NASA
Office of Inspector General

NASA's Electrified Aircraft Propulsion Research and Development Efforts

May 17, 2023

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Office of Inspector General

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COVER IMAGES

Top Left—Illustration of the NASA N3-X, a fully turboelectric concept aircraft with a hybrid wing body airframe.
Middle Right—NASA illustration of an advanced subsonic aircraft with an electrified aircraft propulsion system.
Bottom Left—Illustration of Mod II of the X-57 Maxwell, an experimental aircraft for testing electrified aircraft systems.

Results in Brief

NASA's Electrified Aircraft Propulsion Research and Development Efforts

May 17, 2023 IG-23-014 (A-22-10-00-SARD)

Why We Performed This Audit

NASA plays an important role in efforts to reduce carbon dioxide emissions from commercial aviation. NASA's contributions are critical to supporting the Administration's goal of net-zero greenhouse gas emissions by 2050, as outlined in the Federal Aviation Administration's (FAA) 2021 U.S. Aviation Climate Action Plan. Along with investing in sustainable aviation fuel and other technological advances, a key component of reducing carbon emissions from aviation is advancing electrified aircraft propulsion (EAP) systems—that is, electric motors that drive some or all the propulsors on an aircraft.

NASA's Aeronautics Research Mission Directorate (ARMD) manages the Agency's EAP-related research and development and NASA's efforts to support the goals of the 2021 U.S. Aviation Climate Action Plan. NASA and the FAA are working with the aviation industry through the Sustainable Flight National Partnership to accelerate development of more efficient aircraft and engine technologies that could improve fuel savings up to 30 percent compared to today's airplanes while also substantially reducing noise and emissions. The goal is for these more efficient single-aisle aircraft to enter the U.S. commercial fleet in the 2030s followed by double-aisle aircraft in the 2040s.

In this audit, we evaluated NASA's management of its EAP research and development efforts. Specifically, we assessed NASA's progress toward developing and testing new technologies and sustainable energy options for aircraft propulsion. We also examined whether ARMD met its established goals and priorities. To assess NASA's progress, we interviewed officials and ARMD project managers and reviewed documents from eight EAP projects. We performed work at NASA Headquarters, Armstrong Flight Research Center, and Glenn Research Center.

What We Found

NASA's EAP research and development efforts that began in 2009 include ongoing collaborations with academia, other federal agencies, and industry—as well as investments in test facilities and equipment. These efforts have positioned the Agency to help achieve the Aviation Climate Action Plan's CO_2 reduction goals by 2050. We found that over the years NASA has funded research of conceptual technology and early-stage aeronautics innovations, improved turbine engine performance, and new concept vertical lift vehicles. NASA has also engaged in partnerships to research, develop, and demonstrate EAP technology applicable to different flight ranges and fostered academic development of EAP-related technologies.

NASA has also devoted a significant portion of its EAP resources to partner with the aviation industry for flight demonstration projects. The X-57 "Maxwell" Project—managed by NASA and a contractor—began with plans to modify a test plane in four mods, with Mod IV demonstrating a new propulsion technology known as distributed electric propulsion that could potentially be used by smaller aircraft in an air taxi or commuter role with a small number of passengers. In addition, NASA collaborated with industry on the Electrified Powertrain Flight Demonstration (EPFD) Project that could lead to rapidly maturing EAP technologies for introduction into the U.S. fleet no later than 2035. Ultimately, NASA awarded a contract to GE Aviation to develop a single-aisle commercial aircraft incorporating EAP and another contract with magniX to focus on a regional commuter hybrid turboprop aircraft. Both projects have flight demonstrations planned between 2025 and 2026.

Despite its promising strides in EAP-related research, NASA faces challenges that could impact project costs and schedules. Specifically, all of NASA's EAP-related flight demonstration projects have either experienced or show indications of schedule delays and cost overruns. For example, the X-57 was estimated to cost $40 million but has experienced more than $47 million in cost overruns and an almost 3-year schedule delay. Moreover, NASA decided to terminate the project after the Mod II flight demonstration scheduled for late 2023. In addition, the EPFD Project is showing early indications of similar schedule delays and cost increases with the contractor's probabilistic estimate indicating a 247-day delay to project completion and a $40-million cost overrun. The estimated date for the first magniX flight has also been delayed about a year.

All EAP-related projects are experiencing challenges from COVID-19 impacts to the supply chain, including raw material shortages, delivery delays, and long-lead times for components. Six of ARMD's eight EAP-related projects also listed workforce challenges as one of their top concerns, including worker shortages and wage pressure. Other factors affecting NASA's EAP efforts include a NASA-wide pattern of over-optimism when creating cost and schedule baselines that can be attributed, in part, to a lack of data for past experimental aviation projects. Unstable funding with several projects has also been an issue, with EAP projects receiving less funding than planned both because of congressional funding delays at the beginning of fiscal year 2023 and because ARMD shifted funding to another ARMD project that was running over budget and behind schedule. Finally, an additional challenge for EAP projects is an upcoming relocation of the NASA Electric Aircraft Testbed facility at Glenn Research Center that will result in an estimated 6-month gap in the facility's ability to support testing.

What We Recommended

To increase transparency, accountability, and oversight of NASA's implementation of EAP efforts, we recommended the Associate Administrator for ARMD require that the EPFD Project Manager coordinate with Agency experts in addressing estimation challenges relative to experimental flight-project development and adjust risk analyses to derive higher probability/confidence cost and schedule estimates. In addition, we recommended the Associate Administrator re-evaluate ARMD's planning and support of the U.S. 2021 Aviation Climate Action Plan priorities and commit resources to minimize funding instabilities for these efforts.

We provided a draft of this report to NASA management who concurred with our recommendations and described planned actions to address them. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions.

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Acronyms

ARMD	Aeronautics Research Mission Directorate
AATT	Advanced Air Transport Technology
CDR	Critical Design Review
CO_2	carbon dioxide
DEP	distributed electric propulsion
DOD	Department of Defense
DOE	Department of Energy
EAP	electrified aircraft propulsion
EPFD	Electrified Powertrain Flight Demonstration
FAA	Federal Aviation Administration
FDC	Flight Demonstration and Capabilities
FY	fiscal year
GAO	Government Accountability Office
HyTEC	Hybrid Thermally Efficient Core
JCESR	Joint Center for Energy Storage Research
JCL	Joint Cost and Schedule Confidence Level
KDP	Key Decision Point
LBFD	Low-Boom Flight Demonstrator
MW	megawatt
NEAT	NASA Electric Aircraft Testbed
NPR	NASA Procedural Requirements
OIG	Office of Inspector General
PDR	Preliminary Design Review
RVLT	Revolutionary Vertical Lift Technology
SABERS	Solid-state Architecture Batteries for Enhanced Rechargeability and Safety
SFNP	Sustainable Flight National Partnership
TRL	technology readiness level
TTT	Transformational Tools and Technologies
UI	University Innovation

INTRODUCTION

NASA is playing an important role in the Administration's national and global climate change initiatives. A key example is the Agency's efforts to support aeronautics carbon dioxide (CO_2) emission reductions detailed in the Federal Aviation Administration's (FAA) 2021 U.S. Aviation Climate Plan and the NASA Authorization Act for fiscal year (FY) 2022.[1] The FAA's Climate Action Plan delineated NASA's roles and responsibilities to support the Plan's goal of achieving net-zero greenhouse gas emission by 2050. Specifically, NASA will support basic and applied research on new aircraft technologies and safe and efficient airspace operations with the goal to significantly reduce aviation's negative impact on the environment. Furthermore, the FY 2022 NASA Authorization Act established that it is the policy of the United States to maintain world leadership in civilian aeronautical science and progression and expansion of critical disciplines such as propulsion technology.

Electrified aircraft propulsion (EAP) systems are the most feasible approach to reduce single-aisle passenger plane CO_2 emissions, according to recommendations made by the National Academies of Sciences, Engineering, and Medicine (National Academies).[2] In 2016, the National Academies' Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions (Committee) recommended a research agenda of projects that would advance propulsion and energy system technologies that could be introduced into service during the next 10 to 30 years to reduce global carbon emissions from commercial aviation.[3] These efforts include foundational research as well as ground and flight demonstration of sustainable aviation technologies across a wide variety of programs including fuel alternatives, gas turbine engine improvements, aircraft-propulsion integration, and EAP. NASA's technology development efforts seek to support the Committee's recommendations as well as the 2021 U.S. Aviation Climate Action Plan and are based upon the Agency's commitment to providing the necessary resources in a timely manner to adhere to the framework and timeline. This is particularly important if the United States is to maintain world leadership in civilian aeronautical science and technology.

We initiated this audit to evaluate NASA's management of its EAP research and development efforts. The overall objective was to assess progress towards developing and testing new technologies and sustainable energy options for aircraft propulsion. In addition, we examined the Agency's collaboration and partner relationships and whether the Aeronautics Research Mission Directorate (ARMD) was meeting its established goals and priorities. See Appendix A for details on the scope and methodology.

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[1] FAA, *United States 2021 Aviation Climate Action Plan* (November 9, 2021); National Aeronautics and Space Administration Authorization Act of 2022, Pub. L. No. 117-167, August 9, 2022.

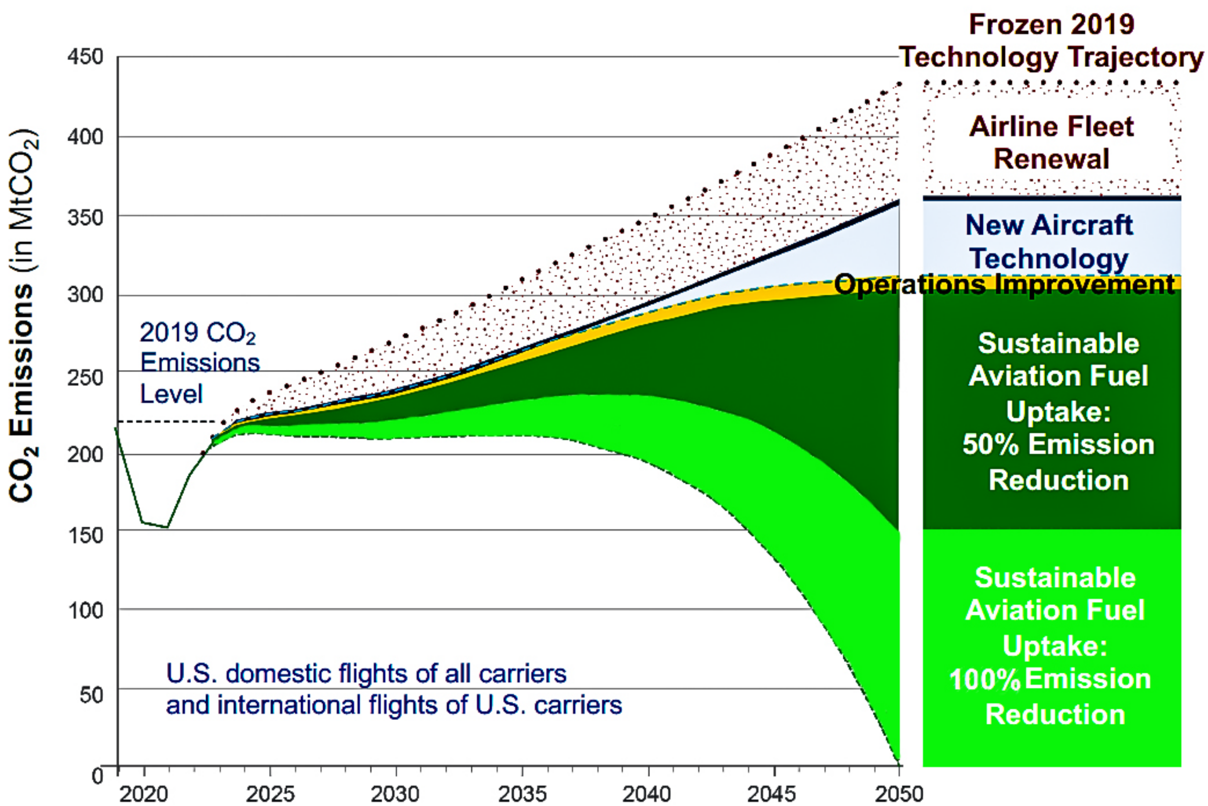
[2] EAP is the use of electric motors to drive some or all the propulsors on an air vehicle. The energy source for the electrified propulsion system can be all electric (electric energy storage, i.e., battery), hybrid (a mix of electric- and fuel-based energy storage), or turboelectric (fuel-based energy storage).

