*, *Aerospace Power Technology*, *Aircraft Propulsion Subsystems Int*, *Space & Missile Rocket Propulsion*, *Advanced Aerospace Propulsion*, and *Advanced Turbine Engine Gas Generator*.

A full description of the programs examined can be found on GitHub under the Engines repository for the organization CSISdefense. The language used mirrors Department of Defense Budget Justification documents, the most recent versions of which for the relevant programs are cited below:

#### **F135 Propulsion System and F136 Propulsion System (Broken out from F-35 - EMD/Joint Strike Fighter):**

U.S. Department of the Navy, *PE 0604800N: JT Strike Fighter (JSF) - EMD* (2011), [https://www.dacis.com/budget/budget\\_pdf/FY12/RDTE/N/0604800N\\_129.pdf](https://www.dacis.com/budget/budget_pdf/FY12/RDTE/N/0604800N_129.pdf).

#### **Advanced Aerospace Propulsion:**

U.S. Department of the Air Force, *PE 0603216F / Aerospace Propulsion and Power Technology* (2018), [https://www.dacis.com/budget/budget\\_pdf/FY19/RDTE/F/0603216F\\_20.pdf](https://www.dacis.com/budget/budget_pdf/FY19/RDTE/F/0603216F_20.pdf).

**Advanced Propulsion Technology:**

U.S. Department of the Air Force, PE 0602203F / *Aerospace Propulsion* (2019),  
[https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/F/0602203F\\_7.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/F/0602203F_7.pdf).

**Advanced Turbine Engine Gas Generator:**

U.S. Department of the Air Force, PE 0603216F / *Aerospace Propulsion and Power Technology* (2019), [https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/F/0603216F\\_21.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/F/0603216F_21.pdf).

**Aerospace Fuels:**

U.S. Department of the Air Force, PE 0603216F / *Aerospace Propulsion and Power Technology* (2018) [https://www.dacis.com/budget/budget\\_pdf/FY19/RDTE/F/0603216F\\_20.pdf](https://www.dacis.com/budget/budget_pdf/FY19/RDTE/F/0603216F_20.pdf).

**Aircraft Propulsion Subsystems Int:**

U.S. Department of the Air Force, PE 0603216F / *Aerospace Propulsion and Power Technology* (February 2019),  
[https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/F/0603216F\\_21.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/F/0603216F_21.pdf).

**Combustion and Mechanical Systems:**

U.S. Department of the Air Force, PE 0602203F / *Aerospace Propulsion* (2019),  
[https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/F/0602203F\\_7.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/F/0602203F_7.pdf).

**Materials for Structures, Propulsion, and Subsystems:**

U.S. Department of the Air Force, PE 0602102F / *Materials* (2018),  
[https://www.dacis.com/budget/budget\\_pdf/FY19/RDTE/F/0602102F\\_4.pdf](https://www.dacis.com/budget/budget_pdf/FY19/RDTE/F/0602102F_4.pdf).

**Turbine Engine Technology:**

U.S. Department of the Air Force, PE 0602203F / *Aerospace Propulsion* (2018),  
[https://www.dacis.com/budget/budget\\_pdf/FY19/RDTE/F/0602203F\\_7.pdf](https://www.dacis.com/budget/budget_pdf/FY19/RDTE/F/0602203F_7.pdf).

**Aircraft Engine Component Improvement Program (USAF):**

U.S. Department of the Air Force, PE 0207268F / *Aircraft Engine Component Improvement Program* (2019),  
[https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/F/0207268F\\_190.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/F/0207268F_190.pdf).

**Aircraft Engine Component Improvement Program (F135):**

U.S. Department of the Air Force, PE 0207268F / *Aircraft Engine Component Improvement Program* (2018),  
[https://www.dacis.com/budget/budget\\_pdf/FY19/RDTE/F/0207268F\\_200.pdf](https://www.dacis.com/budget/budget_pdf/FY19/RDTE/F/0207268F_200.pdf).

**AV-8B:**

U.S. Department of the Navy, PE 0604214M / *AV-8B Aircraft - Engine Dev* (2019),  
[https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/N/0604214M\\_98.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/N/0604214M_98.pdf).

