X-57 Systems Engineering Lessons Learned

Laura K. Kushner[1], Ted B. Holtz[2]
NASA Langley Research Center, Hampton, VA, 23681, USA

Ethan Baumann[3] and Claudia Sales[4]
NASA Armstrong Flight Research Center, Edwards, CA, 93523, USA

The X-57 Maxwell is an electric aircraft based on a 4-passenger, twin engine Tecnam P2006T General Aviation aircraft. The X-57 project originally envisioned a straightforward integration of commercial-off-the-shelf hardware components and software into a novel configuration to demonstrate the aerodynamic and performance benefits of Distributed Electric Propulsion (DEP). The project was initially started with a high-risk venture capitalist approach under NASA's Convergent Aeronautics Solutions (CAS) project, which led to an initial philosophy of Project Management "light" (which was then interpreted as Systems Engineering (SE) "light"). As the project matured, it was forced to transition to one with increasing SE-rigor as the project scope changed, hardware and software deficiencies were found, and the team realized the magnitude of the technical and integration challenges. In hindsight, these technical challenges came in part from an overly optimistic technology readiness assessment (TRA) at the beginning of the project, which resulted in the project assuming that little to no subsystem development would be required. The project's approach to systems engineering evolved throughout three separate informal phases of the project as it underwent two key transitions as a result of the team wrestling with the technical challenges and resultant changing project scope. This paper discusses the assumptions, approaches, and challenges encountered from a Systems Engineering standpoint in each of the three informal phases of the X-57 project. This paper also provides recommendations on how future projects can apply Systems Engineering best practices upfront along with a realistic TRA to aid projects that find themselves with similar challenges.

I. Nomenclature

ATI	=	Asymmetric Thrust Inhibitor
ARMD	=	Aeronautics Research Mission Directorate
BCM	=	Battery Control Module
BM2	=	Original CMC configuration
CAS	=	Convergent Aeronautics Solutions
CDR	=	Critical Design Review
CE	=	Chief Engineer
ConOps	=	Concept of Operations
COTS	=	Commercial, off-the-shelf
DEP	=	Distributed Electric Propulsion
ERB	=	Engineering Review Board
ESAero	=	Empirical Systems Aerospace
FDC	=	Flight Demonstrations & Capabilities
FRR	=	Flight Readiness Review
MCR	=	Mission Concept Review
NASA	=	National Aeronautics and Space Administration
NGO	=	Needs, Goals, and Objectives
ORR	=	Operational Readiness Review
OE	=	Operations Engineer

[1] Aerospace Engineer, Engineering Integration Branch D-208, non-member
[2] Aerospace Engineer, Engineering Integration Branch D-208, non-member
[3] Aerospace Engineer, AFRC X-57 Project Chief Engineer, non-member
[4] Aerospace Engineer, AFRC X-57 Project Deputy Chief Engineer, non-member

OEM	=	Original Equipment Manufacturer
PDR	=	Preliminary Design Review
PI	=	Principal Investigator
PM	=	Project Manager
SCEPTOR	=	Scalable Convergent Electric Propulsion Technology Observation and Research
SIP	=	Strategic Implementation Plan
SDR	=	System Definition Review
SE	=	Systems Engineering/Systems Engineer
SEMP	=	Systems Engineering Management Plan
SRR	=	System Requirements Review
TA	=	Technical Authority
TRA	=	Technology Readiness Assessment
TRL	=	Technology Readiness Level
XM3	=	Final CMC configuration

II. Introduction

The X-57 subproject began under the NASA Convergent Aeronautics Solutions (CAS) project with the goal of flying a distributed electric propulsion (DEP) system. The X-57 subproject is hereafter referred to as the X-57 project or simply the project. DEP technology uses multiple electric-powered thrust sources placed throughout an aircraft, allowing for unique aerodynamic configurations with potential for significant performance benefits. The initial project philosophy under CAS was that of a venture capitalist type “start-up” with a high-risk, high-reward mentality resulting in a project management and systems engineering “light” approach, as demonstrated by the project’s minimal initial documentation and rigor in process. Shortly after project formulation, the team discovered that the Technology Readiness Level (TRL) for the required commercial-off-the-shelf (COTS) electric aircraft subsystems was not as high as initially assessed by Industry. This mis-assessment caused the project to embark on unplanned subsystem development efforts, which presented several technical challenges that the existing project team did not have the appropriate skillsets to address.

Systems engineering is a discipline that includes aspects of both art and science to develop a realized product that functions as required to achieve an objective. The science aspect of SE includes several processes or elements, seven of which are discussed in this paper, that are applied to develop a product. The art aspect of SE comes in terms of how to apply those elements and to what level of rigor. The elements of SE were always present within the X-57 project, but the artful application of those elements changed significantly as the technical scope of the project and the magnitude of the required subsystem development efforts grew. Over time, the project team shifted towards a more rigorous systems engineering approach that was able to identify and slowly overcome some of the technical challenges presented by the immature subsystems, which required unplanned subsystems development efforts not initially scoped during project formulation. A rigorous SE process is best applied from the very beginning of a project’s lifecycle, and it is difficult to implement in later stages. The X-57 project did experience success with applying a more rigorous SE approach, however it was implemented very late in the project and was therefore not as effective as it could have been had a similar approach been implemented earlier before multiple disconnects in objectives and requirements were designed into the system. This paper discusses the X-57 project’s three distinct functional phases of SE, the challenges the project experienced in applying seven elements of systems engineering, and a short series of recommendations for future projects.

III. Project Overview

The X-57 project started in 2015 as a follow-up to previous CAS efforts to develop and demonstrate DEP technologies. The activity that became the X-57 project was part of the CAS project’s inaugural set of activities, as it had just been established about the same time as the X-57 seedling project began. NASA had previously conducted a ground validation demonstration as part of the Leading-Edge Asynchronous Propeller Technology (LEAPTech) project, called Hybrid Electric Integration Systems Test (HEIST), which had been provided by ESAero as lead contractor [1]. The purpose of HEIST was to mature the Technology Readiness Level (TRL) of distributed electric propulsion technology. This demonstration integrated eighteen small electric motors and propellers onto a wing which was mounted onto a large truck and driven at speed over the dry lakebed at the NASA Armstrong Flight Research Center. The demonstration showed that by blowing air over the lifting surface, the high-aspect ratio wing would provide more lift at lower speeds (aerodynamically similar to the concept of “blown flaps”). In 2016, HEIST evolved into a Small Business Innovative Research (SBIR) flight demonstrator project called Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR), which set out to prove distributed electric propulsion on a manned General Aviation aircraft under CAS. The SBIR was awarded to ESAero, who served as the prime contractor and lead integrator. As part of the high-risk, high-reward approach under CAS, SCEPTOR expected to follow a similar Project Management (PM) “light” approach to the product development lifecycle as an attempt to streamline processes and accelerate time to first flight. The PM “light” approach resulted in a streamlining of the systems engineering process hereafter referred to as a SE “light” approach. During the SCEPTOR project formulation, the team performed a Technology Readiness Assessment (TRA), which determined that the required electric subsystems to integrate the Mod II vehicle all had a TRL of 5-6. TRL 5-6 indicates that subsystem development would not be required during the SCEPTOR project, and that the subsystems were ready for system integration. However, the project team experienced numerous challenges when attempting to integrate each subsystem onto the aircraft. In hindsight, the TRL of the required subsystems was much lower as evidenced by the project embarking on several significant subsystem technology development efforts. In hindsight, the PM and SE “light” approaches implemented early in the project lifecycle, and the incorrect assessment of the TRL of the required subsystems would have far reaching implications throughout the lifecycle of the project that the project would continually struggle to address.