[3] National Academies, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions* (2016).

Background

In November 2021, the FAA released its first-ever comprehensive U.S. Aviation Climate Action Plan, which emphasized that the time between now and 2030 is critical to achieving net-zero greenhouse gas emissions goals by 2050. The Plan provided specific 2030 goals that would put the industry on a trajectory toward the 2050 goals. Figure 1 provides a roadmap for how U.S. aviation could reach net-zero levels through coordinated actions by U.S. industry and government. In the Figure, new aircraft technologies represent the research and development efforts, including those related to EAP technology, which NASA has said are critical to new aircraft fuel efficiency improvements, given projected higher emissions due to increased aviation over the next several decades.

Figure 1: 2021 U.S. Aviation Climate Action Plan CO_2 Emissions Predictions



Source: NASA.

Note: $MtCO_2$ is megatonnes of CO_2.

EAP is only one component to achieving the 2050 goal of net-zero greenhouse gas emissions for U.S. aviation. Other efforts include improvements that focuses on procedural efficiencies during aircraft surface, takeoff, cruise, and landing operations. Perhaps most significantly, research into sustainable aviation fuel shows the most promise in reducing overall life-cycle CO_2 emissions. However, the aviation industry is uncertain how much these fuels will actually reduce emissions. The U.S. is focusing on developing sustainable aviation fuels that will provide at least a 50-percent reduction in life-cycle emissions, with the goal shown in Figure 1 depicting the range to a 100-percent reduction.

One of the Aviation Climate Action Plan's seven key initiatives is developing new aircraft technologies.[4] Consequently, NASA and the FAA are working with the aviation industry through the Sustainable Flight National Partnership (SFNP) to accelerate development of more efficient aircraft and engine technologies that could improve fuel savings up to 30 percent compared to today's airplanes while also delivering substantial noise- and emissions-reduction benefits.[5] The goal is for these more efficient single-aisle aircraft to enter the U.S. commercial fleet in the 2030s followed by double-aisle aircraft in the 2040s.

The FY 2022 NASA Authorization Act provided specific mandates to the Agency regarding aviation. The Act requires the United States to (1) maintain world leadership in civilian aeronautical science and technology and aerospace industrialization and (2) maintain as a fundamental objective of the aeronautics research of the Administration the steady progression and expansion of flight research and capabilities, including the science and technology of critical underlying disciplines and competencies.[6]

The Authorization Act also states that:

- developing high-risk, precompetitive aerospace technologies for which there is not yet a profit rationale is a fundamental role for NASA;
- large-scale flight research experimentation and validation are necessary for (a) transitioning new technologies and materials, including associated manufacturing processes, for aviation and aeronautics use and (b) capturing the full extent of benefits from investments made by ARMD; and
- a level of funding that adequately supports large-scale flight research experimentation and validation, including related infrastructure, should be ensured over a sustained period of time to restore NASA's capacity to (a) see legacy priority programs through to completion and (b) achieve national economic and security objectives.

In 2016, the National Academies' Committee examined propulsion and energy technologies on large commercial aircraft—single- and twin-aisle aircraft that carry passengers—which account for more than 90 percent of global commercial aircraft emissions.[7] The Committee recommended NASA contribute primarily by supporting basic and applied research with other government agencies, industry, and academia focusing on the following four approaches in developing propulsion and energy system technologies:

- Advances in aircraft propulsion integration to incorporate components with improved technologies.

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4 The seven initiatives are: 1) the introduction of new aircraft and engine technologies to reduce the amount of fuel required to move people and goods, 2) operational efficiency improvements, 3) success in scaling up the production of sustainable aviation fuel with significant life-cycle emissions reductions, 4) international leadership, 5) airport initiatives and climate resilience, 6) non-CO_2 climate impact initiatives, and 7) additional domestic policies.

5 NASA is partnering with industry, academia, and other agencies through the SFNP to accomplish the aviation community's emission reduction goals.

6 Pub. L. No. 117-167 (2022). The critical underlying disciplines and competencies include computational-based analytical and predictive tools and methodologies; propulsion; advanced materials and manufacturing processes; high-temperature structures and materials; and guidance, navigation, and flight controls.

7 National Academies, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions* (2016).

- Improvements in gas turbine engines to invest in a host of technologies to improve thermodynamic and propulsive efficiency of engines.
- Development of turboelectric propulsion systems, probably the only feasible approach for developing electrified propulsion systems for large passenger aircraft within the next decade.
- Advances in sustainable alternative jet fuels to reduce life-cycle CO_2 emissions from commercial aviation.

According to the Committee's assessment, the U.S. should place a high priority on the research and development of turboelectric systems for future aircraft. The Committee determined that these systems were probably the only approach for developing electric propulsion systems for large passenger aircraft that could be feasibly achieved within the next 30 years. Combined with other technologies, such as distributed propulsion and boundary layer ingestion, these systems could potentially reduce fuel burn by up to 20 percent or more compared to today's aircraft.[8] In addition, the Committee envisioned the research projects within each approach would rely on both academia and industry, as well as federal agencies. In particular, academia would generally participate in the research and development projects at low technology readiness levels (TRL), while industry would focus on more advanced research and product development.[9] For its part, the FAA would be most directly engaged in development of certification standards for new technologies.

To address the Committee's recommendation, NASA's ARMD is expanding sustainable aviation research to address climate change by developing and testing new green technologies for next-generation aircraft, new automation tools for greener airspace operations, and sustainable energy options for aircraft propulsion. The overarching strategy is to enable technology that generates significant advances in capabilities for the aviation industry. ARMD's approach is to conduct conceptual technology research at a low TRL (TRL 1-2), test and develop these concepts in a laboratory environment to a higher TRL (TRL 3-4), and further develop and demonstrate the technology in ground testing and flight test vehicles (TRL 5-6). For technologies that mature to TRL 6 or above, NASA intends to transfer knowledge to industry for future aircraft products. Further, SFNP activities at NASA are focused on multiple commercial transport vehicle technologies, including airframe configurations, manufacturing, airspace operations, sustainable aviation fuels, and propulsion and electrification. Figure 2 shows NASA's schedule to advance megawatt (MW) motors and inverters to meet the 2050 goals.[10]

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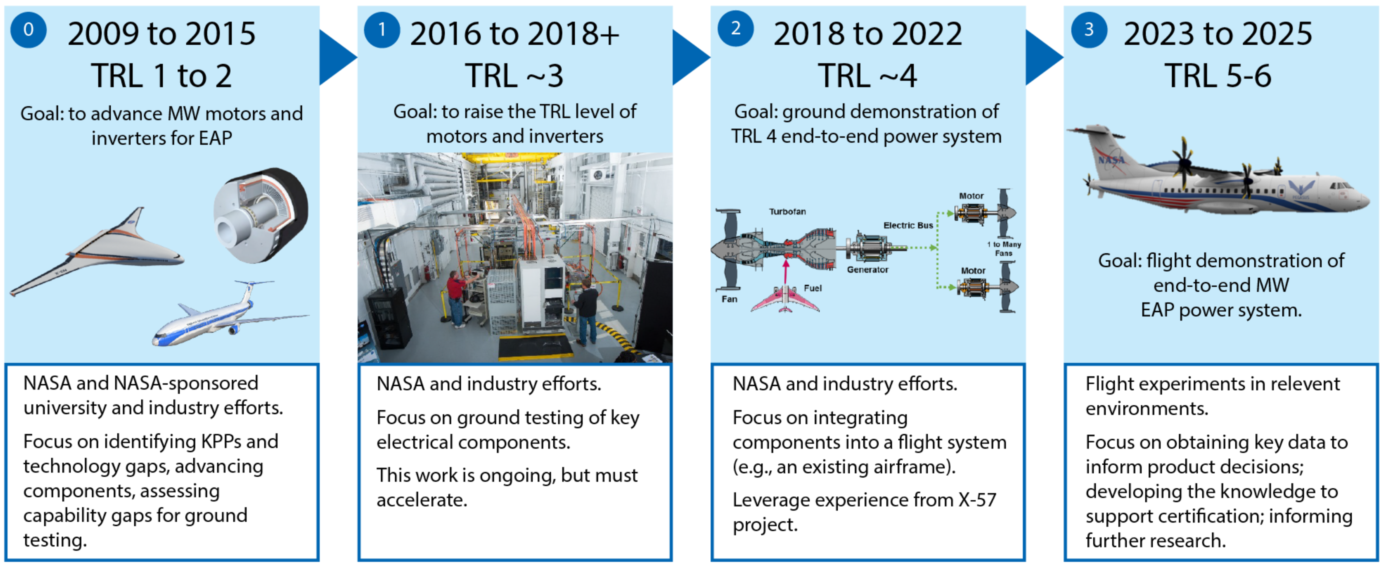
[8] An aircraft with a distributed propulsion system produces thrust from an array of propulsors (e.g., propellers) located across the vehicle to improve the system-level efficiency, capabilities, or performance (see X-57 Project). Boundary layer ingestion is a propulsion concept in which the slower air moving near the surface of a plane becomes part of the mix of air going into (ingested by) the propulsion system and reenergized and accelerated in an effort to reduce the drag on the vehicle.

[9] TRL is a widely used metric for measuring the readiness of new technologies or new applications of existing technologies to incorporate into a product. TRLs are measured on a scale from 1 to 9. Level 1 represents preliminary research of a basic concept, moving to laboratory demonstrations around level 4, and by level 9 the TRL represents proven technology programs in which the technology is integrated into a product and successfully operated in its intended environment.

[10] NASA is advancing this technology via the Electrified Powertrain Flight Demonstration (EPFD) Project, which is discussed later in this report. One MW is a unit of power equal to one million watts or 1,000 kilowatts, roughly enough electricity to power 750 homes. In most EAP aircraft concepts, power inverters are an essential component to convert electricity from direct to alternating current. To support the energy needs of single-aisle commercial passenger aircraft, the Committee recommended NASA address 1- to 5-MW systems, with an initial focus on 1-MW systems. For comparison, a Boeing 747, seating 400 to 600 passengers, needs an estimated 90 MW for takeoff, whereas most electric automobiles charging at home will draw about 7,200 watts—or about 0.0072 MW.