**Aircraft Engine Component Improvement Program (USN):**

U.S. Department of the Navy, PE 0205633N / *Aviation Improvements* (2019),  
[https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/N/0205633N\\_226.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/N/0205633N_226.pdf).

**ACFT Demo Engines:**

U.S. Department of the Army, *PE 0603003A / Aviation Advanced Technology* (2018), [https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/A/0603003A\\_43.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/A/0603003A_43.pdf).

**Veh Prop & Struct Tech:**

U.S. Department of the Army, *PE 0602211A / Aviation Technology* (2019), [https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/A/0602211A\\_19.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/A/0602211A_19.pdf).

**Adv Propulsion Rsch:**

U.S. Department of the Army, *PE 0601102A / Defense Research Sciences* (2015), [https://www.dacis.com/budget/budget\\_pdf/FY16/RDTE/A/0601102A\\_2.pdf](https://www.dacis.com/budget/budget_pdf/FY16/RDTE/A/0601102A_2.pdf).

**Aircraft Engine Component Improvement Program:**

U.S. Department of the Army, *PE 0203752A - Aircraft Engine Component Improvement Program* (2015), [https://www.dacis.com/budget/budget\\_pdf/FY06/RDTE/A/0203752A.pdf](https://www.dacis.com/budget/budget_pdf/FY06/RDTE/A/0203752A.pdf).

**Improved Turbine Engine Program:**

U.S. Department of the Army, *PE 0607139A / Improved Turbine Engine Program* (2019), [https://www.dacis.com/budget/budget\\_pdf/FY20/RDTE/A/0607139A\\_214.pdf](https://www.dacis.com/budget/budget_pdf/FY20/RDTE/A/0607139A_214.pdf).

**Technology Transition Program:**

The Air Force categorized AETP and major funding for adaptive engines under the Technical Transition Program (PE 0604858F). Since 2013, funding under this category has been primarily for adaptive engines, but not entirely. U.S. Department of the Air Force, *PE 0604858F / Tech Transition Program* (2018), [https://www.dacis.com/budget/budget\\_pdf/FY19/RDTE/F/0604858F\\_48.pdf](https://www.dacis.com/budget/budget_pdf/FY19/RDTE/F/0604858F_48.pdf).

The study team once again read the “Mission Description and Budget Item Justification,” this time for each project, and determined which projects were sufficiently relevant to military aircraft engines. For the projects that were, the team collected their spending plan and consolidated the numbers into a single database. The project names, and even the project numbers, sometimes changed from year to year. So, the study team also identified such changes and updated the names to accurately reflect the projects in the trend analysis. For the purposes of reproducible research, the study team makes the source code available on GitHub under the Engines repository for the organization CSISdefense. The data cleaning was accomplished in the program language R and these specific changes can be seen within the `data_processing.R` file in the budget folder:

[https://github.com/CSISdefense/Engines/blob/master/budget/data\\_processing.R](https://github.com/CSISdefense/Engines/blob/master/budget/data_processing.R).

**BUDGET VARIABLES**

The budget variables analyzed for this study include:

`fydp_year`: the President’s Budget Request Year. The most recent justification books utilized were those released for PB 2019.

`fy`: the fiscal year for relevant spending. For example, the PB 2019 request includes a spending plan for fiscal years 2019, 2020, 2021, 2022, and 2023.

account: the RDT&E budget activity. This includes basic research, applied research, advanced technology development, advanced component development and prototypes, system development and demonstration, management support, and operational systems development.

organization: the military service, which includes Army, Air Force, and Navy

program\_number and program\_name: the R-1 Program Element number and name

project\_number and project\_name: the project number and name (a subcategory of the R-1 Program Element)



## About the Authors

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**Gabriel Coll** was a program manager and research associate for the Defense–Industrial Initiatives Group at CSIS from 2015 to 2020. Prior to that he worked as a research intern for the CSIS International Security Program, where he supported the development of the Federated Defense Project and provided research on Asia and the Middle East. He is currently an adjunct fellow (Non–Resident) at the Center for Strategic and International Studies.

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**Asya Akca** was a program manager and research associate for the Defense–Industrial Initiatives Group at CSIS from 2018 to 2020. Prior to that she was a research intern for the CSIS International Security Program where she supported the Cooperative Defense Project and provided research on security cooperation issues.

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