By 2017 SCEPTOR had evolved from a small flight research project into a high-visibility NASA X-plane project; the X-57 Maxwell. The project also transitioned from CAS to NASA’s Flight Demonstrations & Capabilities (FDC) project, which was chartered to develop and maintain NASA’s Aeronautics Research Mission Directorate flight research assets. The X-57 project modified a stock Tecnam P2006T aircraft in successive development phases, or ‘Mods’, for risk reduction and to minimize upfront budgetary commitments. Figure 1 illustrates and summarizes the X-57 Mod configurations.

- In Mod I, NASA flew an instrumented Tecnam P2006T for baseline aircraft performance measurements. The HEIST project was also considered a part of Mod I as it demonstrated the potential benefits of DEP.
- For Mod II, NASA and the contractor team modified a separate Tecnam airframe using batteries and electric motors replacing the original gasoline-fueled engines, along with the associated support equipment and instrumentation to compare performance with the stock aircraft. Mod II was also intended to be a risk-reduction effort for the Mod III and IV configurations by providing a standard aircraft configuration in which to integrate the electric aircraft subsystems.
- In Mod III, NASA intended to replace the original equipment manufacturer (OEM) wing with a newly designed high aspect ratio, narrow chord, laminar flow wing, with the cruise motors moved to the wingtips. Figure 2 shows a comparison between the OEM aircraft wing to be flown in Mod II compared to the new DEP wing to be added as part of Mod III. The propellers in the Mod III configuration rotate to counter the wing-tip vortex to reduce induced drag. The intent was to compare the cruise performance against the OEM-winged vehicle.
- For Mod IV, high-lift motors and folding propellers would be added to the leading edge of the wing, to regain slow speed performance, with similar stall speeds to the OEM aircraft. Although these high lift propellers add small amounts of thrust, the intent is to progressively blow air over the wing at low speeds to increase lift. Figure 3 provides an illustration of the Mod IV configuration, which is the full X-57 aircraft configuration with all DEP related hardware installed. For more details on the design and performance of the aircraft see Borer, et. al [2].

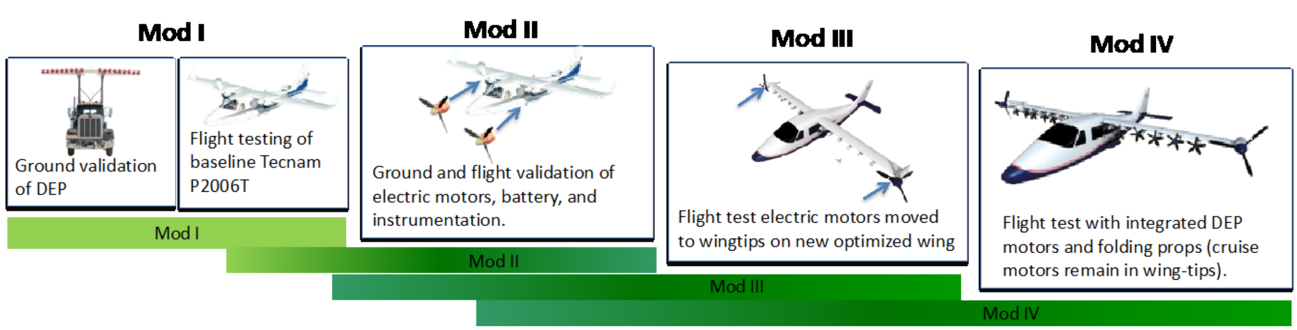

Figure 1 - X-57 Maxwell project evolution and phases.

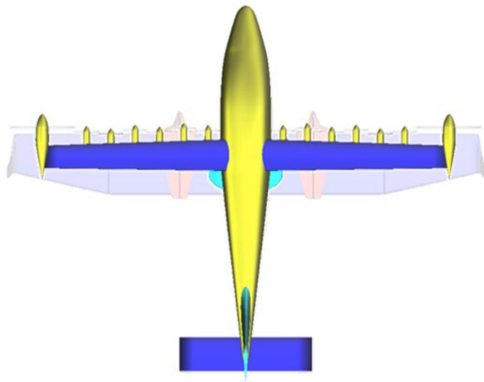

Figure 2 - X-57 Maxwell Mod IV overlayed on OEM aircraft

Figure 3 - X-57 Maxwell in the final Mod IV configuration

In 2015, the project was initially approved only for development of Mods I, II, and III. Mod IV development was formally approved in late 2017. At project kickoff, the contractor was expected to procure commercially available subsystems (electric cruise motors, cruise motor controllers, and a battery system), conduct subsystem verification and integration activities, and deliver a flight-ready Mod II aircraft with the NASA role limited to conducting minimal system-level verification activities prior to starting flight-test activities. Challenges with this approach became apparent starting in 2018 when it became clear the Mod II configuration was not going to meet the current planned delivery date since integration efforts had been delayed. The delayed integration efforts were partially due to challenges with the subsystems, which were unable to be tested or integrated due to technical issues. As a result of the issues with the subsystems, the team had to shift their focus to unplanned work required to address subsystem deficiencies resulting from the initial overly optimistic TRA.

Over the next five years, the project underwent several periods of replanning activities as it became increasingly apparent that the planned flight schedules were not going to be met as the team required additional time and resources to raise the TRL of the required subsystems. Relevant events in the timeline of this five-year period are discussed below.

- Starting in 2018, the project began to bring an increasing amount of subsystem development work in-house to NASA and attempted to apply standard PM and SE management techniques to the project.
- In late 2019, NASA took delivery of the non-airworthy Mod II aircraft and assumed integration responsibilities as well, thus increasing the technical scope of the work done by NASA and the mix of skillsets required for the unplanned development. Also in 2019, NASA set a firm end date for the project of September 30, 2023.
- The COVID pandemic slowed on-aircraft work starting in March of 2020, but counterintuitively was a benefit to the project. The pandemic was an external factor outside of the project's control that provided much needed schedule relief, which allowed the project leadership team to refocus the team on addressing the undeniable technical challenges instead of being pressured to fly. However, the continual technical challenges resulted in further slips to the flight schedule.
- During the Summer of 2021, flight of the Mod IV configuration was de-scoped from the project as it became clear there was not an achievable path to complete first flight of the Mod IV configuration by the end date as the project wrestled with several unplanned subsystem development and integration challenges.
- In the Fall of 2022, NASA de-scoped flight of the Mod III configuration for the same reasons as the de-scope of Mod IV.
- In the Summer of 2023, the project was working to address the latest in a series of subsystem challenges, with the latest challenge being the discovery of latent design issues with the cruise motors, which required a lengthy modification to be made airworthy. NASA elected to not extend the project past the September 30, 2023, end date, which resulted in a decision to not fly the Mod II aircraft.

