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X-57

Maxwell

Lessons Learned Report

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X-57 Lessons Learned

Revision History

REV	DATE	DESCRIPTION	AUTHOR
-	2/23/2024	Initial internal release	Vincent Schultz, Herb Schlickenmaier
A	12/20/2024	Editorial changes and cleanup for public release, updated scope statement and introduction, added best practices for knowledge transfer.	Heather Maliska, Vincent Schultz, Sean Clarke, Nick Borer

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1 Introduction

1.1 Scope

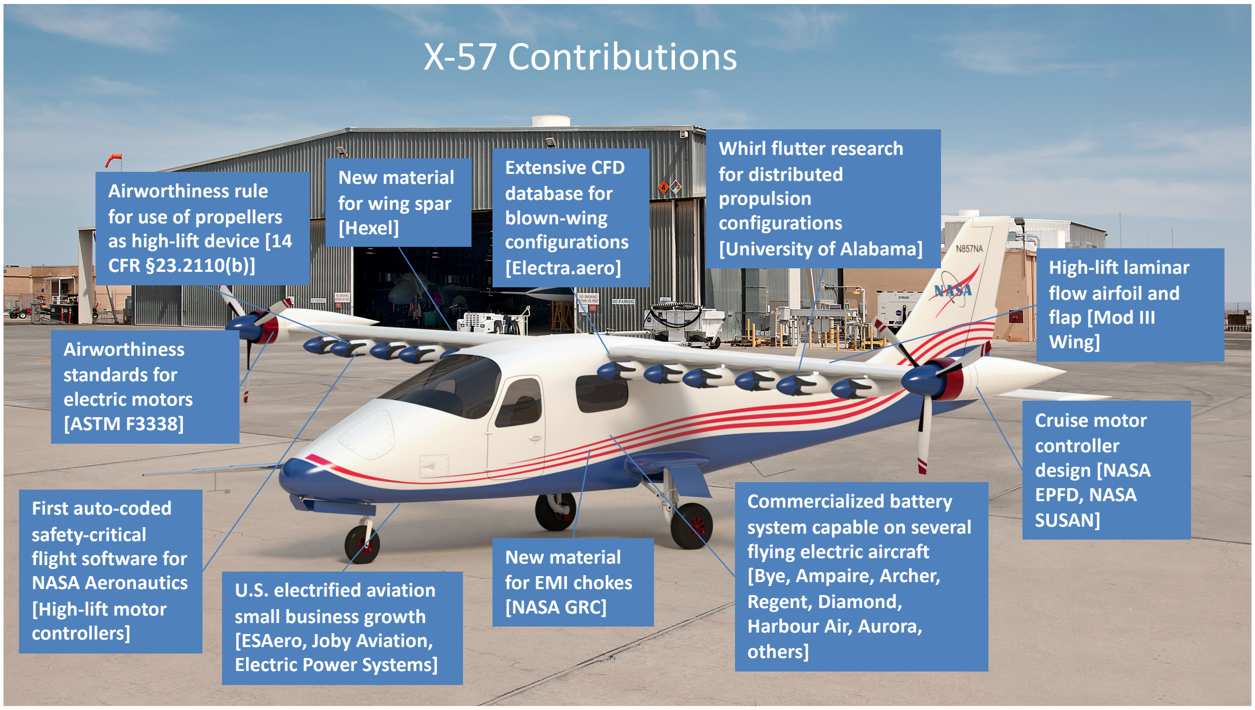
HS Advanced Concepts LLC was contracted to conduct in-person and remote interviews with subproject team members and key stakeholders to collect Lessons Learned and Recommendations related to the technology development challenges encountered during the development of the X-57 subproject. After conducting the interviews, HS Advanced Concepts provided a report and summary of the findings to the X-57 subproject leadership team. The X-57 team took the report and distilled it into the lessons learned and recommendations documented in this report. As the X-57 subproject has closed out, carefully collecting and cataloging key Lessons Learned within the technology maturation process used during X-57 execution is critical to inform future project management best practices and advance standards development in support of electric propulsion.

1.2 Lessons from Ten Years of X-57-Related Research

The goal of the X-57 subproject was to advance the Nation's ability to design, test, and determine airworthiness of distributed electric and aero-propulsive coupling technologies, which are a critical enabler of emerging, advanced air mobility markets. The value of X-57 lies in advancing the Nation's ability to design, test, and certify electric aircraft, which would enable entirely new markets. Mods III and IV had the intention of exploring the benefits of Distributed Electric Propulsion (DEP) which would revolutionize aircraft architecture and performance. Despite not achieving flight, the focus of achieving flight enabled the team to gather and share relevant lessons and data with industry and regulators. Maintaining flight as an objective drove testing and analysis rigor that led to more discovery. The impact of the X-57 lay not in what was originally set out to achieve but was evidenced by the identification of technology and certification gaps in industry and the need then to address those gaps. The identification and resolution of addressing gaps allowed for lessons to be shared early and often with industry and standards bodies and these lessons have been foundational to electrified propulsion. The X-57 subproject had aided in building the US electrified aircraft industry and has enabled commercial products. Figure 1 provides a summary of a handful of the contributions that X-57 has made to electrified aviation[1].

[1] H. Maliska, S. Clarke "X-57 Subproject Overview and Evolution," Spring meeting of ASTM Committee F44 on General Aviation, Cologne, Germany, April 2024. Available at https://ntrs.nasa.gov/citations/20240003363

Figure 1, X-57 Contributions



As compared to the level of NASA investment, the X-57 contributions have been substantial. The subproject elevated the Technology Readiness Level (TRL) of components leading to integration with flight performance specifications. By taking the publishing approach of 'early and often', the subproject shared design tools, component and subsystem test data and operational lessons learned with academia and industry. The X-57 published architecture is a principal reference for academia and standards development. The design and test standards and lessons learned are being adopted and the impact on regulations and standards is ongoing as operational constraints drive further learning. Additionally, the X-57 contractor and subcontractors grew, in part, because of X-57. With this, the X-57 has achieved the goal of advancing the Nation's ability to design, test, and determine airworthiness of electrified aircraft technologies.

The X-57 subproject began by leveraging NASA's Leading Edge Asynchronous Propulsion Technology (LEAPTech) effort, which was funded under an Aeronautics Research Mission Directorate (ARMD) Team Seedling award. LEAPTech focused on a ground test of the low-speed aerodynamic qualities of a wing designed for a uniquely novel vehicle concept of Distributed Electric Propulsion (DEP) to enable a more efficient cruise design. The X-57 subproject began in NASA's Convergent Aeronautical Solutions (CAS) project of the Transformational Aeronautics Concepts Program (TACP) with the goal of completing the LEAPTech ground test and advancing the DEP concept into a flight vehicle. This activity was known as the Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR) effort within CAS, which included flight of vehicles using a spiral development process in what were known as Mods I through III. As the scope of the effort grew, the activity transitioned to become a subproject of the Flight Demonstrations and Capabilities (FDC) Project within the Integrated Aeronautics Systems Program (IASP) and became known as the X-57 flight research vehicle. Mod IV, which integrated all the DEP concepts into a flight vehicle, was added to the FDC X-57 subproject in 2017. An overview of the planned test vehicles associated with each of these activities is shown in Figure 2, and a timeline of the X-57 subproject is shown in Figure 3.

Figure 2, Test Vehicle Scope for X-57 Subproject and Precursor Activities

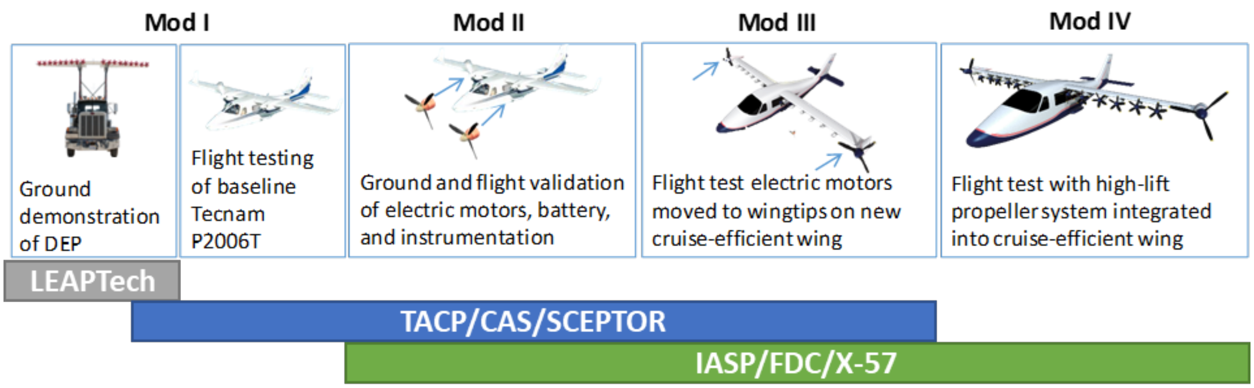
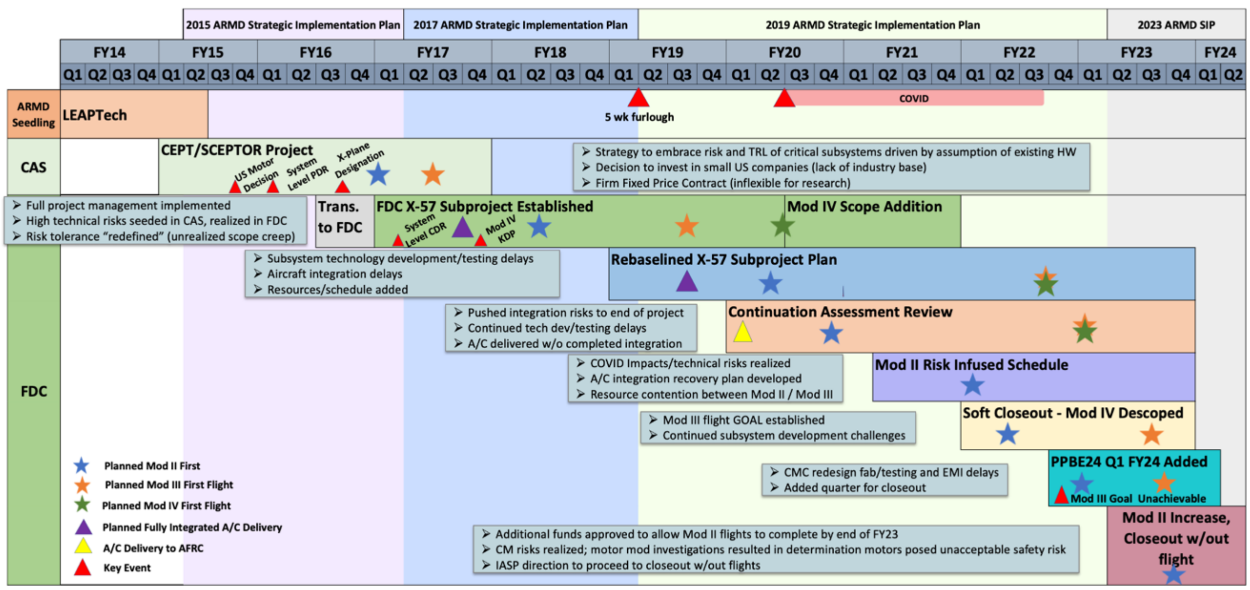


Figure 3, X-57 Timeline from LEAPTech to Close-Out

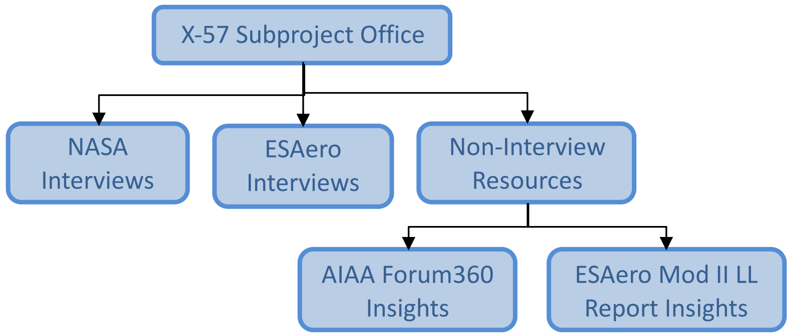


The X-57 subproject scope evolved throughout the lifecycle due to technical challenges, resource limitations, and changing stakeholder and industry needs. Throughout the effort, the team worked diligently to advance the state of knowledge and technology of electric aircraft subsystems and DEP, principally aiding in the development of industry standards.

1.3 Overview of the Lessons Learned Approach

Interviews were conducted with X-57 staff, both past and present staff members. These interviews were augmented through the extraction of lessons gathered from relevant reports (e.g., the AIAA AVIATION 2023 Forum 360 Panel on Lessons Learned, which discussed at a high level several lessons learned). Figure 4 illustrates the breadth of the approach used.

Figure 4, The X-57 Lessons Learned Approach



Consolidating the comments and insights from the breadth of interviews led to a recognition of common themes across the set of interviews. To help organize the key takeaways from the interviews, the team decided to organize around the following approach:

- Identify a key event and its resulting impact on the subproject.
- Document the key lesson or takeaway.
- Identify a relevant and actionable recommendation.

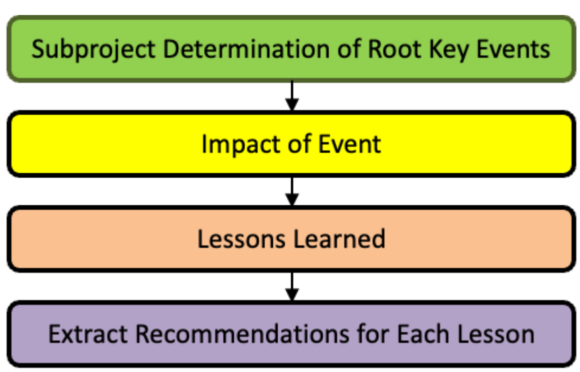
This resulted in the flow as outlined in Table 1.