Figure 2: NASA's Electrified Powertrain Advancement through Flight Demonstration as of January 2023



Source: NASA.

Note: KPPs, or key performance parameters, are used by engineers concerned with the ultimate application of the technology and include information that enables assessment of the maturity of the technology throughout the development process.

EAP Management Structure

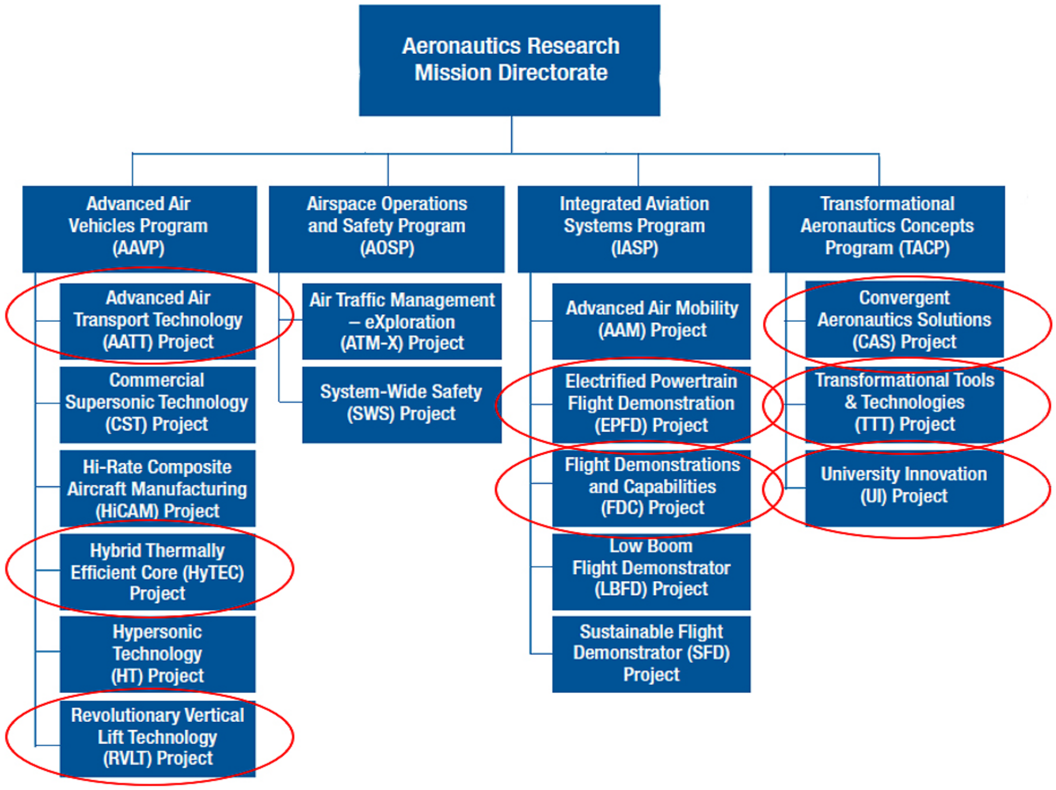
ARMD manages NASA's EAP efforts under a variety of programs each with their respective budgets. These EAP efforts are in support of developing Ultra-Efficient Subsonic Transports, with the goal of developing revolutionary improvements in economics and environmental performance for subsonic transport aircraft with opportunities to transition to alternative propulsion and energy.[11]

As shown in Figure 3, as of January 2023 three ARMD programs are managing eight projects (circled in red) that are performing EAP research and development activities in support of ARMD's Strategic Thrust 3. Most lower-TRL (TRL 6 and below) technology efforts (such as those in the Advanced Air Transport Technology or Transformational Tools and Technologies projects) are managed in accordance with NASA Procedural Requirements (NPR) 7120.8A, *NASA Research and Technology Program and Project Management Requirements.* These are managed differently than flight projects that demonstrate higher TRL technology efforts (such as the Electrified Powertrain Flight Demonstration Project), which are managed in accordance with NPR 7120.5E, *NASA Space Flight Program and Project Management Requirements*.[12]

[11] The *NASA Aeronautics Strategic Implementation Plan* (2019 Update) identifies six strategic thrusts, key elements of the research plan that guide how ARMD organizes its programs and projects. The six strategic thrusts include: 1) Safe, Efficient Growth in Global Operations; 2) Innovation in Commercial Supersonic Aircraft; 3) Ultra-Efficient Subsonic Transports; 4) Safe, Quiet, and Affordable Vertical Lift Air Vehicles; 5) In-Time System-Wide Safety Assurance; and 6) Assured Autonomy for Aviation Transformation.

[12] NPR 7120.8A, *NASA Research and Technology Program and Project Management Requirements (Updated w/Change 2)* (September 14, 2018). NPR 7120.5E *NASA Space Flight Program and Project Management Requirements* (August 14, 2012) was in effect when the project plan was signed. NPR 7120.5F, (August 3, 2021) is NASA's current version of this policy.

Figure 3: NASA's EAP-related Programs as of January 2023



Source: NASA

Collectively, ARMD's projects include research on new vehicle technologies and safe and efficient airspace operations that have the potential to significantly reduce aviation's impact on the environment. Each project has a Project Manager responsible for project execution who reports to their respective Program Director. EAP-related research and development budgets are managed by the individual project or subproject managers within the respective ARMD programs and projects, and coordination among EAP efforts remains an informal process at the working level (i.e., research branches at the Centers and researcher-to-researcher interactions). Table 1 depicts the budget for EAP-related efforts under ARMD programs and projects.

Table 1: FY 2022 NASA Project and EAP Activities Budget

Program	Project	Project Budget (in millions)	EAP Budget (in millions)
Advanced Air Vehicles	Advanced Air Transport Technology (AATT)	$86.7	$14.3
	Hybrid Thermally Efficient Core (HyTEC)	32.0	4.2
	Revolutionary Vertical Lift Technology (RVLT)	34.6	5.8
Transformational Aeronautics Concepts	Transformational Tools and Technologies (TTT)	61.9	6.0
	University Innovation (UI)	27.3	4.7
	Convergent Aeronautics Solutions (CAS)	36.9	6.9
Integrated Aviation Systems	Electrified Powertrain Flight Demonstration Project (EPFD)	70.0	70.0
	Flight Demonstration and Capabilities (FDC) Project X-57 Maxwell Project (X-57)	58.0	17.6
Total		$407.4	$129.5

Source: NASA Office of Inspector General (OIG) analysis of ARMD information.

Note: The EPFD Project was budgeted at $86.2 million in FY 2022, but ARMD held back $16.2 million.

Annual Project Review Process

EAP-related efforts are subject to both program and project level reviews. ARMD conducts an annual review of each program with results leading to adjustments of the project portfolio. Similarly, each program has an annual review of its projects. For instance, the key review for the AATT Project is the Advanced Air Vehicles Program Annual Program Review, which is convened by the respective Program Director. The primary purpose of this review is to provide an assessment of the portfolio for relevance, technical quality, and performance. Additional purposes of this annual review are to:

- review and assess the project's portfolio investments and strategy;
- determine strengths and areas of improvement for the project; and
- identify additional opportunities for collaboration/cooperation with other government agencies.

The Agency uses findings from the annual project review in the annual Agency Planning, Programming, Budgeting, and Execution cycle to adjust the research portfolio. Any adjustments are captured in the annual project plans, which contain specific research activities and goals. The findings from the annual program and project reviews may also result in adjustments to the project's technical challenges.[13]

[13] The technical challenges are elements of research focused on enabling outcomes established in the ARMD Strategic Implementation Plan. The challenges are also major contributors towards achieving specific strategic thrust critical commitments.

NASA's EAP Research Over the Past Decade Positions It to Support New Climate Initiatives

We found that before the 2021 Aviation Climate Action Plan was developed, NASA engaged the National Academies to initiate a study on CO_2 reduction and has since furthered the National Academies' key recommendations pertaining to research and development of the electrification of aircraft propulsion. Efforts that began in 2009 and ongoing collaborations with academia, other federal agencies, and industry, as well as investments in test facilities and equipment, have furthered EAP research and development projects, better positioning the Agency to help achieve the Aviation Climate Action Plan's CO_2 reduction goals by 2050.

NASA-led Research

Over the past 14 years, NASA has funded research of low-TRL technology concepts and early-stage aeronautics innovations, improved turbine engine performance, and new concept vertical lift vehicles. NASA has also engaged in partnerships to research, develop, and demonstrate EAP technology applicable to different flight ranges and fostered academic development of EAP-related technologies. These efforts were undertaken in coordination with industry, academia, and other government agencies.

Basic Research

The Transformational Tools & Technologies (TTT) Project has a subproject focused on lower TRL concepts and investigations in EAP areas. The TTT subproject does not involve manufacturing and is mainly assigned to NASA researchers for the development of new ideas, tools, and proof of low-TRL concepts related to:

- developing and researching materials for cable insulation for use at higher altitudes;[14]
- tools for new aircraft designs and modeling hybrid-electric propulsion concepts; and
- battery pack architecture and integration into the aircraft.

The Convergent Aeronautics Solutions (CAS) Project performs rapid feasibility assessments of early-stage innovations, such as in battery and sensor technologies.[15] The Project focuses on merging traditional aeronautics disciplines with advancements driven by the non-aeronautics world to overcome

[14] Current high-voltage cable technology is not suitable for high altitude operations. EAP applications will require lightweight cables that can meet power and frequency requirements with sufficient insulation to prevent electrical failures.

[15] NASA will complete three CAS activities: Solid State Architecture Batteries for Enhanced Rechargeability and Safety (SABERS); Sensor-based Prognostics to Avoid Runaway Reactions and Catastrophic Ignition; and Scalable Traffic Management for Emergency Response Operations.

barriers and enable new capabilities in commercial aviation. The goal is to identify the most promising capabilities for continued development by other NASA programs or transfer to the aviation community. The Project includes research in the following areas:

- Solid State Architecture Batteries for Enhanced Rechargeability and Safety (SABERS) designs state-of-the-art batteries that meet the performance and safety requirements of electric aircraft.
- Sensor Based Prognostics to Avoid Runaway Reactions and Catastrophic Ignition targets early detection of failure conditions to avoid catastrophic battery fires and enhance reliability.
- High-Efficiency Electrified Aircraft Thermal Efficiency Research involves developing innovative power and thermal management systems to increase aircraft efficiency.
- Subsonic Single Aft Engine Electrofan is an advanced hybrid-electric concept aircraft designed to minimize environmental impacts and introduce innovative technologies for sustainable subsonic regional transport aircraft.

Advanced Technology Research

The Advanced Air Transport Technology (AATT) Project explores basic concepts and matures technologies for transport-class aircraft. Technologies include MW-class components such as electric machines, power converters, and fault management systems, as well as enabling materials and controls. The project also studies technologies that will be needed for twin-aisle, 300-passenger electrified planes and built the MW-scale NASA Electric Aircraft Testbed (NEAT) at Glenn Research Center's (Glenn) Neil A. Armstrong Test Facility to integrate and test full electrified powertrains in sea level and airplane altitude conditions. In addition, the Revolutionary Vertical Lift Tech (RVLT) Project works with partners in government, industry, and academia to develop critical technologies that revolutionize new air travel options, especially those associated with Advanced Air Mobility efforts, such as cargo-carrying aircraft and passenger air taxis. While the project has historically conducted research for traditional rotary wing vehicles, such as helicopters, RVLT is also focusing on electric technology propulsion for new concept vertical lift vehicles across a range of sizes and missions.