IV. Systems Engineering

NASA defines "systems engineering" as a methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system [3]. "Systems engineering requires the [artful] application of a systematic, disciplined engineering approach that is quantifiable, recursive, iterative, and repeatable for the development, operation, maintenance, and disposal of systems integrated into a whole throughout the life cycle of a project or program." [4] Systems engineering at NASA follows the NASA process lifecycle as defined in NPR 7123.1[5]. A typical project follows a standard timeline from system concept to disposal, which can be tailored/customized as needed with concurrence of NASA stakeholders to fit the scope of work. The SE process defines the maturity of products needed throughout the life cycle and provides a framework to set up and plan the technical work. This is done regardless of project size, then the formality and rigor of the work is typically tailored to meet the size of the project. Systems engineering is a defined process that is most useful when employed early in the project when there is ample opportunity to set a firm strategy for development that can be managed upfront. The cost associated with fixing problems and discrepancies goes up exponentially the later problems are identified, and early intervention helps avoid the cost and delays associated with rework. Rework of a specific subsystem also often results in parts of the project being idle while a smaller part of the project is focused on the rework leading to additional costs.

The systems engineering process is also a useful tool to ensure effective communication between different organizations and subsystems teams. Systems engineering is often described through a "V" diagram (See Figure 4), which breaks down the technical effort across the development lifecycle into three discrete phases: design, build, and verification. As one moves through the "Systems Engineering V", the system is progressively defined in greater detail down to the component and part level. Once the lowest level items are built, each level of the design is progressively verified through test, inspection, demonstration, or analysis at higher levels of integration until the final product is complete.

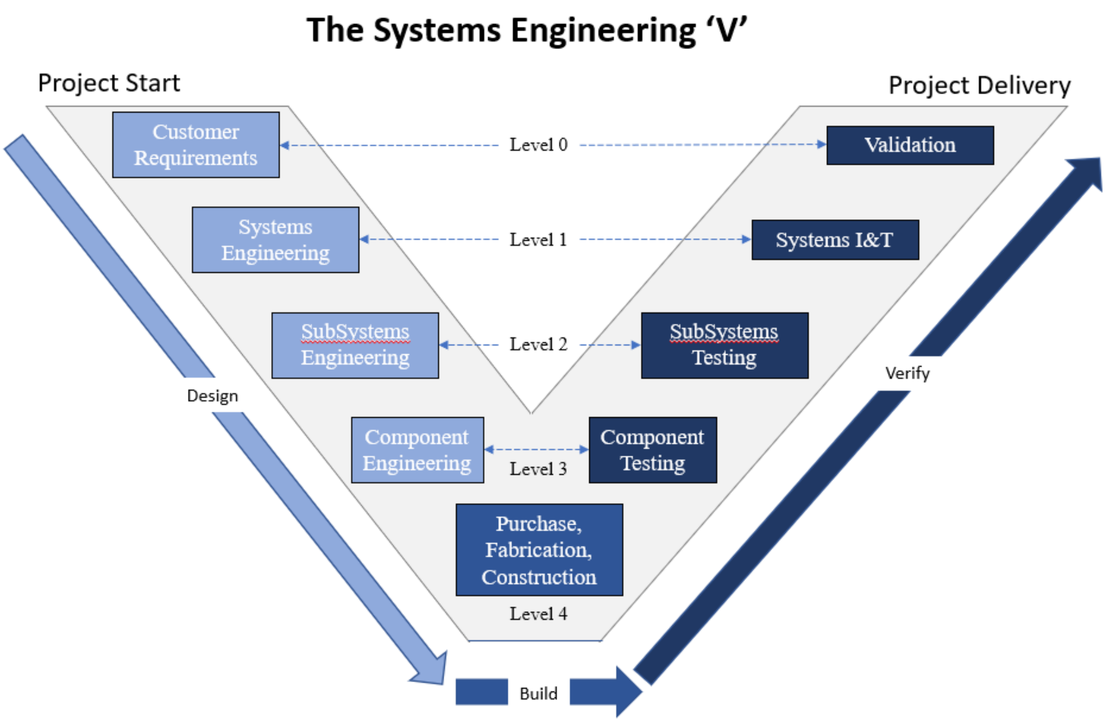

Figure 4: The Systems Engineering 'V' diagram.

NASA matures a system through a series of design phases, with each stage concluding with a designated review board that presents findings to the appropriate decision authority who then authorizes the program to proceed. The scope of the project is used to determine the set of required technical reviews, each with their own entrance and success criteria. The lifecycle reviews may include an outside/independent review board depending on the scope of the project. These reviews are used as gates to determine readiness to proceed to the next phase of the project.

Because the X-57 project was initially conceived with a high-risk, high-reward approach and as mainly a COTS integration effort, the project did not expect to need to follow a traditional lifecycle. The project followed a SE "light" approach meaning some traditional methods were employed, but X-57 performed them with less formality and rigor than specified by the NASA SE process. As the project experienced two significant transitions first from CAS to FDC and then with the addition of more rigor, the story of SE on X-57 can more accurately be broken down into three distinct, informal phases throughout which increasing levels of rigor were applied, rather than the typical lifecycle phases.

V. Project Systems Engineering Phases

The evolution of the X-57 Project's approach to systems engineering can be traced by examining the project during three distinct phases that are unique to the X-57 project and do not a follow typical project phases at NASA; hereafter referred to as Phases A, B, and C. In this section, each Phase is described in terms of the accomplishments, team make-up, systems engineering approach, and challenges. Subsequent sections track the evolution of the seven key elements of systems engineering across the phases and discuss, in detail, the impact on the project along with potential approaches for course correction.

VI.1. Phase A: Project Start – A Research Objective Driven Project

Phase A of the X-57 project began with the project's inception under the Convergent Aeronautics Solution (CAS) Project in April of 2015 and ended with the transition to the Flight Demonstrations & Capabilities (FDC) Project in October of 2016. During this timeframe, the X-57 project completed a Mission Concept Review (MCR), Systems Requirement Review (SRR), and a Preliminary Design Review (PDR). The project completed each of these reviews and proceeded into the next phase by meeting a highly tailored version of the guidance laid out in the NASA SE handbook, NASA SP-2016-6105 or in the AFRC Chief Engineer (CE) Handbook. The handbooks describe how the SE requirements of NPR 7123.1 should be implemented. A prime contractor was also put in place as an extension of an existing Phase III SBIR contract.

The X-57 project was founded with the goal of completing a fast-paced integration and flight-test effort to demonstrate the benefits of DEP technology. The focus of the project in the startup phase was on a shifting set of technical objectives to demonstrate a goal of achieving 5X lower energy use when compared to an equivalent existing general aviation aircraft. X-57 was meant to be a fast-paced COTS (assumed) integration project with a timeline of 3.5 years from start to finish. At the time of kickoff as part of CAS, the X-57 project was only approved through the Mod III configuration, but the project team was primarily focused on the full Mod IV configuration as that is the full DEP implementation. The project was founded on the assumption that the required technologies for the Mod III and IV vehicle configurations were at a minimum at a Technology Readiness Level (TRL) of 4 or 5, which indicates that minimal subsystem development would be required and that the real challenge lay in integrating Commercial Off-The-Shelf (COTS) components into a custom-built DEP wing. Figure 5 illustrates the NASA TRL definitions as defined in Reference [6]. Figure 6 illustrates a typical development approach that culminates in a X-plane technology demonstration flight to advance key technologies to a TRL of 7. This figure illustrates how X-57 was departing from a typical development process by attempting to fly lower TRL subsystems. When the project was kicked off, the approach was to buy COTS motors, controllers, and batteries from European companies, which were leading the electric aircraft industry at the time. Shortly after project kickoff, NASA management directed the project to procure hardware from American companies to stimulate the nascent American electric aircraft industry. This significant change in project scope resulted in the contractor issuing subcontracts to U.S. companies that did not have direct, relevant experience associated with the necessary hardware. The project would later discover that the TRL for the required subsystems available from the selected contractor team was lower and was more accurately assessed as 2 or 3.