Table 1, Terminology Used to Organize the Lessons

Term	Description
Driving Events:	A situation or decision leading to the lesson.
Impact of Event:	Consequences of event (things to avoid or embrace in the future).
Lesson Learned:	Lessons learned based on events and the associated ramifications of the events.
Recommendation:	An actionable proposal to address the lesson learned.

Figure 5 illustrates the hierarchy of the four terms starting with the driving event, to impact of the event, the lesson, and its recommendation. It also shows the color coding used throughout this report for the four characteristics.

Figure 5, Terminology Flow Down and Color Coding Used in This Report



2 X-57 Subproject Key Events, Impacts, Lessons Learned, and Recommendations

There are nine root key events that were distilled from the interview data by the X-57 subproject leadership team. The key events are listed in approximate chronological order.

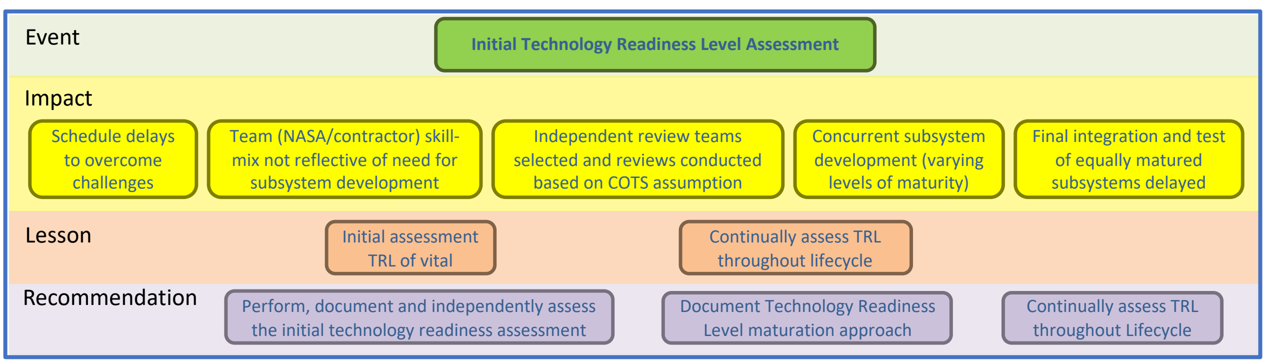
- Initial Technology Readiness Level Assessment
- Firm-Fixed Price (FFP), Phase III Small Business Innovative Research (SBIR) Contracting Mechanism
- Directed to Use US-Based Companies
- Using Small Companies with Limited Experience in Manned Flight Projects
- Subproject Transition from CAS to FDC
- Evolution of Advanced Air Mobility Community Needs
- Always a Year from Flight
- X-Plane Designation
- Take More Risk

In the following sections, each event, followed by the event's impacts, lessons, and recommendations will be described.

2.1 Initial Technology Readiness Level Assessment

At the start of this effort the Technology Readiness Level (TRL) of subsystems necessary and available to NASA to electrify the aircraft was assessed to be at a much higher level than they were in practice. Figure 6 summarizes the Impacts, Lessons, and Recommendations associated with the "Initial Technology Readiness Level Assessment" Event.

Figure 6, Initial Technology Readiness Level Assessment



2.1.1 Initial Technology Readiness Level Assessment Event

The initial NASA technical team was comprised of Subject Matter Experts (SME) in the development of Distributed Electric Propulsion (DEP) technology. The original approach planned to use "best-in-class" available components, as the project was not seen as a technology development effort, but rather an integration effort.

The initial assessment of the TRL for the required subsystems became a foundational cause and driving event for how the X-57 subproject was communicated, scoped, and formulated throughout its development. The initial assessment of TRL implied subsystem development did not need to be accomplished as part of the execution plan, largely based on the existence of and assumed ability to access overseas flight-proven hardware. Therefore, a baseline plan for cost and schedule was developed, assuming that funding and time were not needed to develop subsystems. The schedule and budget were formulated under this overarching assumption. Likewise, the subproject personnel were selected to develop and integrate a wing featuring a Distributed Electric Propulsion (DEP), not to develop the individual subsystems necessary to electrify an aircraft. As a result, few risks relating to subsystem development were identified. Accordingly, no mitigations or reserves were identified.

However, the direction from senior ARMD leaders at NASA HQ was for the subproject to use technology available from the US industry only ("buy American"). When that direction was given, the project may have benefitted from reassessing the TRLs of American components (see the "Directed to Use US-Based Companies" event). During subproject execution, it became apparent that the actual TRL for the subsystems was significantly lower than anticipated, and recovering from this mismatch in planned versus actual TRL resulted in significant challenges for the subproject. This had a lasting impact that led to schedule delays and cost impacts throughout the lifecycle of the subproject.

2.1.2 Impacts of the Initial Technology Readiness Level Assessment Event

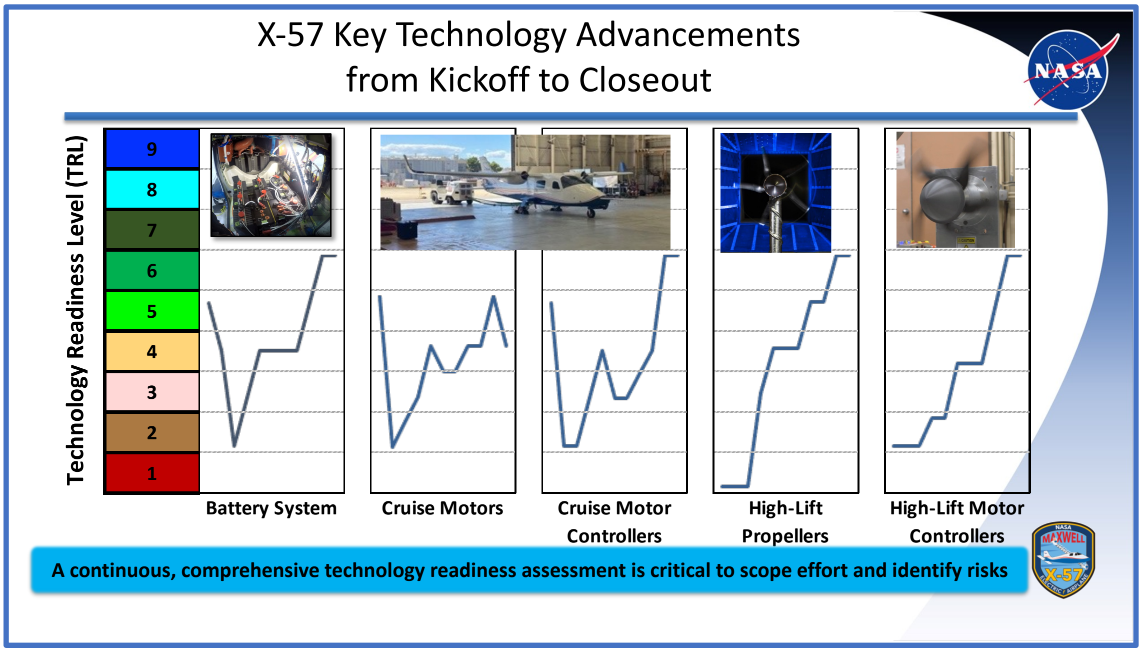
The subproject experienced schedule delays in overcoming technical challenges encountered due to lower-than-assessed TRL for major components of the Traction System - Cruise Motors / Cruise Motor Controllers; Battery Control Modules; and Mod IV High-Lift Motor Controllers (HLMC). Each of these subsystems had to be redesigned as the hardware and software either delivered or planned to be delivered were not at a sufficiently high TRL to support integration and test, let alone flight.

In addition, the team skillset was not originally scoped to resolve subsystem development challenges. The NASA and contractor skillsets were aligned to support the integration of market-available DEP components. There was a recognition of the need to design and fabricate a revolutionary new wing design to support DEP, and those skillsets were made available to the team early on. However, initial expertise was also needed for what turned into major subsystem development.

Independent review teams were selected, and reviews were conducted, but these reviews assumed that existing technology/hardware was already available for use. As a result, subsystem design reviews were not conducted, and independent assessments of Technology Readiness Levels (TRL) were not conducted following the realization of technical challenges.

To address the challenges associated with the TRL Assessment event, the project embarked on development of several subsystems, first serially and then in parallel as the scope of the challenges became evident. The required parallel development of several subsystems increased the technical risk and impacted the readiness of other mature subsystems. Figure 7 below indicates the progression of TRL on each of the indicated subsystems over the life of the subproject. While it was intended to develop the high lift systems for Mods III and IV, the development of battery systems, cruise motors and cruise motor controllers was not intended at the start of the subproject.

Figure 7, X-57 Technology Readiness Level Advancements



As a result of the unplanned subsystem development work, the final integration and test of matured subsystems was delayed, which increased the probability of additional schedule and cost impacts being realized late in the subproject with an inability to overcome realized integration risks (as no additional schedule or funds were available). Specifically:

- The Battery Control Module (BCM) redesign and delivery delays delayed key ground testing on internal power, which did not begin until mid-way through 2021.
- The Cruise Motor Controller (CMC) redesign delayed discovering and understanding the extent of the on-aircraft EMI challenges.
- On- and off-aircraft testing of the Cruise Motors identified further design deficiencies.

2.1.3 The Lessons Learned from the Initial Technology Readiness Level Assessment

Initial assessment of TRL is vital to scope and baseline the subproject approach and resources properly, as it sets the baseline risks, informs cost and schedule, and is foundational for formulation.

Continually assessing TRL throughout the subproject lifecycle provides an opportunity to assess health and adjust to challenges that occur. It should be triggered after technical challenges and at each lifecycle review.

2.1.4 The Recommendations Resulting from the Initial Technology Readiness Level Assessment Event

It is recommended that the initial technology readiness assessment be performed, documented and independently assessed. It is critical to assess where the technology is starting from (baseline) and have that assessment independently reviewed.

Document a technology readiness level maturation approach. One key to project success is to develop an achievable approach that couples with and accounts for airworthiness requirements with the intent to level-set the programmatic, technical, and safety risks. It is also important to maintain and control the configuration of the technology readiness level maturation approach and update it when TRLs are changed or in some way impacted.

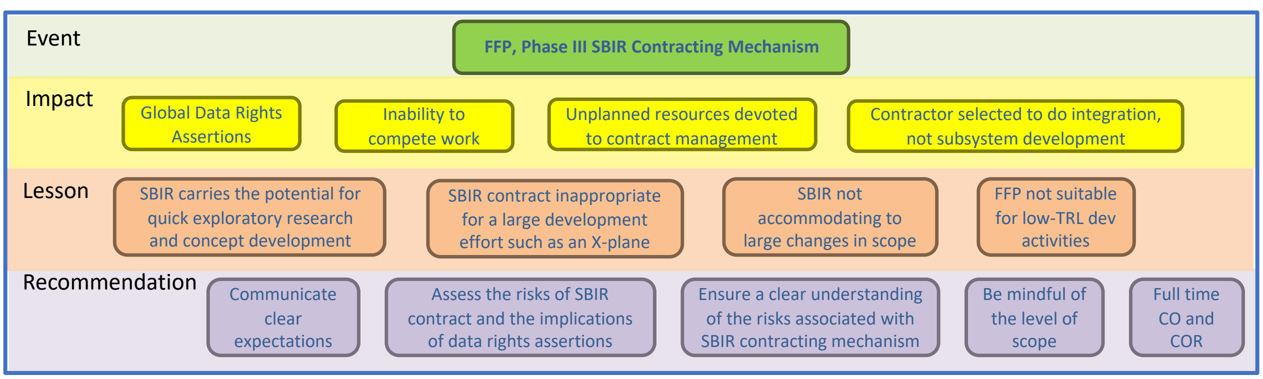
Continually Assess TRL Throughout the subproject Lifecycle is further recommended. At a minimum, the TRL assessment should occur at each subproject lifecycle review, assessing its impact on cost and schedule. At lifecycle reviews, the project team should consider the following questions and recommendations, at a minimum:

- Have subsystem development tasks been added that imply that a critical subsystem is at a lower level of maturity than was in the previous plan?
- Is there an impact on integration and test plans?
- How do the programmatic risks change as a result of changes to TRL?
- Does the skill mix of the team reflect the current TRL and any potential impacts on other subsystems?
- In addition to assessing TRL at the Lifecycle Reviews, be attentive to changes that occur due to technical challenges that arise during a subproject's lifecycle.
- For both the lifecycle review and changes due to technical challenges, the TRL assessment should be independently reviewed, and an assessment of the impact of changing TRL on one subsystem to the resulting TRL of the integrated system.

2.2 Firm Fixed Price, Phase III SBIR Contracting Mechanism

Use of the Firm Fixed Price (FFP), Phase III Small Business Innovative Research (SBIR) contracting mechanism provided access to technology quickly and provided a faster contracting mechanism. Figure 8 summarizes the Impacts, Lessons, and Recommendations associated with the "Firm Fixed Price, Phase III SBIR Contracting Mechanism" event.

Figure 8, Firm Fixed Price, Phase III SBIR Contracting Mechanism



2.2.1 The Event that Triggered the Firm Fixed Price, Phase III SBIR Contracting Mechanism Lesson

SCEPTOR's selection as a "directed" activity in CAS (noting CAS itself was a new ARMD project in 2015 looking into new business models at NASA favoring venture capitalist-style approaches to selecting a portfolio of high-risk/high-reward efforts) did not allow time to accommodate a full and open procurement. Furthermore, the nascent stage of the U.S. market in electrified aircraft meant that the established domestic supplier base did not yet have the capability and/or interest in such a procurement. A sole source Phase III SBIR following the sole source Phase II SBIR was therefore appealing and favored the intent to build up the US small business electric aircraft industry.