NASA's Next Generation Engine Development

The Hybrid Thermally Efficient Core (HyTEC) Project's research aims to accelerate development of the next generation of small-core turbofan engine technologies with improvements in efficiency, durability, performance, hybridization, and sustainability. These developments are intended to help bring an electrified propulsion single-aisle aircraft into service in the 2030s and enable technology for future hybrid-electric aircraft powertrains that will offer additional CO_2 reduction and electric power capability.

Flight Demonstration Projects with Industry Partners

NASA has devoted a significant portion of its EAP resources in partnership with the industry and by implementing a risk-based approach coupled with hybrid fixed-price contract awards. For instance, the X-57 contract, in partnership with small business, accounts for 30 percent of the Flight Demonstration and Capabilities (FDC) Project cost. Likewise, the GE and magniX hybrid fixed-price contract costs account for 58 percent of the Electrified Powertrain Flight Demonstration (EPFD) Project's costs.

X-57 Flight Demonstration Partnerships

The X-57 began as a research project in FY 2016 and is scheduled to make its first flight in 2023.[16] NASA acquired an Italian Tecnam P2006T twin-engine 4-seat aircraft and modified it with an electric propulsion system to augment its flight performance. Under the FDC Project, NASA and Empirical Systems Aerospace, Inc., a Small Business Innovation Research contractor, manage the X-57 as a partnership with the small business community to demonstrate the performance benefits achieved by integrating electric motors and battery systems into an existing aircraft to replace the standard fuel-powered engines.[17]

The X-57 was designed to use a new propulsion technology known as distributed electric propulsion (DEP) that could potentially be incorporated onto smaller aircraft in an air taxi or commuter role with a small number of passengers. Conceptually, DEP uses smaller electric motors across the wing's leading edge as a high lift device and larger motors mounted on each wing tip for cruise, coupled with a wing optimally designed for this electric motor configuration. The project initially intended to modify a test (X-) plane in four iterations to demonstrate performance benefits (see Figure 4). Mod I involved flight testing of a baseline aircraft. Mod II replaces the standard fuel-powered engines and integrates electric motors and battery systems into the baseline aircraft. Mod III would test an optimized aircraft configuration with engines at the wing tips and new longer and narrower wings. Mod IV would utilize DEP for high lift at the takeoff and landing flight phases. Mods III and IV would demonstrate the benefits of DEP, which could revolutionize electric aircraft architecture and performance, such as potentially achieving a 500-percent improvement in energy consumption at cruise, zero in-flight carbon emissions, and the opportunity for significant noise reduction—about 65 percent less than comparable aircraft powered by standard fuel engines.

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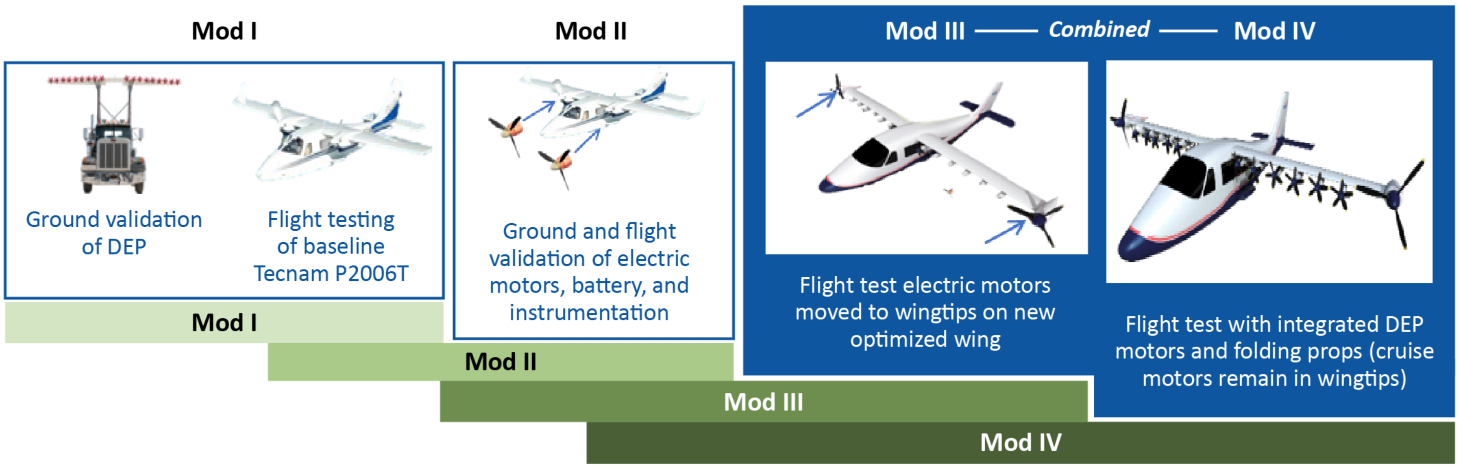
[16] ARMD initiated the X-57 in the CAS Project, which invests in seemingly improbable ideas that might lead to solutions to the problems that plague aviation and impact safety, environmental and community impact, and the global growth in air traffic.

[17] A Small Business Innovation Research funding agreement is a contract between a federal agency and a small business for the purpose of experimental, developmental, or research work.

Figure 4: X-57 Maxwell Mod Layout



Source: NASA OIG presentation of Agency information.

EPFD Project

With a budget of $445.6 million for FYs 2020 to 2027, the EPFD Project plans to accelerate U.S. industry readiness and transition to commercial EAP aircraft products and systems. The purpose of the EPFD Project is to reduce the risk of commercial application associated with EAP powertrains and components.

We found that NASA implemented a reasonable contracting mechanism by using a risk-based approach to target its research and development efforts. Between June 2019 and December 2020, NASA awarded 6 contracts to identify industry capabilities, research risks, and develop 12 steps that would lead to a demonstrator and an additional 5 risk reduction contracts to develop or provide an updated analysis of alternatives for EAP-based transport aircraft. These 11 contracts helped NASA develop a new EPFD project that could lead to rapidly maturing EAP technologies for introduction into the U.S. fleet no later than 2035.

EPFD Project

NASA illustration of an advanced subsonic aircraft with an EAP system

Source: NASA

Through this process, NASA engaged with a broad pool of companies (including Rolls Royce North America, Ampaire, Wright Electric, and GE Aviation) who showed interest and provided visions for their vehicles, identified the industry's challenges, and prioritized these challenges. Based on information obtained through risk reduction contracts, NASA identified technology development barriers and the need to buy down risks, identified and defined what was credible and achievable, and formulated studies to provide the EPFD Project with objectives and performance goals, such as:

- The largest market opportunities for MW-Class EAP.

- A vision vehicle (potential product) for that market.
- Barrier technical risks that needed to be overcome for the vision vehicle.
- Technology maturation needed for the vision vehicle.
- A proposed flight demonstration to reduce the barrier technical risks and increase the TRL for integrated MW-class powertrain systems.
- Probabilistic assessments of costs and schedules for the proposed flight demonstration.

The EPFD Project drafted a set of technical measures of effectiveness and key performance parameters for the conceptual aircraft and established technical performance parameters for the flight demonstration. The Project also identified six barrier technical risks and intended to reduce these risks through the execution of two or more U.S. industry flight demonstrations of integrated MW-class powertrains.[18]

In May 2020, NASA issued a request for information asking industry partners for potential requirements for the "Flight Demonstration of Electrified Aircraft Propulsion Concepts for Subsonic Transports," which provided information for a subsequent request for proposal, resulting in two contracts targeting two sectors of the market:

- A MW-class hybrid powertrain including relevant components and integration of a legacy propulsion system that will potentially lead to a single-aisle plane development.
- A practical vehicle-level integration of MW-class EAP systems to identify and address certification gaps through ground and flight test, leveraging advanced airframe systems to reinvigorate the regional and emerging smaller aircraft markets.

In September 2021, NASA issued two contracts totaling $253.4 million: a $179 million contract to GE Aviation (GE) and a $74.3 million contract to magniX USA Inc (magniX).[19] The contracts are hybrid firm-fixed-price and cost-share contracts, and the work will be conducted through 2026. Specifically, from contract award through Critical Design Review (CDR) the contracts will be firm-fixed price; then from CDR through close-out, the contract costs will be shared 50-50 between government and industry.[20] According to the NASA EPFD Project Manager, the mix of firm-fixed-price and cost sharing is an innovative way of managing risk associated with EPFD, recognizing that the industry partners have a stake in the success of the EAP technologies research. The contract awarded to GE will potentially lead to a single-aisle commercial aircraft that can carry 100 to 200 passengers incorporating EAP. The contractor will conduct ground and first flight tests using an integrated MW-class powertrain on a 34-passenger Turboprop SAAB 340B Test Aircraft. magniX intends to fly a regional commuter, a hybrid turboprop aircraft for 45 passengers with two fully electric 650-kilowatt engines and two turboprop engines, in an effort to reinvigorate the regional aircraft market. These projects are planned for flight demonstrations between 2025 and 2026.

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[18] The six barriers are: 1) high voltage operation at altitude, 2) thermal management, 3) propulsion system integration, 4) powertrain system integration, 5) aircraft system integration, and 6) battery performance and airworthiness. These risks are applicable to future commercial transport applications by U.S. industry.

[19] GE Aviation, a subsidiary of General Electric Company, has since changed its name to GE Aerospace.

[20] The CDR demonstrates that the maturity of the design is appropriate to support proceeding with full-scale fabrication, assembly, integration, and test. The CDR determines that the technical effort is on track to complete the system development, meeting functional and performance requirements within the identified cost and schedule constraints at an acceptable risk. See Appendix B for a complete description of NASA's project life cycle.

Recently, the contractors achieved several key milestones and accomplishments. In July 2022, GE completed testing of a high-power, high-voltage hybrid electric integrated system operating at altitude conditions in the NEAT facility. This successful test positioned NASA and GE for continued development of a MW-class hybrid-electric propulsion system. With ground testing complete, NASA and GE will now transition to flight testing under the EPFD Project. In September 2022, magniX successfully powered the first flight of a zero-emission technical demonstrator aircraft.[21] This demonstrated a new generation of aircraft: an all-electric small passenger plane built from the ground up around an electric propulsion system. While these magniX achievements are outside the EPFD Project, they are significant risk mitigation steps on the path to planned EPFD flight testing. magniX is also on the path to FAA Part 33 certification and was granted the first and—as of January 2023—only set of special conditions for establishing full certification of EAP. [22]

Research Projects through Academic Collaborations

Collaborations with academia are also a key part of NASA's EAP efforts. The University Innovation (UI) Project funds university-led innovation to address system-level challenges in ARMD's strategic thrust outcomes via independent multi-disciplinary awards. One of the UI portfolio elements—the University Leadership Initiative—provides the opportunity for university teams to exercise technical and organizational leadership in proposing unique technical challenges, defining interdisciplinary solutions, establishing peer review mechanisms, and applying innovative team strategies to strengthen their research impact. NASA awarded four cooperative agreements to universities for development of EAP related technologies, including:

- Pennsylvania State University, for working to identify the optimal design of small engine cores that could be used in future single-aisle, medium- and short-haul aircraft that use hybrid-electric propulsion.
- The University of Illinois, for developing hydrogen technologies, superconducting motors, fuel cells and hydrogen cylinders, and other technologies needed to get the aircraft flying.
- Florida State University, for researching integrated zero-emission aviation using a robust hybrid architecture.
- The Ohio State University, for leading the development of EAP technologies for a one-MW-scale aircraft, along with three other university teams:
    - The University of Wisconsin is developing a one-MW design and building a one-MW motor and electronics bar.
    - The Ohio State University is designing the electronics.
    - The University of Maryland and North Carolina A&T State University are developing the thermal management systems.