In keeping with the high-risk, high-reward start-up focus of CAS, the Project Management (PM) "light" approach was interpreted as requiring minimal documentation. PM "light" led to Systems Engineering "light", which resulted in the usual process of developing Need, Goals, and Objectives (NGOs) not occurring, thus NGOs were not flowed down to requirements. Additionally, a formal Concept of Operations (ConOps) was not generated. The project instead developed a Goal that was loosely documented in a non-configuration controlled format in slides and drafted a set of specifications intended to guide the contractor in developing and integrating the airframe. Codifying the project's NGOs in a written formal document is a best practice as it allows for additional information to be provided for requirements definition and forces project teams to engage in the discussions that ensure a common understanding of what the team is trying to accomplish. This additional information typically includes topics such as rationale or further background details that are often not captured in slide format. Following PDR, the team was encouraged to codify the project NGOs and system requirements in writing, and this was accomplished as part of Phase B.

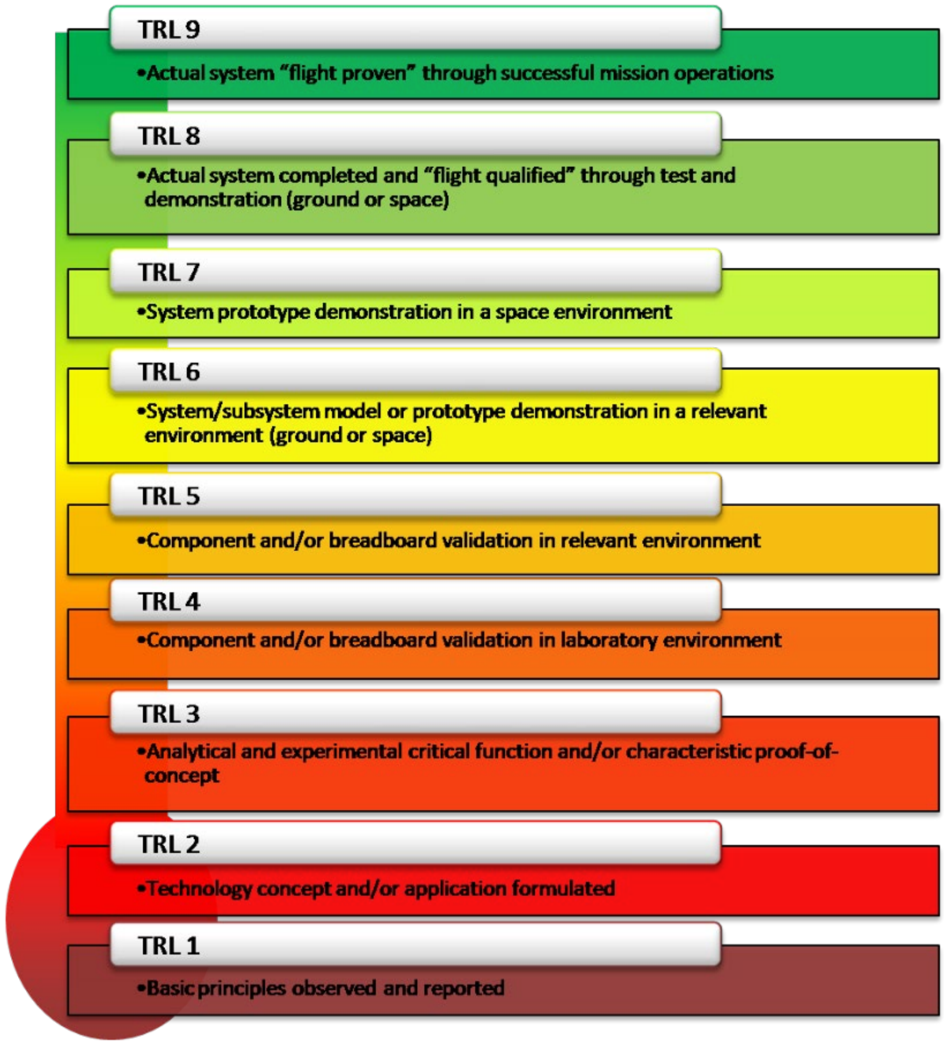

Figure 5: NASA TRL Definitions

CAS activities are led by a Principal Investigator (PI) who is responsible for establishing and managing the project vision and objectives; project planning, resource and contract management, and teaming; and overseeing the technical decisions. Typically, in most NASA projects, you would expect to have a Project Manager focus on programmatics/planning, a CE focus on the development of a system, and the PI focus on the use of the system post-development. This approach was appropriate in the beginning but found to be inadequate as the technical scope of the project increased.

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 "light") and systems engineering (systems engineering "light") tools and methods.

The SE team remained very small during this phase with only one person covering SE responsibilities at the same time as leading the Vehicle Integrated Product Team (IPT). During Phase A, a significant amount of the team's focus was solely on the design, analysis, and fabrication of the DEP wing by the contractor. The project team was structured around Integrated Product Teams (IPTs), with each IPT being focused on specific areas. For example, the Wing IPT was focused on the design, analysis, fabrication, and test of the Mod III DEP wing, and the Power & Command IPT was focused on the integration of the electric aircraft traction system components. The X-57 project team was very small throughout this phase, and both the NASA and contractor teams had limited experience with technology development and integration.