The SBIR Phase III Indefinite Delivery Indefinite Quantity (IDIQ) Contract was awarded to the contractor as a follow-up to the Phase II effort. The FFP contract mechanism did not provide sufficient incentives for on-time deliverables.

2.2.2 The Impact of Experiencing the Firm Fixed Price, Phase III SBIR Contracting Mechanism Event

Data rights became an increasing challenge as the subproject progressed and as challenges (both contractual and technical) arose. The contractor did not initially choose to assert SBIR data rights on most deliverables, and NASA was able to share the information freely with the public or other support contractors without issue. Later, the contractor chose to assert SBIR data rights for all deliverables. This caused tension with the contractor when the NASA team opted to bring some work in-house, since this occasionally required NASA to share marked data with NASA support contractors. NASA's legal team determined that NASA could share SBIR data with support contractors who could then, in turn, support the X-57 subproject. This was at odds with the contractor's legal interpretation, which led to continued tension when working with internal NASA support contractors.

This evolved into challenges to compete or publish work due to concerns associated with data rights and derived data rights. The SBIR data rights limited NASA's ability to engage other external contractors to mitigate subsystem development risks. This resulted in an inability to maintain a flexible contracting approach to solving problems. NASA could either add scope (funding/time) to the contract (task order) or do the work in-house - both options of which posed challenges. Either the contractor did not have the expertise to do the work, and they would need to subcontract the work out (additional funding), or NASA did not have the skill set available within the X-57 workforce to solve the problem and would need to find additional funding to add the skill sets needed to the subproject and the time to find the appropriate personnel. The best solution, from a funding and schedule standpoint, would have been for NASA to find an external contractor with the appropriate expertise to solve the problem. The application of SBIR data rights and issues with derived information associated with these data rights limited this option.

The subproject realized more resources were necessary (from both NASA and the Contractor) to provide detailed Statements of Work (SOW), which were used to communicate detailed requirements and expectations. The Performance Work Statement (PWS) based task orders did not result in hardware that met the project needs, but SOWs were difficult to write for fundamental research when the requirements are not known *a priori*. Additionally, the contractor's minimal experience with aircraft hardware development drove a need to define requirements that reflected a developed subsystem. Later NASA SOWs that attempted to reconcile this lesson documented not only detailed requirements but also the means to meet these requirements.

The subproject conducted an acquisition strategy meeting to investigate potential new contracting mechanisms. Because of the contractor's SBIR data rights, contracting options were limited. An open competition for a new contractor was not an option. Thus, it was recommended and approved to allow for the contract to expire but to maintain the remainder of work on open task orders and potential new work to complete the contract via a new time and materials task order.

2.2.3 The Lessons Learned from the Firm Fixed Price, Phase III SBIR Contracting Mechanism

An SBIR contract carries the potential for quick exploratory research and concept development, but an SBIR contract is inappropriate for a large development effort such as an X-plane. For example, an SBIR may be a great opportunity for a small company to develop a sensor, leverage data rights protections to perfect that sensor, and later patent the sensor. NASA benefits from the ability to collect the data and publish what is collected from the sensor. In the case of X-57, the subsystem development needed to electrify the aircraft became the focus of lessons that the subproject wanted to share with regulators and the industry. The SBIR contract hindered the ability to share those developmental lessons.

SBIR contracts do not accommodate large changes in scope. Large changes in scope can reach beyond the SBIR contractor's ability and may drive the contractor to subcontract which will incur additional overhead and funding from the government. SBIR data rights of the original contractor do not allow the government the ability to seek a new contractor to resolve or accommodate changes in scope.

A Firm Fixed Price (FFP) contract is unsuitable for low-TRL development activities that are doing fundamental research. In the case of X-57, the subsystem development was not a part of the original objective of the subproject and became a necessity as the subproject worked to achieve the goal of DEP in flight.

2.2.4 The Recommendations Based on the Lesson from the Firm Fixed Price, Phase III SBIR Contracting Mechanism

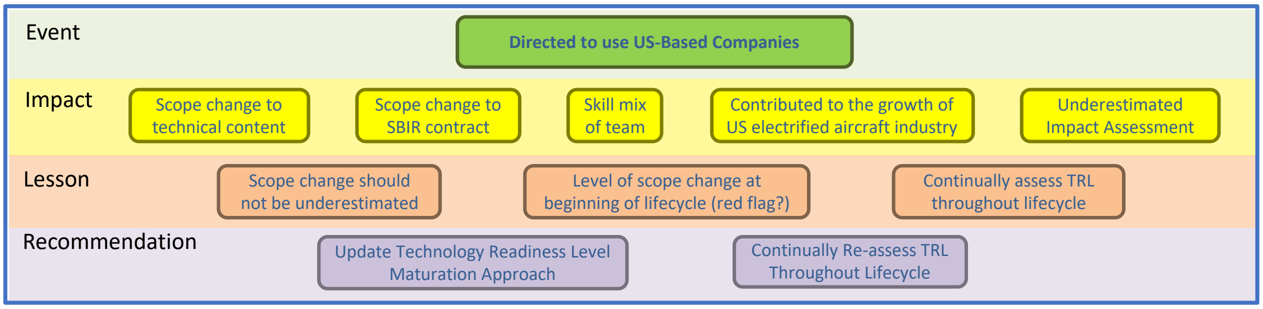
Communicate clear expectations. Understand and provide clear expectations as to contracting mechanisms and their limitations. Although an SBIR contract, this Phase III SBIR held FFP task orders that required deliverables and deliverable dates based on requirements. The risk then falls on the contractor to estimate the work required to meet requirements at the proposal phase and then stay within their estimate. If the scope of work to meet the requirement exceeds their estimate, the contractor assumes that increase within the firm fixed price of the task order. NASA selected the SBIR contracting mechanism due to the perceived ease of making changes to accommodate shifting requirements. NASA needed to make clear to the SBIR contractor that NASA continued to expect the contractor meet the requirements of all tasks, even in the face of challenges.

Consider generating a NASA document that clearly outlines data rights and data rights management at the time of subproject formulation. Establishing clear criteria for marking documents with the appropriate data rights – both from the contractor and any subcontractors – is best done at the beginning of the subproject, and periodically revisited for every major deliverable. Both NASA and the contractor should know and expect which elements of contractor-delivered and derived data should be marked, and how. "Proprietary" vs. "SBIR data rights" have different applications and management requirements.

2.3 Directed to Use US-Based Companies

SCEPTOR, under CAS, planned to use existing Cruise Motors (CM), Cruise Motor Controllers (CMC) and batteries from European manufacturers that had the highest technology readiness level aviation electric propulsion units in existence at the time. However, shortly into subproject execution, the team was directed not to purchase major subsystems from overseas manufacturers but rather to help build a U.S. industrial base in aviation electric propulsion. Figure 9 summarizes the Impacts, Lessons, and Recommendations associated with the "Directed to Use US-Based Companies" event.

Figure 9, Directed to Use US-Based Companies



2.3.1 The Event that Triggered the Directed to Use US-Based Companies Lesson

The CEPT team formulated the CAS activity with the assumption of reasonably mature aviation electric propulsion subsystems (CM, CMC, batteries) that had already been flight-proven, and were at a TRL of 5-6. The CEPT team's original tasks and composition were focused on integration of these systems to develop a DEP aircraft. The direction to source U.S. subsystems was intended by NASA senior management to better the US electric aircraft industry. However, the U.S. aviation electric components were generally at TRL 3, which meant they required technology development and aircraft integration technology development. This direction came after the prime contractor had been selected and the SBIR Phase III contract had already been put in place.

The unintended consequence led to substantial technology development efforts that the subproject was not scoped to handle. In addition, the SBIR contractor was challenged by a skill mix mismatched to developing/maturing new technologies vs. a heretofore expected technology integration effort.

2.3.2 The Impact of Experiencing the Directed to Use US-Based Companies Event

There was a major scope change to the technical content of the SBIR contract during execution. With the prime contractor having originally been selected for its integration experience, the change in scope reflected a new need for a capability that included subsystem development. The contractor did not initially have the capabilities necessary to resolve the technical challenges that were encountered.

The team did not have the necessary skill mix nor the appropriate plan and funding to support a development effort and had to quickly create a plan with very limited budget and schedule options while already in execution. For example, the plan to develop the CMs and CMCs – major subsystems – was developed and approved within about one month.

The initial impact assessment was underestimated on both cost and schedule, as well as both programmatic and safety risks. These impacts were compounded by other events described later in this document, such as the risk posture of the parent project (CAS) at the time of this decision that encouraged more aggressive and/or lean approaches to development.

2.3.3 The Lessons Learned from the Directed to Use US-Based Companies

Impacts of scope change should not be underestimated particularly early in the lifecycle of a project. The direction to use US-Based companies required a thorough review of its effect on the assumptions made within CAS, where a turnkey delivery of CMs and CMCs to be integrated on a novel DEP aircraft had assumptions about its technical objectives, schedule, and cost estimates. The change to a technology development effort for CMs and CMCs required a fundamental assessment of the impact of this change on technical, schedule, cost, and risks. A bottoms-up assessment of the effort to pivot to a US-based motor company was not done.

Continually assess TRL throughout the subproject lifecycle. A drop in TRL was an opportunity to reassess TRL and the impact of the change across the entire system. It was also a missed opportunity to revisit the acquisition strategy that had originally assumed global flexibility to use mature technology sources.

2.3.4 The Recommendations Based on the Lesson from the Directed to Use US-Based Companies

A change in scope that occurs during subproject execution should trigger a pause in execution and a thorough re-assessment of the impact of the scope change before proceeding. As noted later in this document, the rapidly evolving needs of an emerging market segment can lead to changes in subproject scope. Though it can be tempting to apply a “quick fix” to largely maintain previously approved schedule and budget estimates to completion, such large changes in scope warrant a pause in execution and re-evaluation of the project plan, and if necessary, the objectives to meet changing goals and needs.

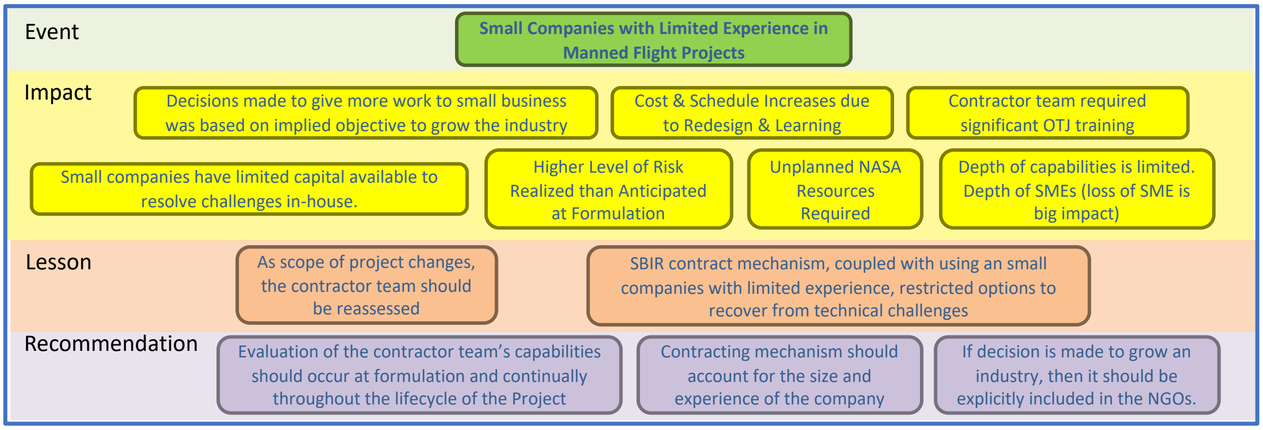
Continually assess TRL throughout a subproject’s lifecycle. Reassess TRL and how the TRL maturation approach is affected. Revalidation of assumptions is a key to success (see more discussion of this in section 2.1, and specifically the associated recommendations in section 2.1.4).

Update the technology readiness level maturation approach as will be further discussed in section 2.1.4.

2.4 Small Companies with Limited Experience in Manned Flight Projects

In 2014 there were no mainstream US companies developing electrified aircraft concepts. A decision was made to use small businesses for the X-57 subproject. Figure 10 summarizes the Impacts, Lessons, and Recommendations associated with the “Small Companies with Limited Experience in Manned Flight Projects” event.

Figure 10, Small Companies with Limited Experience in Manned Flight Projects



2.4.1 The Event that Triggered the Small Companies with Limited Experience in Manned Flight Projects Lesson

NASA selected small companies with limited aerospace development experience to design, analyze, and integrate the aircraft. However, aerospace subsystem design, analysis, fabrication, and testing of manned flight vehicles is a domain where experience can be critical.

In addition to technical expertise, a company that is expected to develop, test, and provide a flight-worthy vehicle to NASA airworthiness standards needs solid quality assurance (QA) expertise. X-57's use of small companies without this expertise, although a great learning opportunity for the contractor, required a lot of support from NASA both in mentoring and development of a QA process which took time and impacted contracting.

2.4.2 The Impact of Experiencing the Small Companies with Limited Experience in Manned Flight Projects Event

The contractor required on-the-job training for technical and programmatic tasks. The contractor ran into challenges executing multiple task orders with similar periods of performance, particularly early in the project when the contractors had not built-up sufficient staffing in critical management areas. Additionally, while the recognition of working for NASA brought in additional business to the contractor team, this growth negatively impacted X-57 by drawing the contractor's and subcontractors' priorities away from X-57.