According to NASA, besides the technical products the UI Project is also benefiting the next-generation workforce with 3- to 5-year programs that provide advanced learning opportunities for the students. These programs increase the participant diversity for aeronautics research by involving historically black

[21] magniX powered the first flight of Eviation Aircraft's zero-emission Alice technical demonstrator aircraft.

[22] Title 14, Part 33, Airworthiness Standards: Aircraft Engines, prescribes airworthiness standards for the issue of type certificates and changes to those certificates, for aircraft engines. FAA 86 FR 53508, Special Conditions: magniX USA, Inc., magni350 and magni650 Model Engines; Electric Engine Airworthiness Standards.

colleges and universities and other minority-serving institutions, as well as connecting students to the industry through an external peer review process.

NASA Partnerships with Federal Agencies

NASA has also engaged with other federal agencies, including FAA and the Department of Energy (DOE), in partnerships that benefit EAP activities. NASA's partnerships with these agencies range from written agreements to informal cooperation.

FAA was the official lead in the Aviation Climate Action Plan while NASA assisted in its development. In working to create the Plan, NASA and the FAA agreed on specific roles and operational and technical initiatives:

- NASA will develop a service-oriented architecture for the future National Aviation System to deliver digitally auto-negotiated operational improvements for the entire gate-to-gate flight path with consideration of pre- and post-flight events. In addition, technologies will be developed for identification of the optimum high-altitude trajectory for reduced climate impacts accounting for contrail formation.
- FAA will evaluate enhancements in technology that can support reduced separation between aircraft and improved accommodation of altitude, speed, and route-change requests, thereby providing safety and efficiency benefits in oceanic flight information regions.
- NASA and FAA will work with the industry to accelerate the maturation of aircraft and engine technologies, enabling a step-change reduction in fuel burn and CO_2 emissions beyond what industry could do alone.

Through a Memorandum of Understanding, NASA is coordinating with DOE on battery technology in support of the broader NASA mission, such as space exploration and scientific discovery, including EAP.[23] In addition, personnel at Glenn and the DOE Joint Center for Energy Storage Research (JCESR) are collaborating to develop next-generation batteries that can be used in future space missions. The coordinated effort combines JCESR's expertise in the science of energy storage with Glenn's expertise in engineering battery technologies with aerospace applications. Glenn is focused on developing next-generation batteries with energy capacities beyond those of lithium-ion batteries to meet the aggressive goals of the space program.

In addition, NASA's SABERS project and NASA iTech researched battery performance to enhance EAP technology. SABERS has generated substantial interest from government, industry, and academia regarding development of a more resilient battery. The team's battery is of particular interest to the NASA Subsonic Single Aft Engine activity, which focuses on developing a hybrid-electric concept aircraft.

[23] The MOU with DOE was established to support NASA's efforts in applied energy and energy-related research and development; fundamental science; space and Earth science; and science, technology, engineering, and mathematics education.

Investment in Test Facilities

NASA's main EAP research and testing facility, the NEAT, was developed in the Hypersonic Tunnel Facility building in 2016 located at Glenn's Armstrong Test Facility in Sandusky, Ohio. The NEAT is a reconfigurable testbed that can accommodate power systems for large passenger airplanes. NEAT also includes a vacuum chamber that can simulate altitudes of up to 60,000 feet to test high-voltage electronics, electric motors, and controls. Its remote location on the Armstrong Test Facility is ideal for safely testing propulsion systems in extreme conditions. GE tested their EPFD powertrain at NEAT in 2022, and magniX plans to test their motor at simultated flight altitudes in 2023.

NEAT Facility

Source: NASA

In addition to NEAT, NASA has smaller scale test facilities located in Armstrong Flight Research Center (Armstrong) and Glenn. See Appendix C for descriptions of these test facilities.

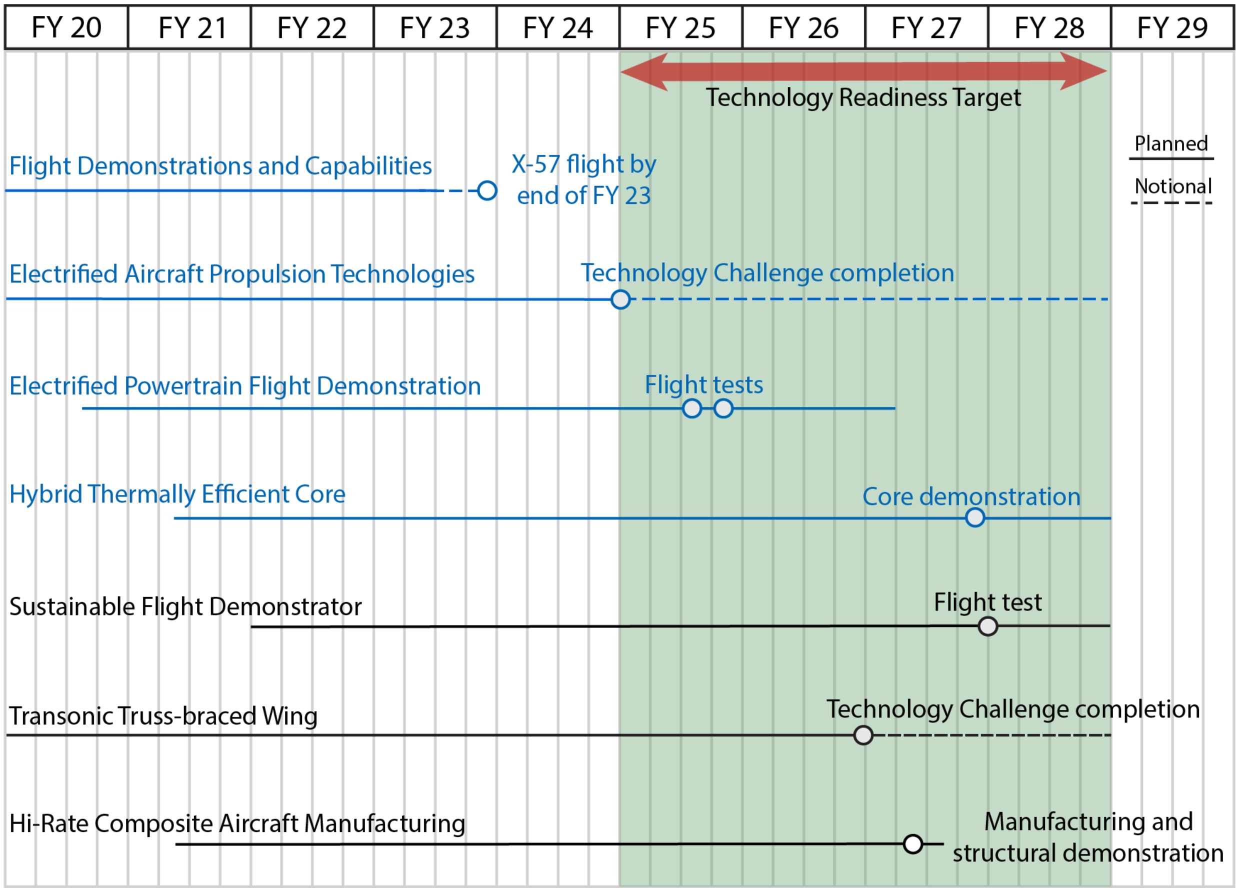
Implementation Timeline

While some of NASA's EAP-related projects and their associated subprojects (like those under CAS, TTT, and UI) focus on emerging concepts and technologies at TRL 1-2, for other efforts, NASA's integrated technology development timeline (see Figure 5) shows that the Agency is aiming to achieve TRL 6 in some of it most vital CO_2 emissions reduction projects between FYs 2025 and 2028 to enable the industry to make informed product decisions. The progress of EAP-related technologies being developed by AATT, HyTEC, and EPFD, as well as efforts not specifically associated with EAP, such as the Sustainable Flight Demonstrator and Transonic Truss Braced Wing development, and studies of Hi-Rate Composite Aircraft Manufacturing to increase the rate of composite aircraft manufacturing, reduce costs, and improve performance, are interrelated, and their success is vital to give the industry 7 years to put the new technologies in production by 2035.[24] NASA's overall subsonic transport development plan and related EAP are designed to ensure U.S. industry is the first to establish the new "S-curve" for the next 50 years of transports.[25]

[24] The U.S. Aviation Climate Action Plan's aircraft development scenario considers the introduction of new single-aisle aircraft in 2035 to replace the current generation.

[25] The S-curve is a commonly observed trajectory of growth for new innovations: slow at first, then rapidly rising, before flattening out again as it reaches market saturation. S-curves mean innovations can scale fast after reaching specific "tipping points," creating losses for slow movers and large opportunities for those who lead.

Figure 5: NASA Subsonic Transport, EAP-related Technology Development Plan as of January 2023



Source: NASA.

Note: In January 2023, NASA selected The Boeing Company to lead the development and flight testing of a full-scale demonstrator airplane as part of the Sustainable Flight Demonstrator Project to inform future designs that could lead to breakthrough aerodynamics and fuel efficiency gains.

EAP Efforts Face Challenges that Could Impact Project Cost and Schedule

Despite NASA's early start and promising strides in EAP-related research efforts, ongoing challenges may inhibit the Agency's ability to achieve its technology development goals in time to meet the U.S. Aviation Climate Action Plan's goals. Specifically, NASA's EAP-related flight demonstration projects have all either experienced or show indications of schedule delays and/or cost overrun due to technical, funding, and project management issues. Furthermore, EAP-related efforts are hampered by industry-wide challenges related to COVID-19, the supply chain, and workforce constraints. Lastly, NASA at times exhibits an overly optimistic culture when developing project plans and timelines, and EAP project planners may need to factor in these and other challenges to develop more realistic cost and schedule estimates.

X-57 Has Experienced Significant Cost Overruns and Schedule Delays

The initial estimated timeframe for X-57 Project development was FYs 2015 through 2018. As a result of unrealistic cost estimates and project management issues, the X-57 Project was transferred to the FDC Project in FY 2016 for further development and flight demonstration. The initial project cost established in 2016 was $40 million with an estimate of demonstrating all four mods by December 2020. However, as of August 2022 the Project incurred costs of $87 million (budgeted for a total of $99 million through FY 2023) and was working on completing Mod II, which was originally scheduled for a flight in May 2018 that will not occur until later in 2023. Consequently, NASA has decided to terminate the project after completion of Mod II without achieving a flight demonstration of DEP benefits planned under Mod IV, which significantly reduces the level of DEP knowledge transferred to the FAA, other standards committees, and industry.[26] Furthermore, given its termination, the Project will not attain its goal of demonstrating 500-percent energy efficiency at high-speed cruise.