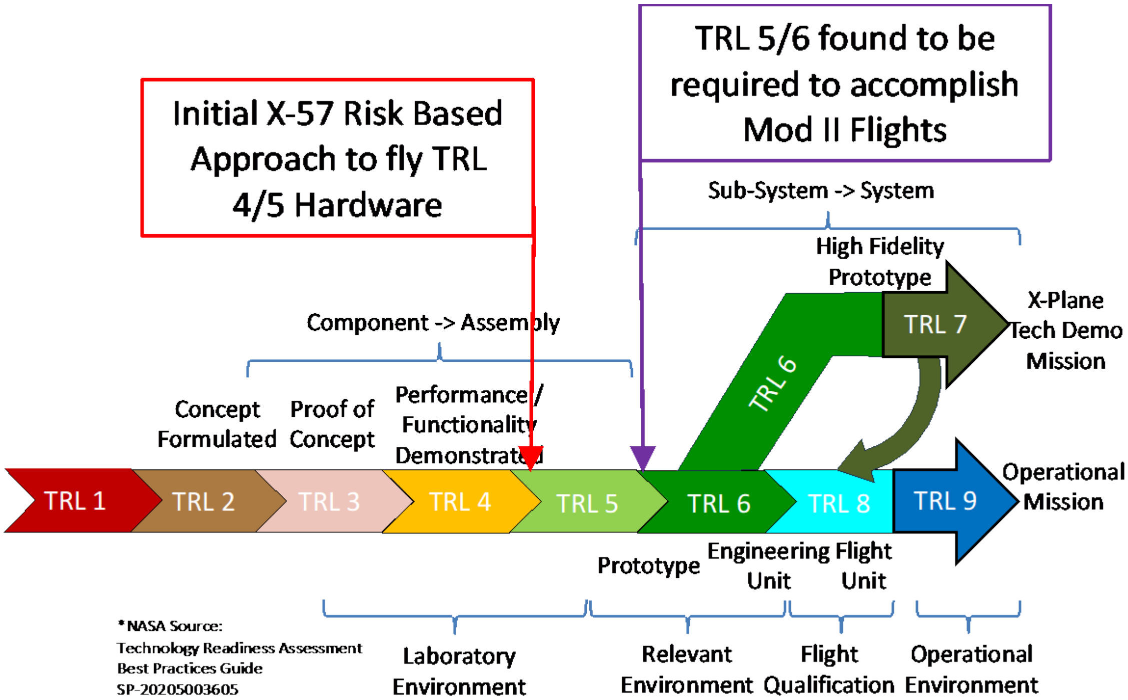

Figure 6: TRL Path to Flight

Phase A was the shortest in duration of the three project phases, but it had the most lasting impact as it set the foundation for the rest of the project's lifecycle. Systems engineering during Phase A was minimal, and this resulted in the team not being on the same page with the Need, Goals, and Objectives of the project, as they kept changing and were largely undocumented. The entire NASA and contractor team achieved tremendous progress with hardware prototyping and conducting a PDR, but the team was not sized or staffed with the appropriate skillsets for the unplanned subsystem development efforts due to missing the technology readiness during the initial TRA and not fully understanding how, in hindsight, the long-lasting impacts of that mis-assessment would affect the planned work The project team was under pressure to meet milestones in an effort to obtain funding for Mod IV and show progress leading to flight. . This pressure resulted in non-optimal decisions from a systems engineering standpoint, such as delaying critical subsystems development in favor of continued integrated systems work on the aircraft.

VI.2. Phase B: Design – An IPT-driven Technical Effort

Phase B of the X-57 project started in October of 2016 with the project transitioning to the FDC project and ended in January of 2018 with the beginning of a shift to a systems-based approach where technical and SE decisions are driven by the system development needs and not the use of the system. During Phase B, the project conducted a Critical Design Review (CDR), a delta-CDR focused on the Mod III DEP wing and obtained approval and funding to develop and flight-test the Mod IV configuration which represented the complete X-57 vehicle. The contractor team also began to procure various elements of the electric aircraft subsystems and attempted to begin integration activities.

As part of the transition to FDC, the project baselined the Objectives and Requirements Document (ORD), which stated the project goal and objectives along with laying out the system level requirements. Requirements for the various Integrated Product Teams (IPTs) were also generated. The specifications meant to guide the contractor in their development efforts were also baselined. Limited systems engineering support was available to the project and was focused primarily on developing the "cockpit ICD", which served simply to describe to the pilot and team members at a high level how the aircraft was to be operated, rather than serve as a document that fully described the connections of the interfaces in the cockpit.

As during Phase A, the project team worked to a highly tailored set of entry and exit criteria for design reviews as a result of the SE "light" approach. In hindsight, the tailoring of the review entry and exit criteria was to the extent that the independent review team was not able to delve into the technical details to the level necessary to identify deficiencies in the analysis and subsystem development approaches.

The team experienced challenges with every subsystem under development during Phase B. The most dramatic example is the development of the battery modules required to power the X-57. During a test meant to demonstrate the ability of the battery module to contain a single cell thermal runaway, the battery module experienced a significant fire that required a complete redesign of the battery module. As part of this redesign effort, a multi-disciplinary team of NASA subject matter experts (SMEs) from across the agency was brought in to aid the contractor team in addressing this design deficiency. The team was ultimately successful in redesigning the battery module, and the technology was successfully commercialized, resulting in one of the most visible examples of the benefit of X-57 to the American electric aircraft industry. In hindsight, the experience with the battery module was an indication that the team had overestimated the readiness of the required technologies along with the ability of the existing NASA & contractor team to develop and integrate the aircraft. This could have served as an indicator or an opportunity for the team to take a deeper look at the entire TRA of the aircraft and reevaluate the technical scope of work planned to complete the objectives.

During Phase B, the NASA team remained small for a project of this magnitude with one chief engineer and one additional person devoted part-time to systems engineering joining the project in the middle of Phase B. Technical decision-making authority shifted from the PI to the IPT leads. This shift served to dilute decision-making authority amongst numerous personnel on the project, with the Vehicle IPT typically being the forum in which consensus-based decisions were made. This flat structure and consensus-based approach to decision-making led to a negation of the utility of the typical SE process; when distributed amongst technical leads each PI, IPT, and/or subsystem lead will tend to prioritize the work of their system and not look for the interconnections and big picture perspective that a traditional SE approach led by a Lead Systems Engineer (LSE)) can ensure. The Systems Engineering Management Plan (SEMP), which describes the full scope of how the technical work will be performed, stated "Technical decisions that do not affect vehicle performance or contract scope, cost, and schedule will be made by consensus among the SCEPTOR engineering teams. Technical decisions that affect the overall aircraft performance, contract scope, cost, or schedule will be made by the SCEPTOR project office in conjunction with the Principal Investigator." This consensus-based approach to decision-making resulted in significant delays and confusion throughout the project, as the technical responsibility was distributed and therefore diluted.

The project team made tremendous progress during Phase B as evidenced by the successful redesign of the battery module, the start of the Mod III DEP wing fabrication, and initial ground testing by NASA of pre-delivery cruise motors and cruise motor controllers. Despite this great progress, the systems engineering challenges were starting to become clear as evidenced by the need to redesign key subsystems such as the battery modules.

VI.3. Phase C: Build & Verify – A System Development-Driven Technical Effort

Phase C of the project began in January of 2018 with the shift from an IPT-driven technical effort to one driven by Engineering Technical Authority, which in this case was the Project Chief Engineer and their deputy. Phase C concluded in June of 2023 when the project abandoned flight of the Mod II aircraft due to technical issues with the cruise motors. During Phase C, the project was forced to grapple with the impacts of PM and SE "light" during Phases A and B. A significant milestone during Phase C was the delivery of the Mod II aircraft to NASA in October of 2019. The aircraft was delivered in a non-airworthy state with no operable battery or propulsive system. The resulting impact of this unplanned aircraft integration and subsystem development challenges was a significant increase in the scope of work for the NASA team and required the team to take several steps back from a systems engineering standpoint and work to understand the subsystem requirements and interfaces. Typically, this requirements development is done early on in a project; not after the system has been delivered and is being integrated.

During the Spring and Summer of 2019, the team attempted to integrate and operate the Mod II aircraft. They experienced significant challenges with integrating and operating immature subsystems. They were able to successfully spin both motors using ground power, but only with a single Cruise Motor Controller (CMC) instead of the dual CMCs required to be operated for flight, due to hardware and software issues that were discovered during this time. The team was unable to operate the aircraft from battery power due to issues with the battery control modules. At this point, NASA elected to take delivery of the aircraft as it was. At the time of delivery, the project assessed the state of the aircraft as needing significant subsystem development and therefore not airworthy. These integration and development challenges were an indication of the realization of the technical risk seeded in Phase A resulting from the PM and SE "light" approaches in conjunction with the overestimation of the subsystem TRL.

In Phase C, the project NGOs were updated and formalized to accurately reflect a common understanding of the current vision for the project's technical effort. This update allowed for the project team and the stakeholders to have a consistent understanding of the project scope. Counterintuitively for a flight project, the Needs and Goals could be met without flying the X-57. However, without the rigor of a flight project that brings increased testing and a focus on airworthiness, X-57 never would have uncovered the challenges and lessons that it did. This change in scope reflected the impact the project had to date on the nascent electric aircraft industry and how that industry seemingly had grown past X-57 in most areas by leveraging the early lessons from X-57. The project elected not to invest the time or resources to flow the updated NGOs down to the system requirements based on an assumption that the System and IPT level requirements were adequate.