Out of necessity, NASA brought increased levels of subsystem development in house to meet schedule and budget. This induced additional cost and schedule increases to allow for redesign and learning.

The contractor's limited experience with flight systems suitable for manned flight drove the need to provide defined requirements that reflected a developed subsystem. This led to defining not only what work needed to be performed, but also "how" to do that work.

This level of engagement required more resources for the NASA team. Examples of these resources were not restricted to funding, but the application of QA by NASA to ensure quality of the developed subsystems as prototype vs. flight hardware. The result was that the contractor built up QA capabilities with NASA's mentoring. But the additional insight, oversight, mentoring, and training required more personnel. Additionally, the NASA subproject workforce had to develop test capabilities to augment or establish capabilities that could not otherwise be met by the contractor.

Through the course of subproject execution, decisions were made to give more work to small businesses because there was a stated objective from NASA senior leadership to grow the electrified aircraft industry in the U.S., which, as an emerging market, was largely comprised of small businesses. Although not a formally documented objective of the subproject, the benefit of building up this domestic industry base was communicated by FDC/IASP/ARMD management to the X-57 team to be an unwritten objective.

The use of a small company had the side-effect that limited capital was available for that company to resolve challenges in-house. Additionally, the smaller workforce limited the depth of capabilities in each subject area. The loss of Subject Matter Experts (SME) by attrition proved to hinder the contractor as they worked to develop a recovery plan to backfill their loss.

The impact of using small companies with limited experience in manned flight projects drove a higher level of risk to be realized during execution of the subproject than was initially anticipated at the time the subproject was baselined within FDC.

2.4.3 The Lessons Learned from the Small Companies with Limited Experience in Manned Flight Projects

First, as the scope of a subproject changes, the contractor team should be reassessed. The X-57 contractor team was selected based on assumptions made during SCEPTOR formulation in CAS based on experience with electrified system integration and not subsystem development. The large change in scope to include development of critical subsystems should have led to a re-evaluation of the contractor team, subproject scope and resources and overall acquisition strategy.

Secondly, the SBIR contract mechanism restricted options to recover from technical challenges. Smaller companies do not tend to have access to funding reserves to recover from these challenges, and attrition within the company can leave it without a necessary skillset. Furthermore, by definition, the small company may not be able to access needed subject matter expertise from within when technical challenges arise in a new domain.

2.4.4 The Recommendations Based on the Lesson from the Small Companies with Limited Experience in Manned Flight Projects

It is recommended that an evaluation of the contractor team's capabilities occur at formulation and continually throughout the lifecycle of the subproject.

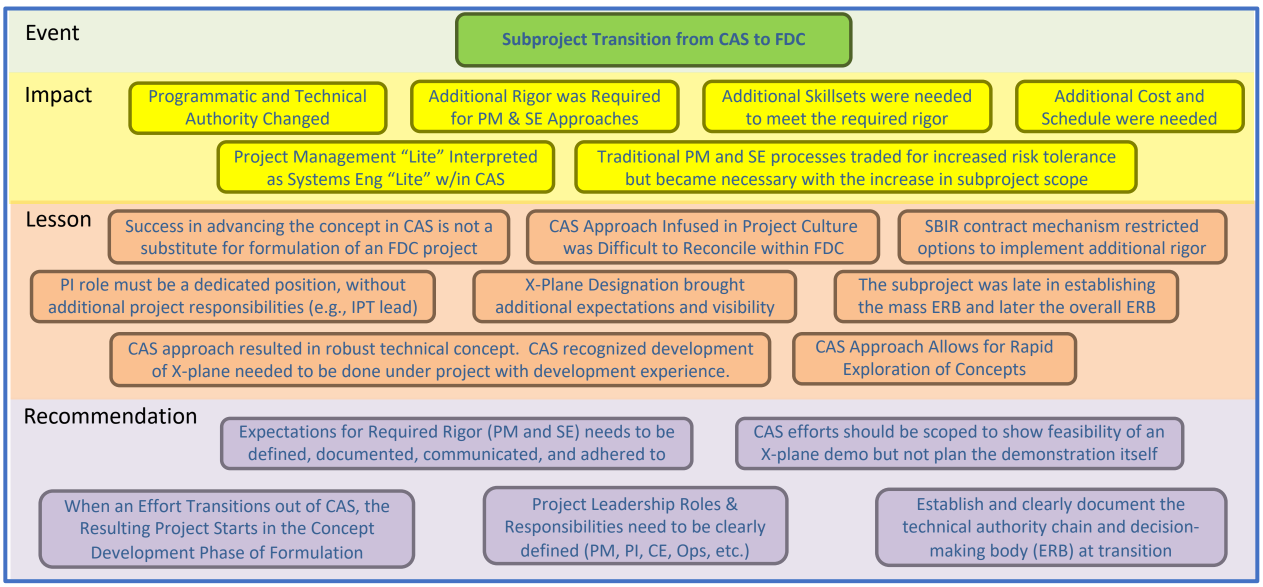
It is also recommended that the contracting mechanism chosen consider the size and experience of the company commensurate with the complexity of the technical challenges that will need to be overcome. For example, if a company does not have a quality assurance process, care should be taken in how the contracting mechanism is set up to work with this company and consideration given for how the lack of a quality assurance process affects the project's requirements.

If a decision is made to grow an industry, then it should be explicitly included in the subproject's Needs, Goals, and Objectives (NGO).

2.5 Subproject Transition from CAS to FDC

The SCEPTOR activity was developed within CAS in FY2015. CAS was a new ARMD project that was patterned after venture capitalist (VC) models of funding activities, in which multiple activities with higher levels of risk were encouraged in the hope that one would be successful. SCEPTOR was the first CAS activity to transition out of CAS into FDC and therefore it served as a pathfinder for transition of CAS activities into other programs and projects. After the CAS preliminary design review the subproject transitioned from CAS to FDC. The changes in project scope necessitated more resources than CAS could provide. FDC stepped through an assessment process and applied additional rigor and resources through a "Baseline Review" (using a bottoms-up approach). In 2017, a year into the execution of X-57 within FDC, Mod IV was baselined. The subproject was designated as an X-plane during the transition, which significantly raised its profile and visibility. Figure 11 summarizes the Impacts, Lessons, and Recommendations associated with the "Subproject Transition from CAS to FDC" event.

Figure 11, Subproject Transition from CAS to FDC



2.5.1 The Event that Triggered the Subproject Transition from CAS to FDC Lesson

The CAS project portfolio was inspired by VC models of development, in which prospective activities are "pitched" to CAS management rather than flowed down through the programs from NASA ARMD strategy (as is typical for other projects). This VC mindset extends to embracing risk. CAS management accepts high risk from a portfolio of several individual activities in the hope that one succeeds, whereas the traditional NASA process manages risks at the subproject level with the goal of ensuring every subproject succeeds. These differing risk postures pose challenges when transitioning from one risk posture to another. The management and mitigation of risks within FDC incurred a new level of scope and rigor that was not originally realized or accounted for at the time of transition. The technical and programmatic risks seeded in CAS were realized in FDC. The transition of a manned X-Plane into a flight subproject within FDC reset or "redefined" the risk posture to one of ensuring airworthiness of a manned X-Plane which, in turn, introduced additional programmatic rigor. The magnitude of scope, and thus rigor, was not initially identified at transition but was rather realized (i.e. scope creep) out of necessity as challenges were encountered and plans to overcome the challenges were generated during subproject execution within FDC.

With the VC model in mind, CAS allowed its activities to streamline NASA processes in a way that likely increased programmatic and technical risk while maintaining the necessary level of safety. The SCEPTOR activity under CAS sought to develop a flight demonstrator with aggressive technology development assumptions, with zero reserves and tight resources, leveraging prime- and sub-contractors as the integrator of an electric aircraft with existing products. The X-57 risk posture under CAS accepted the approach of striving to fly lower TRL subsystems (TRL of 4 or 5), which further compounded risk when the initial, higher TRL electrical subsystems selected by the team became inaccessible early in the execution of the CAS portion of the project (see "Directed to Use US-Based Companies"). Other X-planes have advanced a handful of key technologies from TRL 5 or 6 to TRL 6 or 7. Ultimately, the X-57 subproject within FDC encountered several subsystem challenges that led to subsystem redesigns. Transitioning to FDC and having to meet its risk posture drove the need to develop the subsystems to a TRL 5 or 6 to accomplish flight.

2.5.2 The Impact of Experiencing the Subproject Transition from CAS to FDC Event

At transition, programmatic and technical authority changed. As in the approach in CAS the activity was focused on demonstrating the feasibility of the DEP novel concept vehicle. The CAS activity was led by a Principal Investigator (PI) who was responsible for (1) establishing and managing the project vision and objectives; (2) project planning, resource and contract management, and teaming; and (3) overseeing the technical decisions. In legacy NASA models, these roles are taken by three individuals, respectively: a PI, a Project Manager (PM), and a Chief Engineer (CE). For an effort as comprehensive as a manned flight demonstrator, reconciling these generally full-time roles to a single individual can lead to a "light touch" on traditional NASA PM and CE approaches. In the case of SCEPTOR, this led to a significant reduction in emphasis on the use of NASA legacy project management (project management "lite") and systems engineering (systems engineering "lite") tools and methods[2]. The transition from an integrated product team (IPT) based structure with decisions led by a PI to a traditional technical authority (that was CE-led) was slow and not well communicated within the team. Further, the technical authority chain was not clearly understood or communicated until much later in the subproject lifecycle (2020). Furthermore, throughout both the CAS activity and FDC subproject, the PI also held IPT lead roles, further diluting time and attention away from either leadership role.

It was found that although additional rigor in the areas of Project Management (PM) and Systems Engineering (SE) was applied at the time of transition from CAS to FDC, the scope (or magnitude) of that rigor increased further (out of necessity) as the subproject was executed within FDC. The level of rigor, amount of margin, and reserve allowance in cost and schedule estimates under the CAS subproject was not appropriate for an FDC flight project. The initial lean cost and schedule estimates set early expectations that followed the activity well after its transition to FDC. When a PM estimated cost in transition to FDC, the cost estimate doubled, which was hard for NASA senior management to accept. Similarly, the level of rigor applied to defining the Needs, Goals, and Objectives of the subproject was not appropriate for an FDC

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[2] L. Kushner, T. Holtz, E. Baumann, C. Sales, "X-57 Systems Engineering Lessons Learned," AIAA Aviation Forum, Las Vegas, NV. Available at https://ntrs.nasa.gov/citations/20240006845

flight project and likewise impacted the system-level requirements. Although SCEPTOR's scope was a manned flight demonstrator, it was communicated as a lean and agile path to flight; during the initial CAS kickoff of the project, the PI indicated that the approach outlined by the SCEPTOR team could "streamline NASA design-to-flight process while maintaining safety."

As the risks assumed in CAS were realized within FDC (contracting, unplanned subsystem development), additional rigor (i.e. engineering review board, risk informed budget/schedule margin) was required for project management as well as systems engineering approaches to meet FDC expectations and requirements. Additional skillsets were then needed to meet this required rigor, ultimately requiring additional schedule and funding.

The VC approach within CAS fostered a project management "lite" path of management that was, as is discussed above, the responsibility of the PI. While a good approach for smaller scoped or unpiloted activities, for X-57 this project management "lite" approach led to a "lite" approach to systems engineering. Traditional PM and SE processes were traded for an increased risk tolerance but became necessary with the increase in subproject scope and change in subproject risk posture under the FDC project. It was difficult to insert traditional program management and SE processes at the critical design review phase of an "SE lite" subproject; the risk of scope increase was realized as FDC was executed and practiced with more rigor.

2.5.3 The Lessons Learned from the Subproject Transition from CAS to FDC

The CAS approach allows for rapid exploration of concepts.

The SCEPTOR management approach approved by CAS resulted in a robust concept; however, it was inadequate to apply this management approach to the development of a manned NASA flight demonstrator in FDC. Documenting and agreeing on a "tailored" airworthiness process at the start of the subproject helps baseline the scope of an effort required to prove the airworthiness of a piloted experimental aircraft.

Document the review process up front.

Clearly define the "tailoring;" and take a realistic approach to assessing the feasibility of the tailoring process to flight. This process allows for a baselining of what "…Take more risk…" means from a technical, programmatic, and airworthiness (safety) standpoint.

The CAS approach was infused into the subproject culture and was difficult to reconcile within FDC. Cost and schedule estimates in FDC should be developed by a subproject manager, who provides an "independent" assessment as well as the necessary experience to estimate what it takes to bring research objectives to reality. Even with a different risk posture, it would have been helpful to track risks within CAS activities to help aid in the transition to other larger subprojects, so that the appropriate level of mitigation planning can occur. This would have helped scope the subproject's schedule and cost estimates.

There was a recognition that getting a manned X-57 to flight and proving airworthiness combined with subsystem development was a much larger scope than CAS was chartered to handle. Thus, the decision was made to transition X-57 out of CAS and into FDC, which would implement more rigor and resources appropriate for a manned flight demonstrator development. The budget was adjusted to reflect schedule, labor, risk reduction, and subcontractor changes (reference section 2.3, "Directed to Use US-Based Companies"). However, they did not validate the transition assumptions from one subproject to another.

The success in advancing the vehicle concept in CAS is not a substitute for formulating an FDC subproject that includes the required artifacts for a manned NASA flight demonstrator. The SCEPTOR activity in CAS clearly had a lot of success early on when proving the feasibility of DEP within CAS. The transition to FDC may have benefitted from going through a true project formulation Key Decision Point (KDP). A KDP is a decisional review that serves as a gate through which programs and projects need to pass to continue through their life cycle.