According to NASA's management assessment, full electric flights will only benefit a small part of the commercial aviation market because of the short flight range provided by the current battery-powered technology. X-57 would require another $64 million to complete the Project by 2027, and NASA determined that the small percentage of the industry that would benefit did not justify the additional cost and delay. As such, we believe NASA's decision to close the program is reasonable in light of its assessment that the benefit of an all-electric aircraft would likely be confined to the regional, short to medium route aircraft. In addition, NASA is pursuing hybrid-electric design options for single-aisle aircraft after determining that all-electric systems are not a viable option for the larger commercial aviation market.

[26] The other standards committees include the American Society for Testing and Materials, a developer of international voluntary consensus standards, such as standard procedures governing environmental and engineering services; and SAE International, the world's leading authority in mobility standards development that help ensure the safety and reliability of all aspects of aviation from aircraft design and flight controls to aviation fuel and communications.

X-57 Management Challenges

According to NASA, the X-57 Project cost overrun and schedule delays were caused in large part by awarding a fixed-price contract to a contractor that had little experience or capability to complete the systems engineering processes needed to design multiple interconnected systems. This issue was exacerbated by insufficient NASA oversight, leading to an inadequate project design approach and technical challenges in battery and electric propulsion motor design and development, resulting in the X-57 Project undergoing project reviews and replans in 2018, 2019, 2021, and 2022.

Several unanticipated technical issues required NASA assistance:

- No commercial solutions existed for battery systems with sufficient energy and power to provide meaningful aircraft flight duration. As a result, the NASA project team had to redesign the battery, advance the battery system technology level, and develop the battery management software and control system.
- There were no design standards for the electric propulsion motor, which resulted in several design iterations and testing with the contractors.
- The cruise motor controller was at a low TRL 3 and needed further development. The controller was a key component for high-efficiency power conversion from the battery to the motor for aerospace application.

NASA also identified a series of project and contract management issues with the X-57 Project:

- NASA had insufficient staffing in key areas. As a result, Agency staff could only focus on major supplier hardware issues while other progress suffered. Some NASA reviews and approvals took longer than planned due to lack of staffing. Consequently, NASA had to increase staffing to speed up the project, assist with contractor tasks, and prevent overwork. NASA also added a lead engineer and an assistant project manager at Armstrong to help with contract and project management.
- NASA underestimated the complexity and difficulty of integrating a one-of-a-kind experimental subsystem in an aircraft. X-57 used subsystems developed by new industry companies, which encountered several design issues and integration challenges, thereby delaying the schedule and increasing costs beyond the baseline.
- The contract mechanism did not provide sufficient incentives for on-time delivery. NASA awarded Empirical Systems Aerospace, Inc., an indefinite-delivery, indefinite-quantity contract with capability for fixed-price task orders under the Small Business Innovation Research program.[27] This contract provided no fee incentive to complete the work on time.
- Both the contractors and subcontractors were small companies with limited experience in systems integration and did not budget adequate time and resources to extract subsystem and component requirements from vehicle- or system-level requirements provided by NASA. In addition, they did not have experience interpreting and tracking system-level requirements. Consequently, NASA had to provide training in development of documentation systems to ensure assembly and test artifacts were identified, completed, and collected.

[27] Indefinite-delivery, indefinite-quantity contracts provide for an indefinite quantity of supplies or services for a fixed time.

Between 2018 and 2021, NASA management worked on staffing resource issues, enhanced contractor oversight and support, and increased schedule awareness by monitoring key milestones and activities, tracking progress of long-duration tasks, and planning for schedule contingencies. Ultimately, NASA decided to modify the project goals and objectives to focus on certification and lessons learned versus achieving Mod IV and electrical efficiency improvement.

X-57 Positives and Lessons Learned

Despite significant setbacks and failure to achieve its initial goals and objectives, the X-57 Project produced other benefits as well as lessons learned, typical when developing new and experimental technologies. Specifically, the Project team:

- Published over 100 technical publications since project inception and a public-facing technical document website.
- Supported the development of standards to address certification of electric aircraft.
- Participated directly in the writing of EAP standards.
- Conducted multiple public outreach activities and participated in papers and panel discussions at the American Institute of Aeronautics and Astronautics' Aviation 2021 Forum.[28]
- Spurred NASA investments in a domestic motor design with fewer heritage technologies, a new controller, and passive thermal cooling that eventually produced:
    - An airworthy and air-cooled domestically built motor;
    - A redesigned controller nearly ready for acceptance evaluation and software development; and
    - Extensive thermal modeling and nacelle/duct redesign.

Many of these lessons were discussed during the Project's annual review processes and benefited development of the EPFD Project. For example, X-57 Project management did not conduct comprehensive subsystem development in the Formulation Phase, which increased the likelihood of not realizing risks until late in the project life cycle when hardware failures required more comprehensive rework to fix. Conversely, we found EPFD management invested heavily in risk reduction proposals before the Formulation Phase.

EPFD is Showing Early Indications of Schedule Delays and Cost Increases

Due to the scope and complexity of effort, ARMD manages the EPFD Project according to a tailored version of NPR 7120.5E, *NASA Space Flight Program and Project Management Requirements* (see Appendix B for descriptions of NASA's project life cycle).[29] For example, EPFD is performing Joint Confidence Level analysis and contractor earned value management reporting as required by NPR

[28] The American Institute of Aeronautics and Astronautics is a professional society for the field of aerospace engineering. The 2021 forum brought together experts to share ideas on aeroacoustics; applied aerodynamics; fluid dynamics; multidisciplinary design optimization; air traffic operations, management, and systems.

[29] Tailoring is the process used to adjust or seek relief from a prescribed requirement to meet the needs of a specific program or project.

7120.5E. However, according to 7120.5E, when projects are initiated they are either assigned directly to a Center by the Mission Directorate or are selected by the Agency through a competitive process such as an Announcement of Opportunity.[30] However, EPFD will not have a host Center but instead will be managed under a Systems Project Office, which ensures implementation of the EPFD Project in collaboration with the Centers where the EPFD Project work resides. This project management model aims to take advantage of established organizational structure and processes while allowing for cross-Center interaction at the Project, Program, and Mission Directorate levels.

In November 2020, the EPFD Project established a preliminary life-cycle cost estimate ranging from $311.8 million to $469.4 million and a first flight date range between December 2023 and August 2024. In September 2021, after updating flight test estimates to reflect approved budget allocations, the Project awarded two contracts totaling $253.4 million to GE and magniX and considered awarding additional contracts to industry partners if additional funding were available. As of February 2023, EPFD is working towards its Key Decision Point (KDP)-C, scheduled for the first quarter of 2024—where Project management will have to conduct a Joint Cost and Schedule Confidence Level (JCL) analysis to establish a baseline life-cycle cost and schedule estimate—predicated on both contractors passing their Preliminary Design Reviews (PDR).[31] However, both contractors are already showing signs of delays and higher costs.

While GE passed its PDR in September 2022, it postponed its next review—an Integrated Baseline Review—from September 2022 to the third quarter of 2023 due to COVID-impact delivery delays of specialty hardware needed for testing. The Review's supporting documents estimated a 247-day delay to GE's project completion with a $40-million cost overrun—$20 million of which NASA will share under the contractual agreement.[32] This data is an indication of potentially higher project costs and an estimated 1-year delay to achieve a test flight. In addition, although magniX's PDR is scheduled for early 2024, the estimated date range for the first magniX flight was delayed about a year from August 2024 to the third quarter of 2025. However, this delay would still meet the timeline NASA designed to demonstrate TRL 6 between FYs 2025 and 2028 and enable industry to make informed product decisions.

NASA and Industry-wide Challenges

COVID Impact to Supply Chain

Our review of FY 2022 annual presentations for all eight EAP-related projects showed that five listed supply chain issues due to COVID-19 as a top risk, including EPFD and its two major contractors. Projects

[30] NASA uses Announcements of Opportunity to solicit proposals from the broader community that are reviewed by peer scientists or other appropriate technical experts.

[31] NPR 7120.5E requires, for projects costing $250 million or more, that project managers document the Agency's life-cycle cost estimate and other parameters in the Decision Memorandum for Implementation during KDP-C, and this cost estimate becomes the Agency's baseline commitment. A JCL analysis is required as part of that activity and provides the probability that cost will be equal to or less than the targeted cost and the actual schedule will be equal to or less than the targeted schedule date. The JCL calculation includes consideration of the risks associated with all developmental and operational elements to completion of the project. Among other objectives, the PDR analyzes whether the project is sufficiently mature to begin final design and fabrication. See Appendix B for a descriptions of NASA's project life cycle.

[32] The Integrated Baseline Review ensures NASA and the supplier understand the risks and have realistic expectations for accomplishing all the authorized work within the authorized schedule and budget.

identified supply chain issues that included critical component delivery delays due to COVID-19 impacts, raw material shortages at the supplier level, and unavailability of components. These supply chain issues would be exacerbated when the components' required technical complexity exceeded the capabilities of commercial parts. As a result, NASA would require component redesign at the supplier level that would cause further delays to the project, while the additional design processes would further delay component deliveries.

In another example, the HyTEC Project reported that prices of raw materials had fluctuated during the COVID-19 pandemic, and bottlenecks in global and national shipping during the summer and fall of 2021 caused shortages across many industries. Consequently, procurement of long-lead items became untimely and cost prohibitive. Other project teams, such as RVLT Project, also expressed concerns that the electronic supply chain issue may impact their ability to complete the electric propulsion technology challenge.[33]

Since these supply chain issues are industry wide, acquiring the parts and components becomes more challenging for NASA projects to ensure timely delivery of critical components. For some projects, like EPFD, these delays can have detrimental effects to the project's ability to meet cost and schedule goals. For example, GE and magniX are experiencing lead times of up to 10 months for key components such as electrical current sensors, voltage sensors, control card assembly integrated circuits, high-voltage direct-current link capacitors, and connectors.

Workforce Challenges

We found six of the eight EAP projects listed workforce issues as one of their top concerns. Specifically, the EPFD Project reported concerns about its major contractors and stated that, given the current labor market challenges prompted by COVID-19, there is a possibility that personnel shortages will affect the Project's cost, schedule, and technical capabilities. Labor market challenges included not only those attributed to COVID-19 infections, but also technical workforce shortages and wage pressure.

As COVID-19 variants continued to spread nationwide, industry partners and subcontractors were subject to decreased labor availability or facility shutdowns that limited in-person tasks such as testing, manufacturing, and assembly. GE's labor union contract will expire in mid-2023 when the Project's hardware and system assembly phases are scheduled. Increased hiring demands and competition for required skillsets may affect magniX's ability to meet its hiring goals to support the Project. Though magniX was able to hire half the staff needed in FY 2022 and to bring a flight testing and certification subcontractor on board, hiring the remaining staff may prove challenging. In addition, companies are facing wage pressure due to rising costs and a competitive labor market.