To address the technical and systems engineering challenges associated with developing the required subsystems, the project team grew greatly in size and range of skill sets during Phase C. Prior to the end of Phase C, the NASA team had grown significantly with six personnel making up the systems engineering team; a lead systems engineer who came on partway through Phase C, two part-time systems engineers, a part-time weight manager, and a chief and deputy chief engineer. In addition to increasing the number of NASA personnel, NASA Glenn Research Center (GRC) played an increasing role on the X-57 project. During the Summer of 2020, GRC team members stepped in to lead and support a growing number of subsystem development and analysis efforts. As project personnel were added during Phase C, the depth and breadth of the technical and systems engineering challenges resulting from the initial TRA were starting to hinder integration activities.

In order to visualize and communicate the scope of the challenges the team faced, the CEs developed the diagram shown in Figure 7, which provided an estimate of the state of each of the key subsystems required for each Mod six years into the project. Ideally, each of the subsystems for a Mod would be at the same level of maturity. Instead, what is seen for X-57 is a large spread with subsystems still being designed or even in the requirements phase while the aircraft is being integrated and tested. At the time, the project was under programmatic pressure to fly the Mod II configuration, begin Mod III integration activities, and complete development of the Mod IV subsystems. The project faced a tremendous challenge with attempting to complete the subsystem development activities while proceeding with integration activities. This approach was difficult, in part due to available project resources and the challenge of integrating an aircraft while the subsystems and their interfaces were in their final design phase.

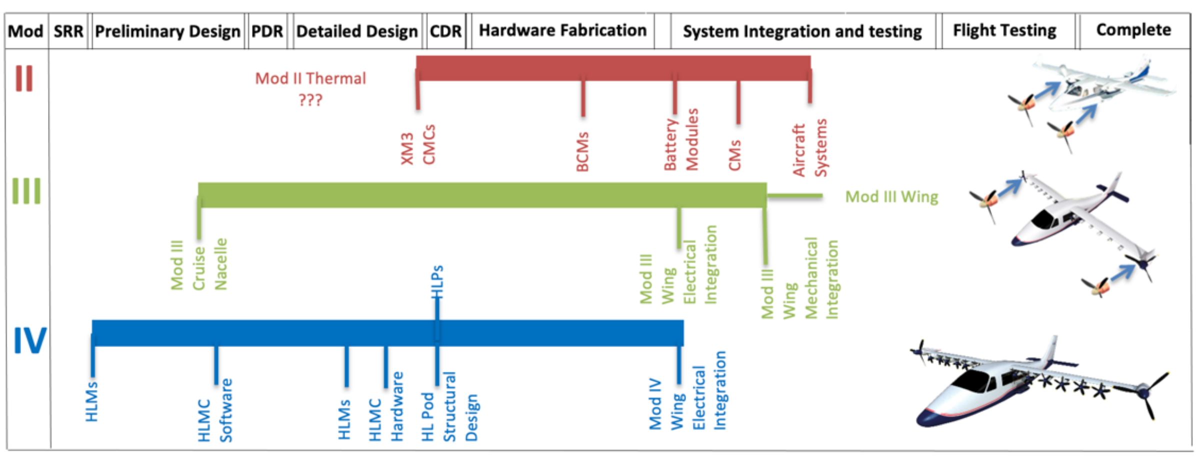

Figure 7: X-57 Subsystem Maturity as Assessed by CEs on 10/22/20.

To address this challenge, the project developed subsystem requirements for each element that needed to be redesigned along with implementing a robust independent review process. This approach allowed the team to understand what each subsystem needed to do, and the review process allowed for valuable external input on how the design was progressing. Counterintuitively, the COVID-19 pandemic aided the project team since it gave the engineers an opportunity to identify and begin to address the technical issues. This organic pause allowed some reevaluation of the scope of work and objectives, however in hindsight it was not extensive enough to uncover all the latent issues.

The project's systems engineering decision-making process and application of the art of SE underwent great changes during Phase C. The phase started with the addition of a Deputy Chief Engineer and a Deputy CE for Mod III/IV who both worked with the team to address the development and systems engineering shortfalls. In Mid-2020, all technical and systems engineering decisions began flowing through the CE and Deputy CE. This process was codified in the Fall of 2020 with the chartering of a Weight Engineering Review Board (ERB), which led to the chartering of the project ERB in the Spring of 2021. The addition of a Lead Systems Engineer (LSE) in the Fall of 2021 completed the transition to a more ideal systems engineering based approach.

The project's approach to design reviews changed significantly during Phase C by following NPR 7120.8 [7] tailored to aeronautics projects extensively, which provides clear guidance for review entry & exit criteria based on the NASA SE handbook. During Phase C, the project conducted a Mod IV PDR, with individually tailored entry & exit criteria along with the associated rationale. The review criteria had been developed to aid the review team in assessing the project's status, and they were used by the review team to clearly communicate potential pitfalls to the project. The project was unable to sufficiently address those development and integration pitfalls identified by the review team at PDR, and the result was the review team assessing that the project team did not successfully pass their Mod IV CDR. The use of the properly tailored review criteria allowed the review team to provide an accurate independent assessment of the state of the technical work for the first time. As a result of a programmatic decision to prioritize and focus resources on addressing Mod II and Mod III technical challenges, the project was not able to address the Mod IV pitfalls.

Each of the hardware and software subsystem elements being redesigned were now required to undergo formal design reviews. Prior to Phase C, subsystems were reviewed via informal Subsystem Tabletop Reviews (STTRs) with few to no independent reviewers. The use of formal subsystem design reviews, tailored entry & exit criteria, and formal subsystem requirements resulted in hardware and software being developed that could be successfully integrated onto the Mod II aircraft, such as the battery subsystem.

Subsystem and system level testing proved to be a continual challenge throughout Phase C as the project team worked to integrate the subsystems at varying levels of maturity. The early assumptions about the maturity of the technology resulted in the project team foregoing the development of an "iron bird"/system level test capability along with most subsystem level test capability. That assumption along with programmatic pressures to maintain a success-oriented schedule and budget resulted in subsystem development and integration activities being performed on flight hardware, which is a very inefficient approach and led to late realization of technical issues Under these pressures, decisions were made based on a schedule that reflected the project consistently a year from flight, leading the team to pursue inadequate solutions to design deficiencies instead of starting with a clean sheet design, which in hindsight would have been the faster approach instead of only partially fixing the issue.

Phase C resulted in the project team wrestling with the ramifications of the PM and SE "light" laid out in Phase A. First, Mod IV flights (Summer 2021) and then Mod III flights (Fall 2022) were de-scoped as it became apparent that completing the subsystem development and integration tasks would require more resources than the project team had available. Flight of the Mod II configuration was abandoned when it became apparent that latent design deficiencies in the cruise motors resulted in unacceptable safety hazards that the project had insufficient time and budget to address. Despite these challenges, the team was able to build on the foundation of clear subsystem requirements, a robust review process, and a clear decision-making process to address technical issues, which included EMI and thermal challenges, resulting in extended, successful ground runs.