Implementing additional rigor was further restricted because of the SBIR contract mechanism that was selected. This induced scope creep and, although intended as mentoring, was interpreted by the contractor as unwanted oversight and incurred additional documentation.

The PI role must be a dedicated position without additional subproject responsibilities (e.g., also being an IPT lead). This split of attention did not provide adequate time for the PI to advocate for the research both "up and out" of the subproject and "down and in" within the subproject. The added visibility brought on by the X-Plane designation, along with the evolving landscape of industry (needs of industry) and changes to the ARMD Strategic Implementation Plan (SIP) required a full-time effort of the PIs to advocate and communicate the ever-changing relevance of the X-57 subproject in a rapidly evolving market segment. Impacts of a changing SIP will be discussed within the "Evolution of Advanced Air Mobility Community Needs" event.

The subproject was late in establishing the hardware mass Engineering Review Board (ERB) and even later establishing the overall ERB. These changes occurred because the team needed a forum to manage the mass of the aircraft that was growing as the team resolved development challenges. Likewise, the general ERB was added out of necessity to resolve technical challenges or disagreements and make recommendations to the subproject manager (assuming they impacted cost and schedule). The subproject may have benefited from these forums being instituted at the transition into FDC.

2.5.4 The Recommendations Based on the Lesson from the Subproject Transition from CAS to FDC

When developing a manned flight demonstrator that will be subject to NASA airworthiness requirements, it is recommended the activity transition out of CAS start at the concept development phase of formulation (KDP A). It is difficult to reconcile the differences in execution philosophy for agile, lean approaches like CAS and more traditional approaches that are required for other NASA projects. By transitioning after concept development, these traditional approaches to project management and systems engineering can be costed and scheduled as appropriate.

Building off the strengths of CAS, it is recommended that research activities associated with manned flight demonstrators be scoped to show the feasibility of such a demonstrator, but it may not be appropriate to plan the demonstration itself when the receiving project has a different risk posture than CAS. It is recommended that the planning of how to execute the effort fall on the receiving subproject.

Define, document, communicate, and adhere to expectations for required level of rigor for FDC (e.g., project management and systems engineering).

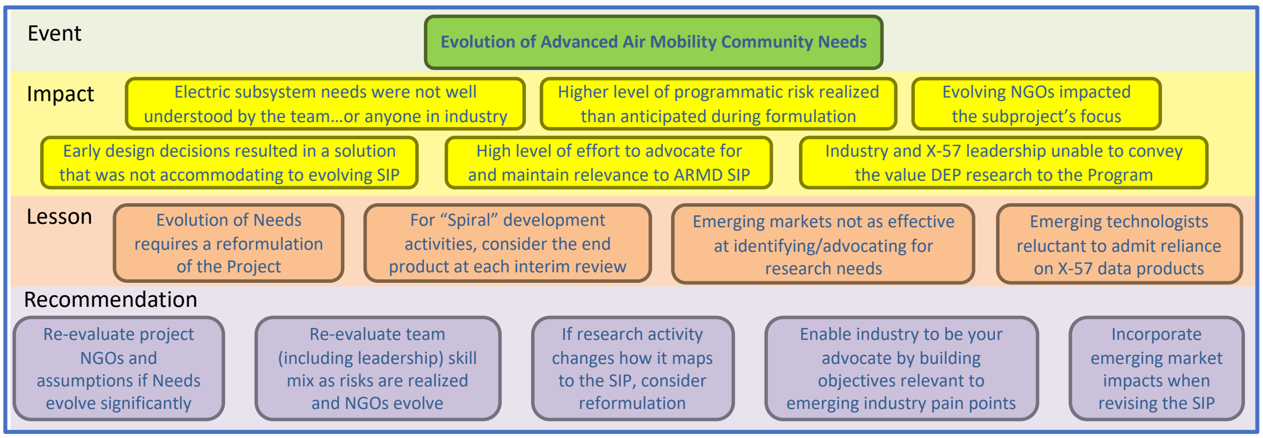
Establishing and clearly documenting the technical authority chain and decision-making body (such as an Engineering Review Board, ERB) at transition, and explicitly note changes in technical authority if the authority moves from one individual or group to another is also recommended.

It is recommended that subproject leadership roles and responsibilities be clearly defined (Project management, Principal Investigator, Chief Engineer, Operations, etc.) and any changes in titles or authorities be communicated at transition.

2.6 Evolution of Advanced Air Mobility Community Needs

Because X-57 was a flight research subproject in an emerging field, the needs of the aviation community and the response of the ARMD Strategic Implementation Plan (SIP) changed throughout the lifecycle of the subproject. Figure 12 summarizes the Impacts, Lessons, and Recommendations associated with the "Evolution of Advanced Air Mobility Community Needs" event.

Figure 12, Evolution of Advanced Air Mobility Community Needs



2.6.1 The Event that Triggered the Evolution of Advanced Air Mobility Community Needs Lesson

Electrified propulsion technologies and distributed propulsion architectures for manned aircraft were not established at formulation of the X-57 activity. As these technologies and designs began to be adopted in industry in parallel and in response to the progress of the X-57 systems development, the gaps in adopting these technologies changed, and the X-57 research products needed (e.g., data sets, lesson presentations, technical papers, system models) changed as well. In parallel, the ARMD SIP was also reacting to the research needs of industry, albeit at a broader level, and its goal to balance NASA aeronautics research across industries resulted in a different emphasis. With stakeholder needs changing more frequently and more drastically in these research areas than would be typical there was a mismatch between the formal Needs and subsequent Goals and Objectives driving the X-57 subproject activities. Accordingly, the subproject needs, goals, and objectives (NGOs) evolved to remain relevant to the evolving community and to the strategic thrusts identified in the ARMD SIP.

2.6.2 The Impact of Experiencing the Evolution of Advanced Air Mobility Community Needs Event

Electric subsystem needs were not well understood. Initial technology surveys found that there were few high-TRL components upon which to base system designs, so there was heavier reliance on parametric scaling to extrapolate to the component sizes that would be needed for the Maxwell aircraft. Specific design features required for the safety needs of manned were not yet established for these technologies so identifying manned aircraft safety needs was a product of the X-57 activity.

The evolution of advanced air mobility community needs led to a higher level of risk than anticipated. As development of individual components progressed and prototypes were produced, many gaps between the expected technical maturity and what was readily available from US aircraft manufacturers were identified. These potential shortcomings in the state of the art had been highlighted as risks to the subproject execution plan, and over the course of development of multiple core subsystems it became clear that these risks were being realized. Each of these risk areas required additional resources to close to develop components and subsystems that could be candidates for flight readiness.

Evolving NGOs impacted focus. While the project team revised the NGOs to maintain alignment with the rapidly changing stakeholder needs, this had a side effect of shifting the emphasis of the project activities which is time consuming and distracting to the team developing the aircraft systems. The original objectives were adapted into “design drivers” which were intended to establish that the built-to requirements of the aircraft systems were not modified, but there were still impacts as the publication products changed from specific design data to focus more on the process artifacts and lessons learned such as design reviews and the airworthiness approach details.

Early design decisions did not accommodate later revisions to the SIP. The subproject was formulated to build a vehicle with a “5x improvement in efficiency” as responsive to Thrust 4 (Transition to Low-Carbon Propulsion) of the ARMD SIP. As the SIP evolved to emphasize focus on vertical takeoff and transport-class aircraft, the research focus of X-57 on enabling technologies on what would become known as Regional Air Mobility (RAM) was not directly related to the new Research Thrusts.

A high level of effort was required to map to the revised ARMD SIP. The process to update the research activity of the X-57 subproject to map to the revised Strategic Thrusts at each round of continuation assessments was time consuming and impacted the research focus. The day-to-day activities on the project did not always clearly trace to ARMD’s vision while reformulating the X-57 NGOs.

The X-57 team struggled to convey the value of DEP research to the Program. As this research area and industry segment was new as the project was forming, there were no legacy advocacy channels within NASA (researchers to Projects and Programs) or in industry (to NASA or to other agencies or legislators). This made it difficult to substantiate the technology gaps in the state of the industry, and for NASA to identify which gaps were appropriate for NASA investment.

2.6.3 The Lessons Learned from the Evolution of Advanced Air Mobility Community Needs

Changing Needs may require reformulation. The disruption caused by changing the root of the requirements traceability network could be avoided by halting project execution and reformulating to a clean sheet of updated Project Needs and then deriving fresh Goals, Objectives, Mission Concept, and System Requirements. This would also be disruptive but would make subproject activities explicitly aligned with the external stakeholders driving the changing Needs such as a revised SIP or industry evolution.

"Spiral" development activities should reduce the risk surrounding an end product much like traditional technology maturation approaches. Spiral development can rapidly iterate through component challenges, but system integration complexities are easy to miss and also impactful, especially for new technologies. As the NGO environment evolves, the risk driving the "spirals" may need re-evaluation to ensure that the "spiral" is still reducing the risk of the end product.

Emerging markets are not as effective at identifying/advocating for research needs. The X-57 research leads were tightly embedded with industry counterparts including civil aviation authorities, consensus standards developers, and academics. This gave the subproject team detailed insight into the industry needs and technology gaps that were most pressing, but that perspective was not well understood in the larger aeronautics research and technology community at NASA.

Emerging industry leaders were reluctant to admit reliance on X-57 data products. There is a fundamental tension for early adopters of emerging technology to publicly amplify the potential benefits and optimistic roadmaps even when there remain critical obstacles that require research investment. These barriers are often freely discussed in private when investors or regulators are not in the room but that limits the visibility of NASA's contribution. In the case of X-57, many companies are building upon the electric and distributed propulsion research produced by this subproject activity, but they did not effectively communicate that to NASA leadership at the Program and Directorate levels and did not understand that their reliance on continued X-57 progress was not accounted for in NASA portfolio management. This, coupled with the "lower volume" of an emerging industry's voice, is not heard as much as the "higher volume" of an established, larger market.

2.6.4 The Recommendations Based on the Lesson from the Evolution of Advanced Air Mobility Community Needs

Re-evaluate Goals, Objectives, and assumptions when Needs evolve: Large shifts in high-level subproject Needs or in the subproject risks must be accompanied by a re-evaluation of the rest of the subproject activity that flows from the Objectives. Needs will need more frequent review when supporting emerging aeronautics markets, and technology development risks will be more common during spiral development activities of fundamental technology.

Re-evaluate team (including leadership) skill mix as risks are realized and NGOs evolve: The type of expertise to conduct integration and aerodynamic research is obviously different than that required to develop high voltage electronics, but there was not a clear signpost in the case of X-57 for when the project focus changed from the former activity to the latter. More frequent review of the skill mix in comparison to the expected work would help identify these gaps.

If research activity changes how it maps to the SIP, consider reformulation: If the project relevance to industry changes enough, it may be time to reset and reformulate. While this might be disruptive in the short term, it could result in better alignment and products in the longer term when accompanied by systems engineering validation.

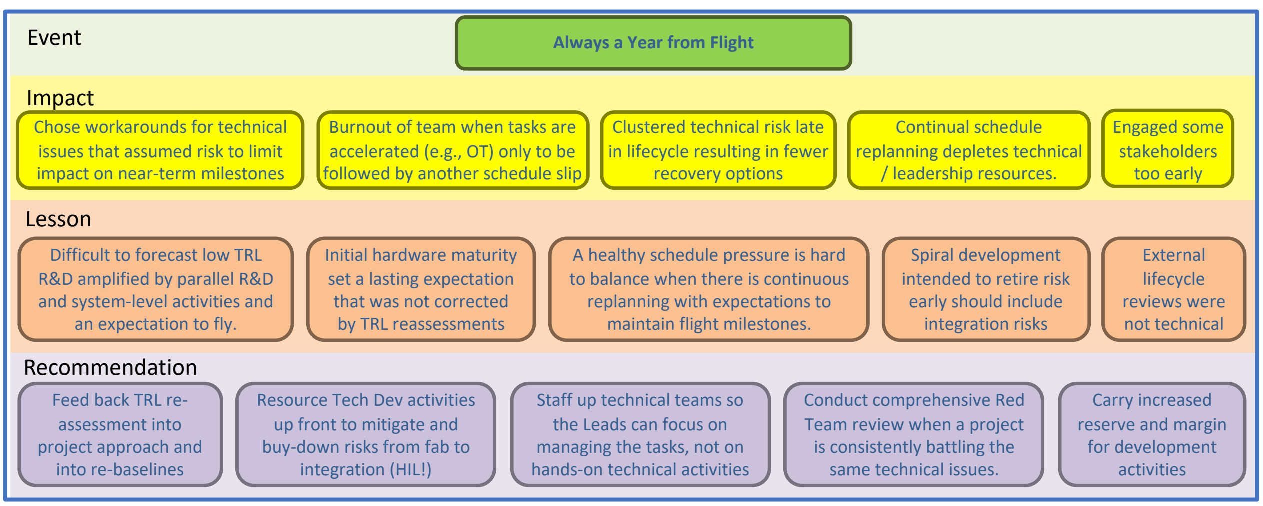
Enable industry advocacy with objectives relevant to emergent pain points: The close interaction between the technology gaps in industry and the X-57 publication and sharing was highly effective and actionable. As the project activity responded to the needs of adopters being expressed in private and small group settings, the industry groups began to build their development plans around the published X-57 researched plans. When this could be documented and reported within NASA it was valuable.