Since November 2019, NASA's Office of Inspector General (OIG) has listed workforce as a major Agency challenge.[34] Our prior work shows that NASA is facing interrelated workforce challenges such as not having enough employees with the right skills in technical areas; implementation shortfalls; an aging workforce; and Science, Technology, Engineering, and Mathematics pipeline risks. NASA's engineering technical disciplines faced significant risks to their specialized workforces, in particular the loss of unique

[33] The electric propulsion technology challenge is one of the technical challenges established and tracked in RVLT that NASA will develop design and test guidelines, acquire data, and explore new concepts that improve propulsion system component reliability, culminating in a demonstration of two to four orders of magnitude in improvement in 100-kilowatt-class electric motor reliability.

[34] NASA OIG, *2021 Report on NASA's Top Management and Performance Challenges* (November 15, 2021).

skillsets from retiring employees before their knowledge could be passed on to others within the Agency. RLVT and FDC projects listed an inability to maintain system expertise and the impact of workforce losses on electric propulsion as their top risks.

Likewise, a Government Accountability Office (GAO) report stated that the Advanced Air Mobility industry could face workforce issues similar to those faced by the broader aerospace industry, which struggled in recent years to recruit and retain workers.[35] Factors affecting workforce availability included high educational costs, a lack of workplace diversity, inadequate awareness of opportunities, and limited training capacity. NASA is also expending efforts in Advanced Air Mobility in its RVLT Project and will face similar issues.

Other Factors Affecting NASA's EAP Efforts

History of Unrealistic Cost and Schedule Estimates

The OIG has consistently reported on NASA's challenge in meeting cost and schedule commitments in its space flight projects and, in 2012, attributed these challenges in part to the Agency's penchant towards over-optimism.[36] We found the same sense of optimism and its resulting negative effects on cost and schedule estimates in NASA's aircraft research and development efforts.

As previously discussed, X-57's cost and schedule estimates turned out to be grossly underestimated. As of October 2022, 2 years after the expected completion date, the Project was working on completing Mod II of the four planned, will cost about 150 percent more than originally estimated, and will be terminated soon after the Mod II flight planned for FY 2023. Likewise, EPFD is showing early signs of cost and schedule issues, most of which are out of NASA's control but nonetheless should be accounted for in future estimates.

We believe that these overly optimistic cost and schedule estimates can be attributed, in part, to a lack of cost and schedule data from past experimental aviation projects. For example, in May 2020 we reported that the Low-Boom Flight Demonstrator (LBFD) Project team did not have cost growth data for flight demonstrator programs when preparing its JCL, because LBFD was the first ARMD project to use such analysis for its cost and schedule estimate.[37] Instead, the team had to use Air Force and private sector data to support their JCL. However, these approaches did not yield a realistic cost and schedule estimate for that $582 million Project, which has experienced about a 26-percent increase in costs and about a 2-year delay to its first flight.

In light of ARMD's prior experience of X-plane cost overruns and schedule delays and lack of sufficient historical data, we are concerned whether the research and development project approach can yield a credible JCL analysis without a comprehensive analysis of the additional risks being taken into consideration when establishing project cost and schedule baselines.

[35] GAO, *Transforming Aviation: Stakeholders Identified Issues to Address for 'Advanced Air Mobility'* (GAO-22-105020, May 9, 2022).

[36] NASA OIG, *NASA's Challenges to Meeting Cost, Schedule, and Performance Goals* (IG-12-021, September 27, 2012).

[37] NASA OIG, *Management of the Low-Boom Flight Demonstrator Project* (IG-20-015, May 6, 2020).

Unstable Funding

Funding instabilities have impacted schedules for four out of eight EAP related projects. For example, in FY 2022, the LBFD Project overran its budget and was behind schedule; this meant additional funding was required to complete that Project. To cover LBFD funding shortfalls, AMRD shifted funding among projects, which resulted in EPFD receiving $16 million less than planned requirements. The HyTEC Project also listed funding issues as its top risk and indicated that insufficient funding could result in HyTEC not meeting all of its key performance parameters or affect its ability to award two core demonstrations with two companies. HyTEC budgeted $33.7 million and $35.9 million for FY 2022 and FY 2023, respectively; instead, it received $27 million for FY 2022, about $6.7 million less than planned. At the beginning of FY 2023, the Project was operating based on Continuing Resolution funding; the result was $8.9 million less than planned to start their FY 2023 efforts. This meant the Project was about 25 percent behind its spending plan when it started FY 2023 and had about 9 months remaining in the FY to try to catch up to receive full funding covering both years. These fluctuations further stressed both the Project's and the contractors' ability to manage already demanding workforce requirements.

Facility Availability

NASA will need to relocate its NEAT test facility that was constructed within the Hypersonic Tunnel Facility building because the Department of Defense (DOD) has an urgent need for additional testing capacity associated with the development of hypersonic vehicles. Per a July 2022 interagency agreement, DOD will pay NASA to move the NEAT facility to another location. NASA selected the Cryogenic Components Laboratory Control Building—also located at the Armstrong Test Facility—and the Agency will relocate or reconstruct the NEAT, without upgrades, into the new building. DOD will provide the total estimated cost, $29 million, for relocating the facility. The NEAT relocation is planned to be completed 25 months after receiving DOD funds. As of December 2022, NASA planned to start the relocation in late March 2025 and complete the setup by the end of October 2025, resulting in an estimated 6-month gap in the facility's ability to support testing, which could affect at least one future magniX test requirement.

CONCLUSION

Since the publication of the 2021 U.S. Aviation Climate Action Plan, NASA has made progress in addressing the Plan's goals and objectives. As early as 2009, NASA started leading in-house and NASA-sponsored university and industry efforts to advance electric motors and inverters for EAP. However, despite having a head start, there are indications that NASA is facing some setbacks and challenges in meeting cost and schedule goals in its larger EAP development efforts, such as the X-57 and EPFD. These setbacks were largely due to overly optimistic schedules regarding X-57 technology development and both projects' funding instability—internally and externally derived. The situation has been further exacerbated by aerospace workforce and facility availability, COVID-19 shutdowns, and related supply chain issues. Collectively, these challenges may affect progress toward the larger effort to meet Climate Plan goals. Lastly, the setbacks and challenges may lead to a further delay in progress and thus will hinder NASA's ability to stimulate and further research and development of EAP technologies, which may further erode the U.S. lead in the aeronautic science and aviation market.

While efforts underway show promise, the ability to meet the FYs 2025 to 2028 timeframe is largely contingent upon the projects' ability to establish realistic cost and schedules estimates and ARMD committing funding and physical resources to support those estimates. We also recognize the challenges in establishing estimates for lower TRL technologies, such as those associated with X-57 development, without reliable history and unknown risks, in addition to relying on estimates from contractors who may have minimal experience in probabilistic cost and schedule estimations.

RECOMMENDATIONS, MANAGEMENT'S RESPONSE, AND OUR EVALUATION

To increase transparency, accountability, and oversight of NASA's implementation of EAP efforts, we recommended the Associate Administrator for ARMD require that the EPFD Project Manager:

1. Coordinate with Agency JCL experts in addressing estimation challenges relative to X-plane development and lower TRL efforts and adjust risk analyses accordingly to derive higher probability/confidence cost and schedule estimates.

In addition, we recommended the Associate Administrator for ARMD:

2. Re-evaluate ARMD's planning and support of the U.S. 2021 Aviation Climate Action Plan priorities and commit project resources and funding accordingly to minimize funding instabilities for these efforts.

We provided a draft of this report to NASA management who concurred with our recommendations and described planned actions to address them. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions.

Management's comments are reproduced in Appendix D. Technical comments provided by management and revisions to address them have been incorporated as appropriate.

Major contributors to this report include Ray Tolomeo, Science and Aeronautics Research Audits Director; Stephen Siu, Assistant Director; Anh Doan; Jiang Yun Lu; Frank Martin; and Courtney Daniels.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 2023581543 or laurence.b.hawkins@nasa.gov.

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Paul K. Martin
Inspector General

APPENDIX A: SCOPE AND METHODOLOGY

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

The objective of this audit was to evaluate NASA's management of its EAP research and development efforts. Specifically, we assessed NASA progress towards developing and testing new technologies and sustainable energy options for aircraft propulsion. In addition, we examined whether ARMD met its established goals and priorities. We also reviewed internal controls as they relate to the overall objective. The audit was primarily conducted at NASA Headquarters, Armstrong Flight Research Center, and Glenn Research Center.

To assess NASA's progress, we interviewed officials from NASA Advanced Air Vehicles, Integrated Aviation Systems, and Transformational Aeronautics Concepts programs, as well project managers on a variety of EAP-related projects and contracting officers. We obtained and reviewed applicable documents related to eight EAP projects, such as project plans, 2021 and 2022 annual review reports, and current project status reports. We also reviewed NASA contracts and partnership agreements, visited the NEAT test facility at Glenn, and interviewed the officials in charge.

Finally, we reviewed federal and NASA criteria, policies, and procedures and supporting documentation; prior audit reports; external reviews; and other documents related to EAP. We also reviewed newly enacted public law related to the reduction of greenhouse gas emissions from new aircraft and demonstration of new technologies related to regional and single-aisle aircrafts. The documents we reviewed included, but were not limited to, the following:

- United States Aviation Climate Action Plan (2021)
- NASA Authorization Act of 2022, Pub. L. No. 117-167 (2022)
- National Academies of Sciences, Engineering, and Medicine 2016. Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. Washington, DC: The National Academies Press. https://doi.org/10.17226/23490.
- NASA Strategic Plan (2022)
- NASA Aeronautics Strategic Implementation Plan (2019)
- NPR 7120.5F, NASA Space Flight Program and Project Management Requirements (August 3, 2021)
- NPR 7120.8A, NASA Research and Technology Program and Project Management Requirements (Updated w/Change 2) (September 14, 2018)
- NPR 7900.3D, Aircraft Operations Management (May 01, 2017)
- NPR 8600.1, NASA Capability Portfolio Management Requirements (April 22, 2019)
- NPR 9090.1B, Partnership Agreements-Financial Requirements and Administration (March 04, 2020)

Assessment of Data Reliability

In this audit, computer-generated data was not significant to the audit finding. We used public domain information to validate contract related data presented to the public and found no discrepancies. Any reference to contract information were referred to the contract as source document as opposed to the electronic data generated. No electronic data was used for analysis purposes.

Review of Internal Controls

We assessed internal controls and compliance with laws and regulations necessary to satisfy the audit's objectives. While we may conclude that the internal controls were adequate, our review was limited to these internal control components and underlying principles, and it may not have disclosed all internal control deficiencies that may have existed at the time of this audit.

Prior Coverage

During the last 5 years, the NASA Office of Inspector General (OIG) and the Government Accountability Office (GAO) have issued five reports of significant relevance to the subject of this report. Unrestricted reports can be accessed at https://oig.nasa.gov/audits/auditReports.html and https://www.gao.gov, respectively.