VI. Key Elements of Systems Engineering

Systems engineering in practice requires elements of both art and science. The art aspect of SE is in how the project leadership tailors the team's technical and systems engineering approach to meet the project objectives. The science aspect of SE includes several elements that are used to ensure the team members have a clear understanding of what the system is required to do and how to ensure it meets those requirements. The evolution and challenges associated with each of the following SE elements is discussed below:

1. A clear project vision as evidenced by the Project Need, Goals, and Objectives. See Figure 8, Items 1 and 2
2. A Concept of Operations that provides guidance on how the vision is to be translated into hardware operations. See Figure 8, Items 1 and 2.

3. A clear set of requirements at the system and subsystem level that clearly map to each other and to the Project Objectives. See Figure 8, Items 3 and 4.
4. A verification and validation test approach which verifies requirements are fulfilled and validates that the system will meet the project objectives. See Figure 8, Items 6-8.
5. Configuration management processes ensure the state of the system is understood. See Figure 8, Item 14.
6. A robust decision-making process for the project leadership to apply the art of managing and tailoring the systems engineering approach. See Figure 8, Items 10-17.
7. A robust independent review process to identify and address project technical and systems engineering gaps. See Figure 8, Items 16.

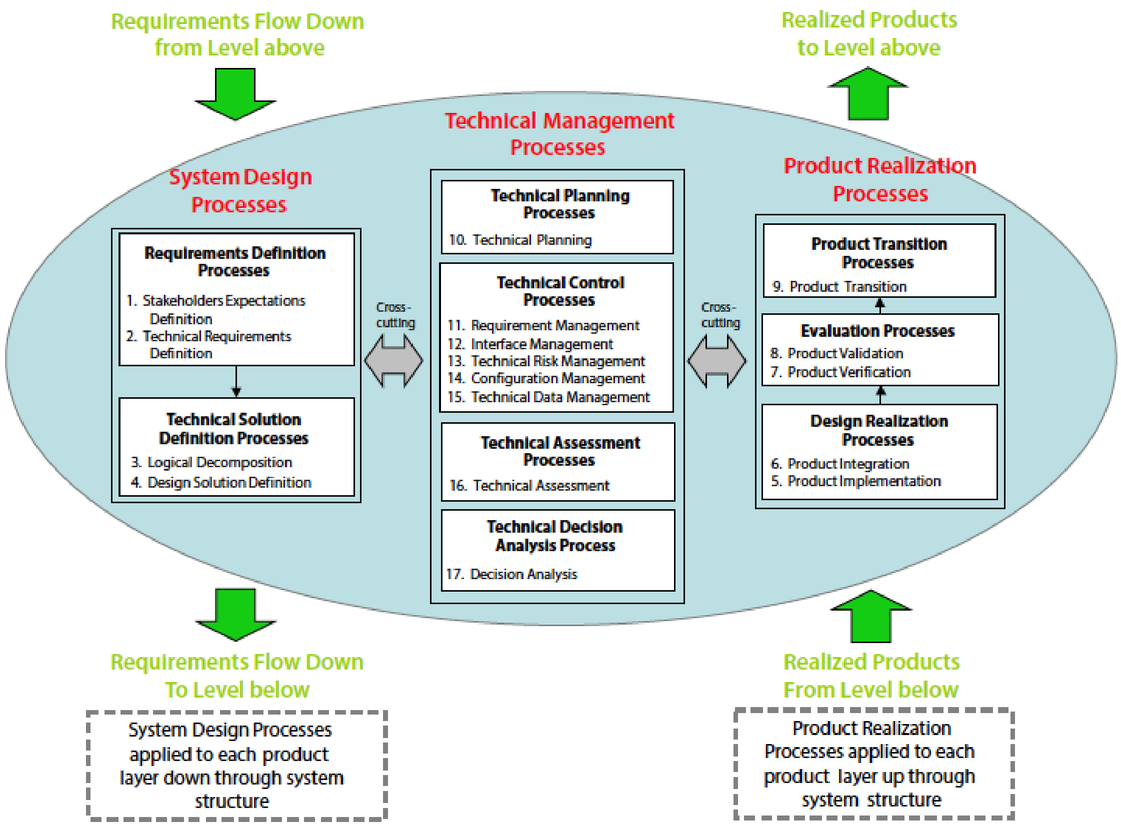

Figure 8 – Systems Engineering Engine from NPR 7123.1

VI.1. Clear Project Vision

The NASA SE handbook states that "Needs, Goals, and Objectives (NGOs) provide a mechanism to ensure that everyone (implementer, customer, and other stakeholders) is in agreement at the beginning of a project in terms of defining the problem that needs to be solved and the scope." With the PM and SE "light" approaches employed on the project in Phases A and B, the project did not generate a comprehensive set of NGOs, and this had lasting consequences for the project. In general, at the beginning of Phase C, the team was largely focused on the development of the DEP wing, and the team had not yet recognized that the TRL of the electric aircraft subsystems was not at a high enough level to begin aircraft integration. As a result, the team was still prioritizing design and analysis of the Mod III and Mod IV configurations as they did not yet fully appreciate the technical risk incurred at project formulation was being manifested in the challenges emerging with the Mod II risk reduction configuration.

At the beginning of Phase C, there was no universal agreement amongst the project team members nor the stakeholders as to the scope and NGOs of the X-57 project. A contributing factor to the lack of understanding was the fact that the current project scope was not covered by the informally documented NGOs. The team and stakeholders understanding fell into three overlapping but conflicting goals:

1. Demonstrate successful operation of an electric aircraft, with the criteria for a successful demonstration being only one flight in the pattern.
2. Extensive flight-test of the X-57 configuration to demonstrate the aero-propulsive benefits of the DEP configuration and to advance the TRL of the electric aircraft subsystems.
3. Transfer knowledge about electric aircraft development to industry, standard committees, and other government agencies (OGAs). Development of the X-57 configuration was a vehicle for generating information to feed to external stakeholders, and this knowledge transfer oftentimes took precedence over development of the X-57 vehicle.

The evolution of the X-57 Sub-Project Need, Goals, & Objectives (NGOs) can be traced by examining the NGOs at the following discrete points:

- Phase A - Systems Requirement Review (SRR) – May 2015
  - First in-depth review of the X-57 project Goal and Objectives.
- Phase A - Preliminary Design Review (PDR) – November 2015
  - Goal and Objectives presented as part of the initial technical work.
- Phase B - Objectives & Requirements Document (ORD) Baseline – November 2016
  - NGOs codified in a document.
- Phase B - Objectives & Requirements Document (ORD) Rev A – September 2017
  - NGOs updated to reflect the approval of the Mod IV (full X-57) configuration.
- Phase C - Objectives & Requirements Document (ORD) Rev B – December 2019
  - NGOs updated to reflect the evolving project Need, Goals, & Objectives.

During Phase A, there was no project Need identified, and the Goals and Objectives were documented informally in non-configuration managed slide presentations that traced to the Aeronautics Research Mission Directorate (ARMD) Strategic Implementation Plan (SIP). Having these in slides does not serve to convey the full rationale to ensure all stakeholders share a common understanding since, within CAS, formal documentation was not required. This was in keeping with the PM and SE light approach, but ultimately led to information disconnects in what the project was prioritizing. Phase B saw the addition of a Project Need and the NGOs were formally documented in a signed ORD. Approximately two years into Phase C the project NGOs were updated to accurately reflect the current scope of the project and to maintain relevance to the American electric aircraft industry which had changed significantly since project inception. This update allowed for the project team and the stakeholders to have a consistent understanding of the project scope and to document the project’s contributions to the industry. Counterintuitively for a flight project, the Need and Goals could be met without flying the X-57. This change in scope reflected the impact the project had to date on the nascent electric aircraft industry and how parts of that industry had grown past X-57 in several areas by leveraging the project’s lessons learned.