Incorporate emerging market impacts when revising the SIP: When forming the SIP, industry views from *EMERGING MARKETS* should also be considered. The SIP lagged the needs of the industry in this emerging market space, and the X-57 struggled to map to the SIP because it was targeting research thrust gaps that had not yet been identified in the SIP. Industry wants to rely on NASA to close technology gaps, but emerging companies soliciting investment capital can't admit it publicly. The volume of the industry's voice in a small emerging market is less than that of a large market.

2.7 Always a Year from Flight

As mentioned in other events, the culture of CAS (VC-like investment decision-making and spiral development vs. defined technology maturation plans) instilled a schedule pressure, or pace, early in the life of X-57 that became an expectation that was hard to overcome after transitioning to a project (FDC) that requires additional rigor to get a manned X-Plane to flight. As integration and unplanned subsystem development challenges hindered the ability to maintain steady progress to first flight the subproject found themselves continually one year from flight for the last six years of the ten-year lifecycle. Figure 13 summarizes the Impacts, Lessons, and Recommendations associated with the "Always a Year from Flight" event.

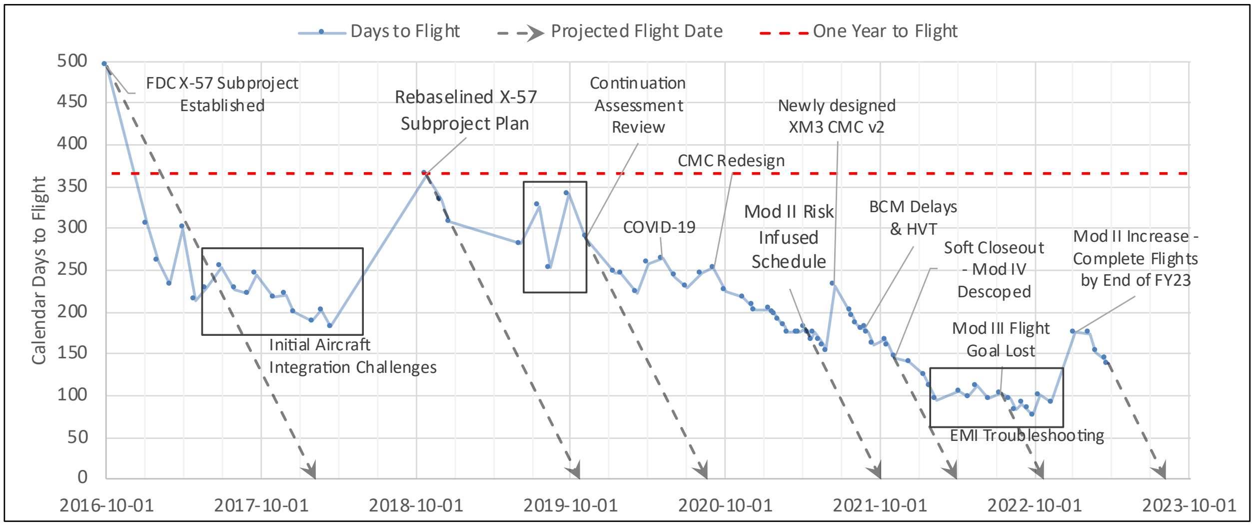
Figure 13, Always a Year from Flight



2.7.1 The Event that Triggered the Always a Year from Flight Lesson

This event is, perhaps, an impact of the collective "Events" reported in this document. There was pressure to hold the flight milestone while addressing challenges without reducing the subproject scope. The initial assessment of higher TRL was a foundational contributor to this event. Through the course of the subproject, it was as though the team was always one technical challenge away from flight, in other words, "…this is the last thing to resolve." Figure 14 shows the days forecasted to X-57's Mod II first flight. The first forecast in October 2016, is reflective of when the FDC subproject for X-57 was established, indicating 500 days to the first flight of Mod II.

Figure 14, X-57 Mod II First Flight Forecast from 2016 through 2023



2.7.2 The Impact of Experiencing the Always a Year from Flight Event

When an issue was encountered, with the milestone of the first flight in the perceived near term, the subproject chose workarounds to overcome technical issues that assumed either programmatic or technical risk to limit the impact on the near-term milestones. These workarounds were vetted within the project to be feasible stand-alone solutions that were assessed from both a programmatic risk perspective and an airworthiness perspective (system safety) perspective. As an example, given the amount of time it would have taken to stop redesigning and test a CM, the team chose a progressive approach to operationally mitigating hazards (i.e., additional inspections, limiting ground testing prior to hardware replacements) when hardware issues arose in 2018, 2021 and 2023. The battery defect was discovered early enough in the lifecycle that there was time to redesign it. Hindsight tells us that redesign time placed an increased risk on the subproject, such that there would not be time later in the lifecycle to overcome additional subsystem development challenges. The high-lift (HL) systems had time for technology maturation mostly because of Mod II subsystems slipping, allowing schedule for the dedicated HL team to mature the HL system. Given the perceived near-term Mod II flight milestone, decisions were made to mitigate challenges rather than stop to redesign and test individual subsystems. Pausing to redesign these systems would have allowed for more sustained development of the technology that was on the critical path to the Mod II flight.

This approach to mitigating challenges by introducing workarounds placed technical risk late in the lifecycle of the subproject, resulting in fewer recovery options due to the lack of time to execute those recovery options. For example, the CM rotor issues were “resolved” operationally which delayed a root cause discovery until years later in the subproject when there was little appetite for additional schedule.

The subproject was continuously reacting to technical or subsystem development challenges and could not pause to assess the collective impacts of challenges. A constant “push to flight” schedule can’t be endured long-term, and the interview data indicated that this was extremely hard on the team. Burnout of team members is a high risk when tasks are accelerated, or specific teams are asked to work overtime to make up the schedule only to be followed by another slip to the schedule because of a new subsystem development challenge. Interview data showed that personnel were discouraged when asked to work overtime on their tasks when they believed that another subsystem was at a high level of risk of not meeting their optimistic schedules. It was difficult to communicate the integrated workflow to the entire team in a way that expressed the need for prioritization and conveyed importance. As an example, the operations team is, by the nature of a development effort, on the critical path at the end of the task lifecycle conducting aircraft integration and testing, and when risk reduction is not conducted early, the expectation of success during final integration and test is placed on the operations team.

Early in the subproject, no funding was available for an “iron bird,” which would have allowed for off-aircraft testing, thus mitigating risks early and off the critical path of testing on the aircraft. The residual risk of not investing in an “iron bird” was accepted by the subproject. This lack of an “iron bird” did not allow for early risk mitigation with developmental components. This forced integration testing to be conducted using flight components on the flight vehicle, and did not address a full system integration risk or allow for incremental development and testing.

*“*It’s a lot of work to be behind.*”* With the schedule slipping so often, re-planning to move resources to parallel tasks or accelerate or delay efforts to use the available bandwidth was time-consuming for the leadership team Uncovering one subsystem development challenge at a time also resulted in engaging some stakeholders too early which resulted in losing time on premature planning. For example, the Flight Readiness Review (FRR) for Mod II was rescheduled three times, and team members had to develop and update material for the FRR each time. Additionally, engaging the systems integration team at a point where progress toward flight was being made only to encounter a new subsystem development challenge resulted in this systems team being underused while the needed development team was understaffed.

Comprehensive replanning was challenging. Technical teams were saturated with the need to address subsystem development challenges and tended to have the resources and personnel to resolve these one at a time. This serial, reactionary response consumed more time and resources than a top-down technology maturation approach.

2.7.3 The Lessons Learned from the Always a Year from Flight

It is difficult to forecast the effort required to mature low TRL subsystems to a TRL suitable for a manned flight demonstrator. This is further amplified when executing parallel subsystem development and system-level activities with an expectation to fly. This is an example of compounding risk.

The initial hardware maturity set a lasting expectation that was not corrected by TRL reassessments. If the TRL drops, it is important to reassess the TRL and the system-wide impacts actively. The team needed to look across the entire system rather than triaging one thing at a time. The team did not have time to pause and be deliberate. Additionally, the team would have benefitted from considering how a drop in TRL impacted the airworthiness approach and likewise the impact to cost and schedule.

A healthy schedule pressure is hard to balance when there is continuous replanning with expectations to maintain flight milestones. Often times maintaining pace and progress toward a milestone as documented by a schedule is a difficult balance between applying an appropriate amount of pressure to continue efficient forward progress that applies a tolerable level of stress on the team and applying heavier pressure that, although it may continue forward progress, induces an unhealthy level of stress on the team which in the long run may hurt the quality of the work. Not only will it hinder the efficiency of forward progress, but it weighs on team morale. Repeated replanning without allowing relief in the schedule or relief in scope introduces a high risk of team burnout.

A spiral development approach, intended to retire subsystem development risk using an iterative approach, should also include a scalable approach to addressing integration risks, including integration testing using development hardware in an appropriate environment (e.g., an "iron bird"). Expectations of the propulsion system TRL at CAS baseline (flying products quickly adaptable) were not reset when the subproject scope changed to develop US-based products from scratch.

External lifecycle reviews were not focused on assessing the technical state of the subsystems. While "red team" reviews/continuation assessments were performed, the technical and development challenges continued to hinder the subproject. The red team reviews conducted for the X-57 subproject did not assess TRL and what was left to mature the subsystem. They looked closely at the schedule and documented risks related to the schedule.

2.7.4 The Recommendations Based on the Lesson from the Always a Year from Flight

It is recommended that TRL re-assessments be incorporated into the subproject approach and fed into re-baselines.

Technical development activities should be afforded appropriate up-front resources to mitigate and buy down risks from fabrication to integration (e.g., an "iron bird" is critical to eliminate early integration risk for newly developed components).

It is also recommended that technical teams be staffed to allow for the lead to focus on managing and leading the work and development within their discipline as opposed to doing the technical work. Having a dedicated lead focused on managing affords the leadership team an additional team member to manage tasks and schedule down-and-in as well as communicate up-and-out to the leadership team. This may help communicate within the discipline teams the integrated approach of the overall schedule and alleviate some team stress when asked to work over-time to complete a task. Additionally, it will provide bandwidth of the lead to support schedule replanning efforts without impacting technical work that would need to continue in parallel with replanning.

Conducting comprehensive "red team" reviews when a project is consistently battling the same type of technical issues is also recommended. Additionally, conduct deep-dive TRL re-assessments at baseline updates, such as program transitions and continuation assessments. A project team should consider verification by an independent red team or board of SMEs.

Apply reserve at formulation commensurate with the risks that are identified. As the subproject encounters new or realizes existing risks, reassess the reserve posture and determine whether reserves should be adjusted or if descoping is needed. An independent assessment of the project scope and plans may aid in determining an "adequate" level of reserve.

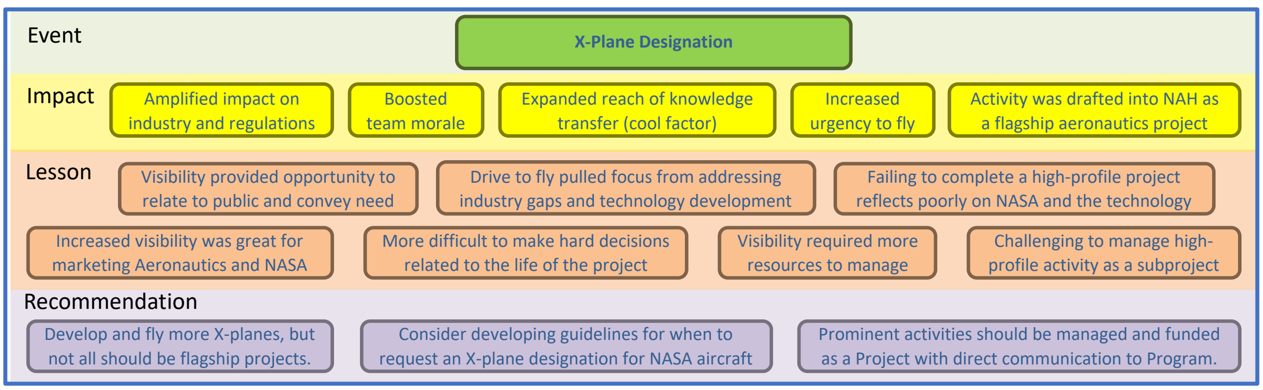
2.8 X-Plane Designation

The SCEPTOR project was awarded an X-Plane designation, X-57, in June of 2016. Separately, in 2017, the New Aviation Horizons (NAH) Initiative was developed in parallel and ultimately added the X-57 subproject to the initiative. Figure 15 illustrates the breadth of the NAH. Figure

16 summarizes the Impacts, Lessons, and Recommendations associated with the "X-Plane Designation" event.

Figure 15, New Aviation Horizons Initiative

Figure 16, The X-Plane Designation



2.8.1 The Event that Triggered the X-Plane Designation Lesson

The "X" designation for X-57 was announced while the subproject was transitioning into FDC and out of CAS. This process, although approved and granted through the Air Force process and vetted within AFRC, was not coordinated with ARMD. In addition to gaining the X-Plane designation, which alone attracts additional visibility, that visibility, was amplified by NAH, which stated: "the centerpiece of NASA's 10-year acceleration for advanced technologies testing is called New Aviation Horizons, or NAH. It is an ambitious plan to build a series of five mostly large-scale experimental aircraft – X-planes – that will flight test new technologies, systems, and novel aircraft and engine configurations."[3]

2.8.2 The Impact of Experiencing the X-Plane Designation Event

The X-plane designation further catalyzed the aerospace research community's interest in electrified propulsion seriously and amplified the impact on industry and regulations. The X-57

[3] *New Aviation Horizons Initiative and Complementary Investments* (NP-2016-06-2167-HQ). (2017). National Aeronautics and Space Administration. Available at https://www.nasa.gov/wp-content/uploads/2017/11/nasa-aero-10-yr-plan-508-reduced.pdf (last accessed 2 December 2024)

was featured in several AIAA events, and the work of the X-57 team received greater influence in the development of the Advanced Air Mobility (AAM) market. The AIAA partnered with IEEE and formed the Electrified Aircraft Technology Symposium, which continues today, and the ARMD established the AAM Mission Office.