NASA Office of Inspector General

2021 Report on NASA's Top Management and Performance Challenges (November 15, 2021)

Management of the Low-Boom Flight Demonstrator Project (IG-20-015, May 06, 2020)

Government Accountability Office

NASA: Assessments of Major Projects (GAO-22-105212, June 23, 2022)

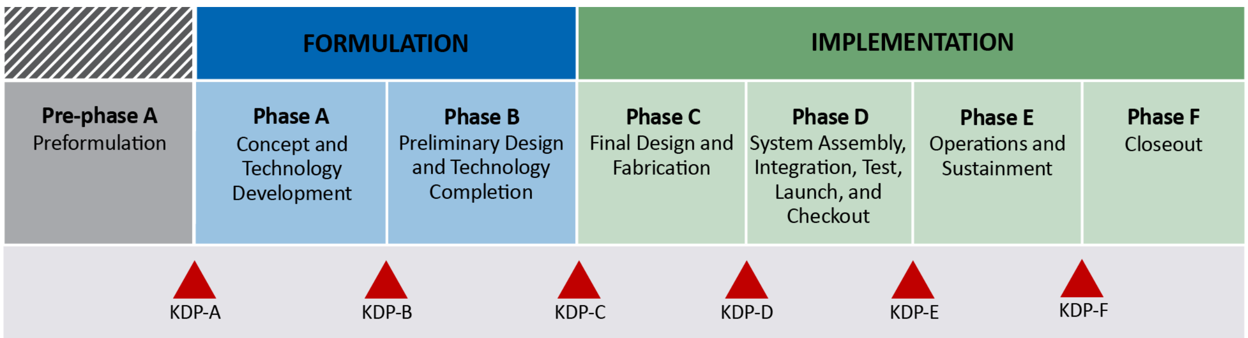
Transforming Aviation: Stakeholders Identified Issues to Address for 'Advanced Air Mobility' (GAO-22-105020, May 9, 2022)

Federal Contracting: Implementation of Changes to Cost or Pricing Data Requirements (GAO-22-105307, April 14, 2022)

APPENDIX B: PROJECT LIFE-CYCLE COST, SCHEDULE, AND STATUS

NASA divides the life cycle of its flight projects into Phases A through F (see Figure 6). This structure allows managers to assess the progress of their projects at Key Decision Points (KDP) throughout the process, or points in time when the Decision Authority (approving official) decides on the readiness of the project to progress to the next life-cycle phase.

Figure 6: Project Life Cycle



Source: NPR 7120.5F.

During Phases A and B (Formulation), projects develop and define requirements, cost and schedule projections, acquisition strategy, project design, and complete development of mission-critical technology. Towards the end of Phase B, project personnel conduct a Preliminary Design Review (PDR) and present results to an independent Standing Review Board that (1) evaluates the completeness and consistency of the planning, technical, cost, and schedule baselines; (2) assesses compliance of the preliminary design with applicable requirements; and (3) determines if the project is sufficiently mature to begin Phase C (final design and fabrication).

To receive management approval to proceed to Phase C (the start of Implementation), a NASA project must pass through KDP-C, which includes a final assessment of the preliminary design and a determination that the project is sufficiently mature. As part of the KDP-C review process, cost and schedule baselines are established against which the project is measured. To establish these baselines, NASA policy requires that projects with an estimated life-cycle cost greater than $250 million develop a resource-loaded schedule and perform a risk-informed probabilistic analysis that produces a JCL.[38] This analysis measures the likelihood a project will complete all remaining work at or below the budgeted levels and on or before the planned completion of Phase D (all activities prior to the start of operations).

The Standing Review Board performs an independent assessment of a project's JCL analysis with the results of that review presented to the relevant Decision Authority, who makes the final budget and

[38] A resource-loaded schedule is the process of recording resource requirements—time and cost—for a scheduled task or group of tasks.

schedule determination to establish the Management Agreement and Agency Baseline Commitment.[39] Once approval is received to move from KDP-C to the next phase, the project prepares its final design, fabricates test units that resemble the actual hardware, and tests those components during the first half of Phase C. A second design review, known as the Critical Design Review (CDR), occurs later in Phase C. The purpose of the CDR is to demonstrate the design is sufficiently mature to proceed to Phase D, which entails full-scale fabrication, assembly, integration, and testing, and that the technical effort is on track to meet performance requirements within identified cost and schedule constraints. Phase E consists of operations and sustainment, while Phase F is project closeout.

[39] The Management Agreement is between the Agency and project manager and provides the parameters and authorities over which the project manager is accountable. The Agency Baseline Commitment contains the cost and schedule parameters NASA submits to Congress and the Office of Management and Budget.

Appendix C: NASA's Smaller Scale EAP Test Facilities

Airvolt Test Stand at Armstrong

Source: NASA.

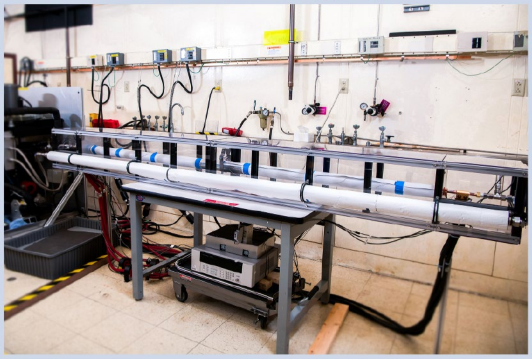
Airvolt is a modular electric propulsion test stand designed to lead to a better understanding of an electric propulsion system from its electrical, aerodynamics, and structural perspectives. Steps toward that understanding are being implemented at the Armstrong Flight Research Center in California. Airvolt is designed and implemented to accommodate small systems on the order of 100-kilowatt motors and propeller diameters up to 6 feet (1.8 m). Its data acquisition systems monitor thrust and torque; currents and voltages between power sources, inverters, and motors; and vibrations, temperatures, and acoustic levels of the system.

The Hybrid Propulsion Emulation Rig facility at Glenn is a new capability for hardware-in-the-loop testing of EAP concepts. The facility provides for rapid testing of EAP concepts that span all of the major ARMD programs, with planned testing that supports the Hytec, X-57, and TTT projects.

Hybrid Propulsion Electromagnetic Rig

Source: NASA

Advanced Cable Technology Rig



Source: NASA

The Advanced Cable Technology Rig at Glenn is designed to test the thermal performance of cables for electrified aircraft systems. Data collected by the Rig will help inform future standards and close the technology gaps for commercial aircraft electrification.

The Advanced Reconfigurable Electrified Aircraft Lab is a testbed at Glenn supporting the RVLT project. The Lab is a 200-kilowatt, 700-volt testbed that utilizes direct current and motor emulators that can be adjusted to represent different configurations. Reconfigurability allows RVLT researchers to investigate different electrified powertrain architectures, including both single-string and multi-string arrangements.

Advanced Reconfigurable Electrified Aircraft Lab

Source: NASA

Scaled Power Electrified Drivetrain

Source: NASA

Also located at Glenn, the Scaled Power Electrified Drivetrain is a low-power, direct current, single-string testbed that uses a dynamometer as a load and can support power levels up to 9 kilowatts. This facility helps familiarize NASA engineers with electrified aircraft-related powertrains and is used to verify operations and characterize motor and inverter components before integration into the Advanced Reconfigurable Electrified Aircraft Lab.

APPENDIX D: MANAGEMENT'S COMMENTS

National Aeronautics and Space Administration

Mary W. Jackson NASA Headquarters
Washington, DC 20546-0001

Reply to Attn of: Aeronautics Research Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator Aeronautics Research Mission Directorate

SUBJECT: Agency Response to OIG Draft Report, "NASA's Electrified Aircraft Propulsion Research and Development Efforts (A-22-10-00-SARD)

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Electrified Aircraft Propulsion Research and Development Efforts (A-22-10-00-SARD), dated April 13, 2023.

In the draft report, the OIG "found that over the years, NASA has funded research of conceptual technology and early-stage aeronautics innovations, improved turbine engine performance, and new concept vertical lift vehicles." The OIG determined that despite its promising strides in electrified aircraft propulsion (EAP)-related research, NASA faces challenges that could impact project costs and schedules. Specifically, all of NASA's EAP-related flight demonstration projects have either experienced or show indications of schedule delays and cost overruns. In the report, the OIG makes two recommendations to the Associate Administrator for the Aeronautics Research Mission Directorate (ARMD) intended to increase transparency, accountability, and oversight of NASA's implementation of EAP efforts.

Specifically, the OIG recommends the following:

Recommendation 1: Coordinate with Agency JCL experts in addressing estimation challenges relative to X-plane development and lower TRL efforts and adjust risk analyses accordingly to derive higher probability/confidence cost and schedule estimates.

Management's Response: NASA concurs. ARMD will undertake an action to identify lessons learned from ARMD Joint Confidence Level (JCL) activities with Agency experts and document those lessons learned within our program/project lessons learned registry. The results will be presented broadly to program/project leadership during the Mission Directorate Review.

Estimated Completion Date: December 29, 2023.

Recommendation 2: Re-evaluate ARMD's planning and support of the U.S. 2021 Aviation Climate Action Plan priorities and commit project resources and funding accordingly to minimize funding instabilities for these efforts.

Management's Response: NASA concurs. ARMD is committed to the tenets and priorities articulated in the U.S. 2021 Aviation Climate Action Plan (the Plan). ARMD is using the plan to provide guiding principles around investments supporting aviation sustainability including airframe, propulsion system, and operations-related technology research and development.

During Planning, Programming, Budgeting, and Execution 2025 budget planning cycle, ARMD will assess the complete portfolio of ARMD-sponsored activities that support the Plan priorities and evaluate the risk associated with those dedicated activities within the context of the suite of activities supporting ARMD critical commitments.

Budget submissions will reflect ARMD's best efforts within a resource-constrained environment to continue steady progress toward the priorities and ultimate goals associated with the Plan.

Estimated Completion Date: September 29, 2023.

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Natasha McNeill at (202) 358-2638.

Robert Pearce
Digitally signed by Robert Pearce
Date: 2023.05.15 10:38:33 -04'00'

Robert A. Pearce
Associate Administrator,
Aeronautics Research Mission Directorate

cc: Chief Financial Officer/Ms. Vo Schaus
Director, Armstrong Flight Research Center/Mr. Flick
Director, Glenn Research Center/Mr. Kenyon
Director, Langley Research Center/Mr. Turner

APPENDIX E: REPORT DISTRIBUTION

National Aeronautics and Space Administration

Administrator
Deputy Administrator
Associate Administrator
Chief of Staff
Associate Administrator for Aeronautics Research Mission Directorate
Director, Armstrong Flight Research Center
Director, Glenn Research Center
Director, Langley Research Center

Non-NASA Organizations and Individuals

Office of Management and Budget
  Deputy Associate Director, Climate, Energy, Environment and Science Division

Government Accountability Office
  Director, Contracting and National Security Acquisitions
  Director, Physical Infrastructure

Empirical Systems Aerospace, Inc.

GE Aerospace

magniX

Congressional Committees and Subcommittees, Chairman and Ranking Member

Senate Committee on Appropriations
  Subcommittee on Commerce, Justice, Science, and Related Agencies

Senate Committee on Commerce, Science, and Transportation
  Subcommittee on Space and Science

Senate Committee on Homeland Security and Governmental Affairs

House Committee on Appropriations
  Subcommittee on Commerce, Justice, Science, and Related Agencies

House Committee on Oversight and Accountability
  Subcommittee on Government Operations and the Federal Workforce

House Committee on Science, Space, and Technology
  Subcommittee on Investigations and Oversight
  Subcommittee on Space and Aeronautics

(Assignment No. A-22-10-00-SARD)