The designation boosted team morale and induced excitement not only within the team but also externally. The X-designation brought attention from the public in a way that the public could relate to the need for an electric aircraft. There was an expanded reach of knowledge transfer brought on by the “cool factor” of an X-plane. This amplified visibility and increased NASA’s urgency to fly the aircraft in the context of the NAH initiative.

The inclusion in NAH was unexpected by the subproject team. The added visibility of the designation and inclusion in the NAH initiative resulted in an undocumented impression of the X-57 becoming a flagship X-plane for NASA.

2.8.3 The Lessons Learned from the X-Plane Designation

The increased visibility provided an enhanced opportunity to relate to the public and convey the need of the X-57 subproject. Similarly, the visibility provided great marketing for the good work of Aeronautics within NASA.

The drive to get to flight pulled focus from addressing industry gaps and conducting technology development that X-57 uncovered out of a necessity to electrify the aircraft.

The added visibility resulting from the X-plane designation required more resources to manage. With added visibility comes added reporting and status briefings to many layers of management. Therefore, information was filtered through several layers of management that provided opportunities to introduce gaps in communication. As a subproject it was challenging to manage a high-profile activity.

Additionally, failing to complete a high-profile project reflects poorly on NASA as well as on the technology.

2.8.4 The Recommendation Based on the Lesson from the X-Plane Designation

NAH noted that NASA should develop and fly more X-planes, but not all X-planes are necessarily flagship projects. Pushing the realm of possibility should accommodate failure in a way that does not reflect poorly on the agency.

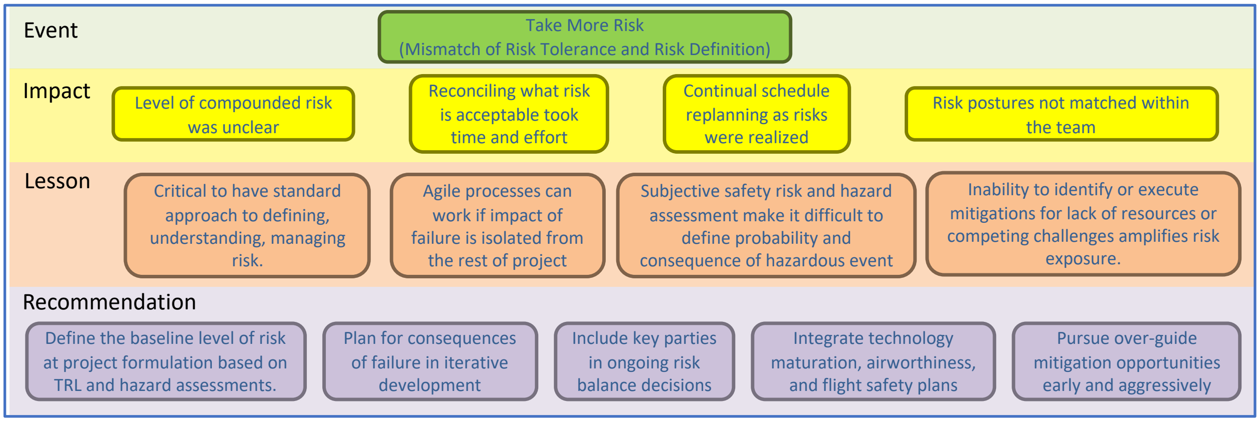
Consider developing guidelines for when to request an X-plane designation for NASA aircraft to ensure the project is scoped, funded, and staffed appropriately to meet expectations and requirements.

It is recommended that prominent activities be managed and funded as a Project with direct communication to the parent Program to avoid opportunities to introduce gaps in communication.

2.9 Take More Risk

The X-57’s origins within the CAS subproject embraced a higher programmatic and technical risk tolerance than traditional NASA flight projects, which led to a team and management culture to “take more risk.” The transition to a more traditional NASA flight project structure in FDC introduced a mismatch in risk tolerance and definition within the X-57 team and among subproject and center leadership. Figure 17 summarizes the Impacts, Lessons, and Recommendations associated with the "Take More Risk" Event.

Figure 17, Take More Risk



2.9.1 The Event that Triggered the Take More Risk Lesson (Mismatch of Risk Tolerance and Risk Definition)

Throughout the subproject's lifecycle it became apparent there was a mismatch of risk tolerance and risk definition with the implicit direction to "take more risk" from external leadership. The message of "take more risk" was instantiated under CAS. As part of CAS, the subproject was formulated with a "high-risk/high-reward" approach that encouraged taking technical and programmatic risks to meet ambitious goals. Part of this approach under CAS was encouraging the team to reimagine how to accomplish the mission, not just tailor existing processes. As noted in the Project Transition from CAS to FDC event, CAS followed a VC model where failure was expected of a number of activities within its portfolio, so higher risk was to be expected from an individual activity like SCEPTOR. The transition from CAS to FDC did not establish a clear change in risk tolerance under the FDC project which led to confusion within the team. Following the transition to FDC, the message from external leadership to "take more risk" was intended to push the team to get to flight as soon as possible while meeting the airworthiness needs required of a flight project. Throughout the subproject's lifecycle, the meaning of "take more risk" was not documented and not understood within the team or with external stakeholders.

The "take more risk" message affected all aspects of the subproject's approach to programmatic, technical, and safety risk management. Without a clear understanding of what "take more risk" meant, the subproject's risk tolerance was continually misunderstood both internal and external to the team. It was unclear to team members if the "take more risk" approach applied to the Risk Management Process (RMP) used to manage the programmatic and technical risks, or if it applied to the System Safety process, or both.

2.9.2 The Impact of Experiencing the Take More Risk Event

The "take more risk" message resulted in some technical and programmatic decisions that resulted in compounding risk. It was difficult to evaluate the compounded level of risk on the subproject when a baseline understanding of risk tolerance was unclear and had changed from the formulation and initial execution under the CAS project to later execution under the FDC project.

Significant time and effort were spent reconciling and communicating the different perceptions within the subproject team and with NASA Leadership regarding what level of risk was acceptable. In addition, "take more risk" was understood by some team members to include omitting some processes for faster execution in lieu of the assurance the process might provide. This led to conflicts within the team as the subproject moved to incorporate more of the legacy NASA airworthiness processes vs. the "high-risk" plan formulated early in the subproject's life cycle.

Risk postures were not matched within the team. For example, the team was challenged during system safety discussions associated with defining an acceptable failure rate and failure outcome of the experimental X-57 propulsion system. Some team members perceived a lakebed landing following an engine failure as an unacceptable safety risk as well as programmatic risk (loss of program due to mishap investigations, etc.) whereas other team members considered this to be a low-impact event. There was no consensus on the subproject and statements by external leadership were unclear in terms of providing guidance. Neither the subproject nor NASA leadership shared a common understanding of how to define an acceptable level of safety, programmatic, or technical risk.

2.9.3 The Lessons Learned from the Take More Risk Event

It is critical for a subproject team to have a standard approach to defining, understanding, and managing risk. The X-57 subproject team began to more formally track risks partway into execution as an FDC subproject, and in doing so, the team was better able to identify and mitigate programmatic and technical risk. However, the very high level of risk load realized early on, particularly when the team was required to shift from subsystem integration to actual subsystem development for so many critical subsystems, meant that risk was often realized despite mitigations and planning.

The "take more risk" approach did pay off with the agile approach used for battery development. The subproject chose a startup manufacturer with little experience for this scale product, and they saw the original design fail, only to be iterated, and a year later, they produced battery storage modules that changed the state of the art for the entire market. A more traditional development approach would likely have taken longer and consumed more resources, though the result would be more assured.

Subjective (in lieu of quantitative) safety risk and hazard assessment make it difficult to define the probability and consequence of a hazardous event occurring. A qualitative hazard assessment is possible when all involved in the process share a common understanding of the hazards and what is an acceptable level of safety risk. Without that common understanding, there is no consensus and endless debate as to what risks are acceptable.

The inability to identify or execute mitigations for lack of resources or competing challenges amplifies the risk exposure. For example, an electromagnetic interference (EMI) and electromagnetic compatibility (EMC) risk could have been mitigated early in the project by conducting subsystem development and integration activities with an "iron bird" lab setup. This mitigation approach was not taken as the team did not have the resources to develop these test setups, nor was the level of risk fully understood. As a result, significant resources were expended during aircraft integration testing to identify and address the EMI challenges.

2.9.4 The Recommendations Resulting from the Take More Risk Event

It is recommended that the baseline level of risk be defined at subproject formulation based on TRL and initial hazard assessments. A technology readiness assessment will allow for all stakeholders to understand what development tasks are required along with the scope of the efforts. An understanding of the hazards will allow for the stakeholders to define what constitutes an acceptable level of safety risk. With an understanding of the required development efforts and a common safety definition, the stakeholders can have a realistic discussion as to what level of baseline risk the subproject should work to.

It is further recommended to plan for consequences of failure in iterative development. Challenges inevitably arise when developing and integrating subsystems, and the subproject should be scoped to include adequate schedule and budget reserves to account for these challenges. An independent assessment of the subproject scope and plans should be conducted by independent personnel to aid in determining what level of reserves are "adequate." This assessment should examine not just the schedule and budget reserves, but also the subsystem TRL and maturation plans.

Include key parties in ongoing risk balance decisions. A common definition of risk along with ongoing discussions are necessary to ensure all stakeholders understand the risks that a subproject is operating with.

Integrate technology maturation, airworthiness, and flight safety plans. Following the initial technology readiness and hazard assessments, it is recommended the formulation team develop a plan to mature the technology and demonstrate airworthiness and flight safety. This integration effort should lay out required subsystem TRL maturation at key project milestones and detail how airworthiness and flight safety requirements will be met.

Pursue over-guide mitigation opportunities early and aggressively. Project resources tend to be fixed and lagging in terms of matching additional mitigations to realized risks. Over-guide opportunities can be an effective means of supplementing project resources to buy down technical risk.

3 Recommendations

The X-57 subproject has developed three recommendations from the lessons learned exercise. These recommendations are related to overarching takeaways associated with Compounding Risk, Subproject Formulation and Execution, and Knowledge Transfer.

3.1 Compounding Risk

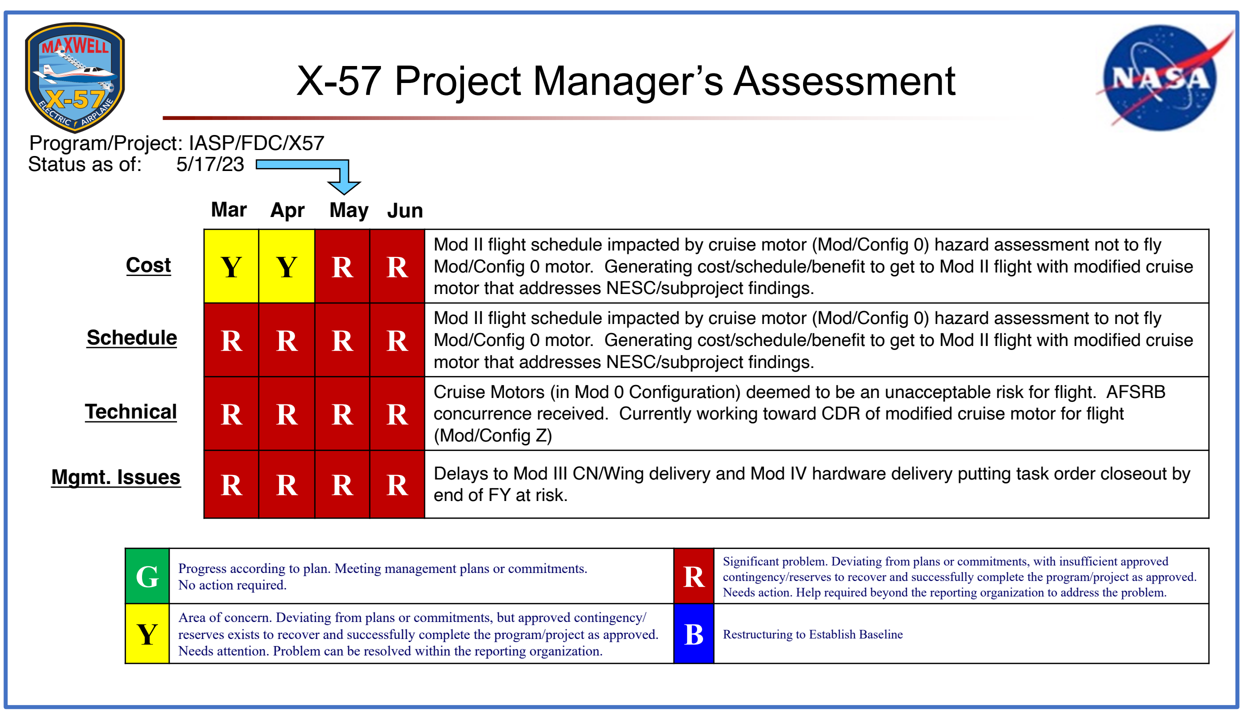
Risks are not necessarily stand-alone, and they tend to interact in complex ways. The compounded level of risk is difficult to fully assess, but it is certainly greater than the sum of the individual risks. As detailed throughout this report, the X-57 subproject carried many risks with few mitigation options. Figure 18 illustrates how five of the events discussed in this report combined to create compounding risk to the project. Individually, each of these events and their associated risks presented a challenge, and the magnitude of that challenge only increased when the project was forced to address all of them simultaneously. The subproject has concluded that the current risk management process as identified by FDC and IASP and the associated risk matrix does not provide an effective mechanism to communicate compounded risks.

Figure 18, The Overarching Lesson of Compounding Risk

To communicate the impact of compounded risks more effectively on project execution, the "Project Manager's Assessment" summary chart as developed for and briefed at the integrated Center Management Council briefings is a good example of a way to assess an overall risk level that the project is running. This summary chart provides a snapshot of the project cost, schedule, technical, management issues, and overall risk level that can be used in conjunction with the programmatic risk matrix to communicate the magnitude of the compounded challenges. Figure 19 shows the X-57 subproject Manager's Assessment Chart, dated May 17, 2023.

This example clearly shows the subproject was experiencing several challenges at the time, but what is not clear is the level of compounded risk that was exacerbating the project's abilities to address these challenges. The addition of an **overall risk assessment** to the chart would provide the subproject a forum to communicate the compound nature of the programmatic risks alongside the individual risk matrix.

Figure 19, X-57 subproject Manager's Assessment Chart



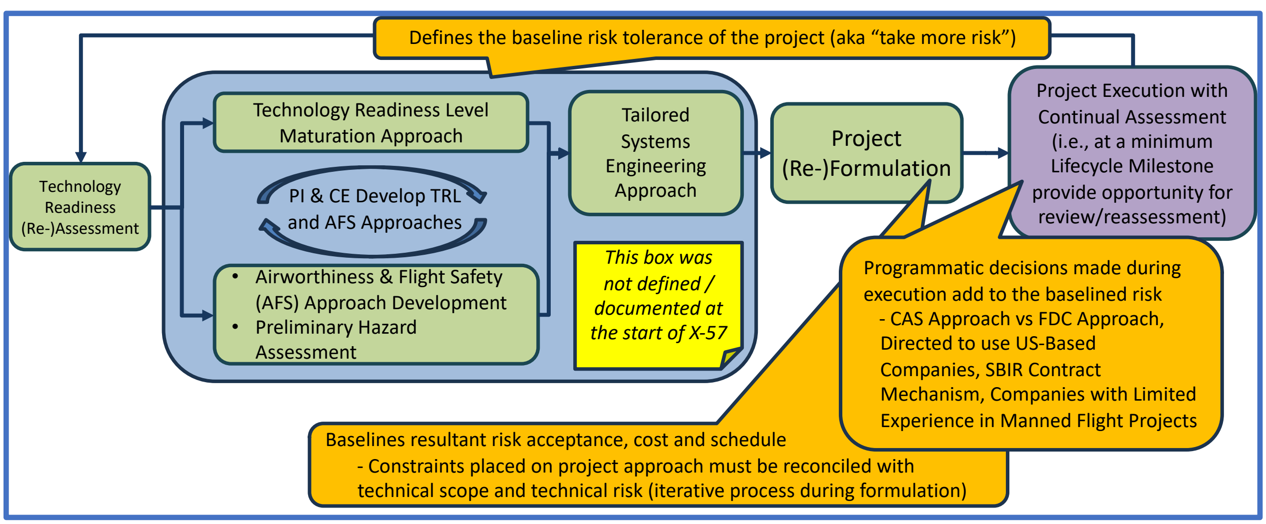
	Mar	Apr	May	Jun	
Cost	Y	Y	R	R	Mod II flight schedule impacted by cruise motor (Mod/Config 0) hazard assessment not to fly Mod/Config 0 motor. Generating cost/schedule/benefit to get to Mod II flight with modified cruise motor that addresses NESC/subproject findings.
Schedule	R	R	R	R	Mod II flight schedule impacted by cruise motor (Mod/Config 0) hazard assessment to not fly Mod/Config 0 motor. Generating cost/schedule/benefit to get to Mod II flight with modified cruise motor that addresses NESC/subproject findings.
Technical	R	R	R	R	Cruise Motors (in Mod 0 Configuration) deemed to be an unacceptable risk for flight. AFSRB concurrence received. Currently working toward CDR of modified cruise motor for flight (Mod/Config Z)
Mgmt. Issues	R	R	R	R	Delays to Mod III CN/Wing delivery and Mod IV hardware delivery putting task order closeout by end of FY at risk.

G	Progress according to plan. Meeting management plans or commitments. No action required.	R	Significant problem. Deviating from plans or commitments, with insufficient approved contingency/reserves to recover and successfully complete the program/project as approved. Needs action. Help required beyond the reporting organization to address the problem.
Y	Area of concern. Deviating from plans or commitments, but approved contingency/ reserves exists to recover and successfully complete the program/project as approved. Needs attention. Problem can be resolved within the reporting organization.	B	Restructuring to Establish Baseline

3.2 Subproject Formulation and Execution

In hindsight, many of the events and impacts experienced by the X-57 subproject may have been mitigated during formulation or by implementing a robust assessment and feedback process during subproject execution. With this in mind, the first step of formulating a new manned flight subproject should be to complete a detailed technology readiness assessment as this defines the starting point of the project. This assessment should then be reviewed by independent subject matter experts to provide a verification of the assessment. The next step is an iterative development of a defined TRL maturation plan, an Airworthiness & Flight Safety (AFS) approach, and a preliminary hazard assessment are necessary steps to develop a tailored systems engineering process. These iterative steps are where the baseline risk tolerance of the subproject is defined, and this definition is used to set what "take more risk" means for the subproject. Once the preferred technical approach and risk tolerance is defined, the subproject undergoes formulation where the contracting approach, cost, schedule, and resources are estimated based on the technical approach and proposed risk tolerance. Key to a successful project formulation is having a good understanding of the technical approach and the associated risks. During the project formulation step, constraints will be placed on the subproject in terms of schedule, resources, and other necessary elements, all of which must be reconciled with the technical scope and baseline risk as part of an iterative process to arrive at a viable subproject plan. The subproject formulation plan should also be reviewed by independent personnel. Once a subproject has transitioned to execution, a continual assessment of the subproject's progress, scope, and technology readiness is required by both subproject personnel, stakeholders, and independent subject matter experts. This assessment should be completed at a minimum at lifecycle milestone reviews and whenever there is a change in scope or significant development challenges arise. Figure 20 illustrates a recommended formulation and execution approach for future NASA manned flight projects based on the lessons learned by the X-57 subproject.

Figure 20, Continual Assessment Throughout the subproject Starting with a Solid Baseline



3.3 Knowledge Transfer

The enduring legacy of the X-57 subproject is the vast amount of technical information produced by the team associated with distributed electric propulsion technology. This information has been widely shared through many dozens of public documents and presentations[4] at technical conferences and workshops, most of which are available on the NASA Technical Report Server (NTRS). Beyond this, the X-57 subproject engaged in detailed interactions with other U.S. government agencies and directly participated with regulatory and standards bodies associated with determining the airworthiness and operational requirements for electrified aircraft. These publications and engagements were not a byproduct; these were deliberate objectives that drove the subproject activities.[5]

As discussed in the Evolution of Advanced Air Mobility Community Needs lesson, the X-57 subproject was executed during a time of transient technology development associated with electrified propulsion as used for Advanced Air Mobility operations. As other electrified propulsion technologies were developed and operated outside of the X-57 subproject, the subproject objectives pivoted from demonstrating that distributed electric propulsion aircraft were possible to the use of the X-57 as a public reference platform for new analysis tools, assurance methods, and test techniques associated with distributed and electric propulsion technologies. A challenge with any new technology effort in aerospace lies in safety assurance – regulators and operators do not have a broad enough historical database to inform necessary changes in certification approaches. By establishing detailed public data on the X-57, regulators and standards organizations could access this data without running afoul of ongoing proprietary efforts to develop similar technology. This, in effect, enabled concurrent development of technology by Advanced Air Mobility manufacturers with assurance methods used by standards organizations and regulators. The data, experiences, and participation of X-57 team members within standards organizations were a small but important part of bringing nascent electrified aircraft propulsion technology into more widespread public use.

These interactions and publications were targeted based on persistent involvement of X-57 team members in the Advanced Air Mobility space. Rather than focus on static objectives, the team members were highly active in conferences, workshops, and consensus standards organizations associated with Advanced Air Mobility. This enabled the X-57 subproject to identify which of its ongoing activities associated with the design, development, and airworthiness assurance of the X-57 aircraft could have the most impact in the Advanced Air Mobility space. In fact, the X-57 subproject elevated knowledge transfer discussions and status as part of the overall project meetings, and had personnel dedicated in part or whole to survey this emerging technology landscape and manage involvement associated with development of consensus standards for distributed and electrified aircraft propulsion technology, integration, and flight performance.

A final recommendation of this section is that future NASA flight projects emulate this highly successful model for effective knowledge transfer. This is not simply an objective for a static project or report as a milestone, but rather a comprehensive and "living" approach for continuous engagement with the community of interest. Without this continuous engagement, the X-57 subproject would not have been even modestly impactful. However, through continued publication, engagement, and re-assessment of targeted community needs (in this case, the Advanced Air Mobility community), the X-57 subproject was able to influence the appropriate

[4] Many of these papers and presentations can be found at https://www.nasa.gov/x57/technical/ (last accessed 18 November 2024).

[5] S. Clarke, N. Borer, V. Schultz, "X-57 Knowledge Transfer and Wrap-Up," Spring meeting of ASTM Committee F44 on General Aviation, Cologne, Germany, April 2024. Available at https://ntrs.nasa.gov/citations/20240003422 (last accessed 18 November 2024).

research community even with the absence of flight and remains an ongoing and powerful influence on advancing key standards to enable electric propulsion.

4 Conclusion

It should be noted that although the X-57 subproject did not achieve flight, the focus on achieving flight enabled the team to gather and share relevant technical and operational lessons and data with industry and regulators. Maintaining flight as an objective drove testing and analysis rigor that led to more discovery. The impact of the X-57 lies not in what was originally set out to achieve, but that the subproject identified and addressed technology and certification gaps in industry that needed to be filled. The lessons learned were foundational to electrified propulsion and built up electrified aircraft US small businesses and enabled commercial products. The X-57 subproject advanced the Nation's ability to design, test and determine airworthiness of distributed electric and aero-propulsive coupling technologies, which is a critical enabler of emerging advanced air mobility markets. The subproject had a significant impact on industry and standards/regulations despite the absence of flight.

The X-57 subproject contributions have been substantial, especially compared to the level of investment. The subproject elevated the electric propulsion TRL of components leading to integration testing of hardware with flight performance specifications. The publishing approach of the subproject was early and frequent and included the sharing of design tools, component and subsystem test data, and operational lessons learned with academia and industry.

The X-57 subproject prime contractor and their subcontractors grew, in part, because of X-57. The motor subcontractor is currently working through certification of a full-scale flight demonstration. The battery system subcontractor commercialized the X-57-series battery systems and continues to advance the product line, and the prime contractor grew substantially during execution and has integrated quality assurance practices (AS9100 certification) into their company.

Additionally, the subproject had a wider impact across the electrified aviation space, including industry, regulators, and academia. The published architecture is a principal reference for academia and standards development. The design and test standards and lessons learned are being adopted, with the impact on regulations and standards ongoing as operational constraints drive further learning.

In short, the X-57 subproject ***HAS*** advanced the Nation's ability to design, test, and determine airworthiness of electrified aircraft technologies. The X-57 subproject produced significant technical insights and developed and established best practices that will significantly benefit future electric aircraft research and technology flight research projects. The subproject also learned hard lessons from its inception as a CAS effort and its transition into a FDC subproject. The lessons learned and associated recommendations are documented in this report, along with the driving events and their impacts, which led to the formulation of the lessons and recommendations.

Appendix A – Acronyms and Abbreviations

Acronym	Defined
AAM	Advanced Air Mobility
AFRC	Armstrong Flight Research Center
AFS	Airworthiness & Flight Safety
AFSRB	Airworthiness and Flight Safety Review Board
AIAA	American Institute for Aeronautics and Astronautics
ARMD	Aeronautics Research Mission Directorate
BCM	Battery Control Module
CAS	Convergent Aeronautical Solutions
CDR	Critical Design Review
CE	Chief Engineer
CM	Cruise Motor
CMC	Cruise Motor Controller
COTS	Commercial, off the shelf
DEP	Distributed Electric Propulsion
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ERB	Engineering Review Board
FDC	Flight Demonstrations and Capabilities
FFP	Firm Fixed Price
FRR	Flight Readiness Review
FY	Fiscal Year
GRC	Glenn Research Center
HL	High Lift
HLMC	High-Lift Motor Controllers
HQ	NASA Headquarters
IASP	Integrated Aviation Systems Program
IDIQ	Indefinite Delivery Indefinite Quantity
IEEE	Institute for Electrical and Electronics Engineering
IPT	Integrated Product Team
KDP	Key Decision Point
LaRC	Langley Research Center
LEAPTech	Leading Edge Asynchronous Propeller Technology
NAH	New Aviation Horizons
NASA	National Aeronautics and Space Administration
NGOs	Needs, Goals and Objectives
PDR	Preliminary Design Review
PI	Principal Investigator
PM	Project Manager or Project Management
POP	Period of Performance
PWS	Performance Work Statement
QA	Quality Assurance
RAM	Regional Air Mobility

Acronym	Defined
RMP	Risk Management Process or Risk Management Plan
SBIR	Small Business Innovative Research
SCEPTOR	Scalable Convergent Electric Propulsion Technology and Operations Research
SE	Systems Engineering
SIP	Strategic Implementation Plan
SME	Subject Matter Expert
SOW	Statement of Work
TACP	Transformational Aeronautics Concepts Program
TRL	Technology Readiness Level
US	United States
VC	Venture Capital