The evolution of the Project NGOs was driven by several factors. First and foremost, the development of the project did not rigorously follow the standard SE process, which lays out the necessity of and the process for generating NGOs. This process is vitally important as it ensures that all stakeholders agree with the scope and expectations for the project. The significant evolution that the NGOs underwent throughout the length of the project is evidence that the stakeholders and team did not have a clear understanding of the scope of the project. Realistically, if project NGOs change significantly, so has the scope of the project and it should undergo reformulation or a replanning effort. In addition, the project was formulated with the assumption that several required subsystems were COTS and that little to no development effort would be needed. The project was also formulated with the assumption that foreign COTS products could be used. Shortly after the Project was formally kicked off, the Project was required to buy only American products. This decision required the project to scramble to find domestic suppliers for the electric aircraft subsystems, which were limited and affected the assumed TRL for the electric propulsion subsystems.

Figure 9 illustrates the evolution of the X-57 project Need. In Phase A, there was no Need for the project identified. With the ORD baseline in Phase B, a Need was introduced, and this Need described X-57 as being necessary to advance the readiness of aero-propulsive coupling and electric propulsion to achieve benefits in energy use, emissions, noise, and costs. The Need in Phase B is solely focused on technology development, which is at odds with the unwritten project objectives at the time of transferring knowledge and developing the nascent electric aircraft industry in the USA. With Phase C, the Need was updated to document the full scope of the X-57 project, which was to develop DEP technologies for the benefit of the nation. This revised Need accurately covered all work that the Project stakeholders had tasked the project to accomplish.

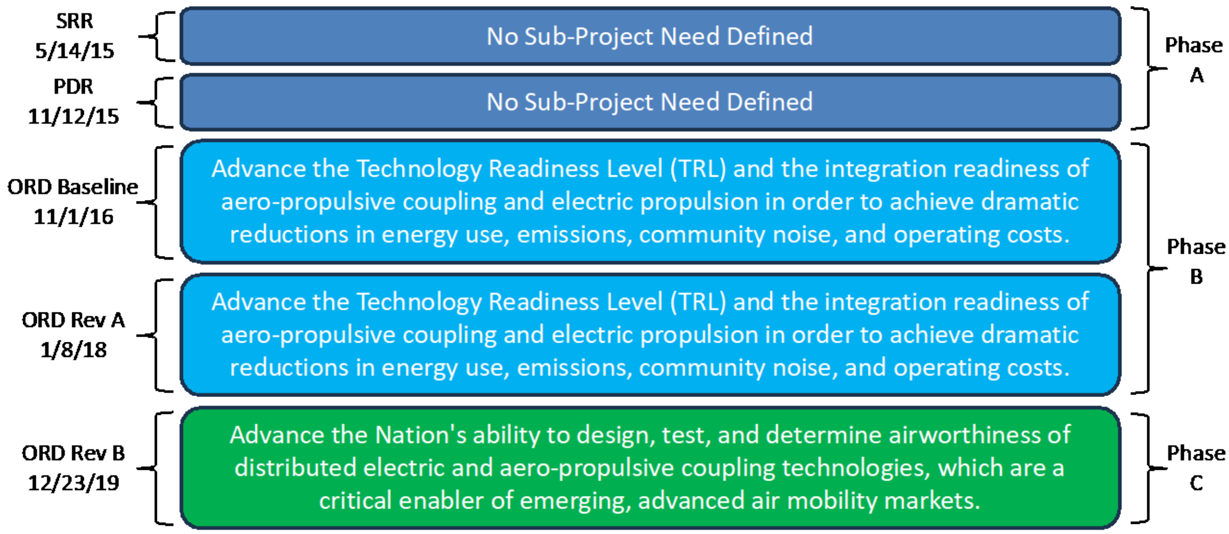

Figure 9: X-57 Project Need Evolution

Figure 10 illustrates the evolution of the Project Goals. During Phases A and B, the Goal essentially remained the same, which was to demonstrate significantly lower energy use when compared to a comparable General Aviation (GA) aircraft. In Phase C, the project Goals were updated to reflect a more formalized and traditional SE approach to the NGOs. The specific performance-based Goal of Phases A and B was replaced with a Goal to share knowledge with the industry and regulators about how to develop and fly a DEP aircraft along with a Goal to use X-57 as a reference platform to benefit the Nation's ability to develop electric aircraft. This change in Goals in Phase C reflects a recognition by the stakeholders that the real value of X-57 lay in aiding the rapidly growing electric aircraft community through technology development and knowledge transfer and not in demonstrating a specific performance achievement.

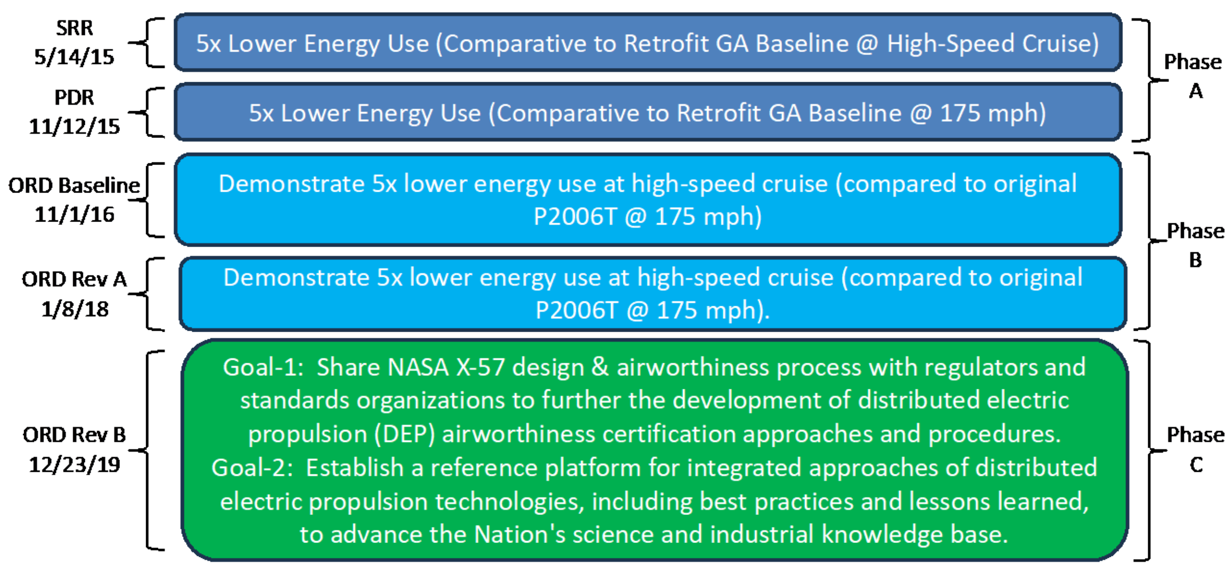

Figure 10: X-57 Project Goal(s) Evolution

Figure 11 illustrates the evolution of the X-57 Project Objectives. Phase A saw a wide range of Objectives that in general were focused on demonstrating specific system level performance objectives. Phase B initially saw the project Objectives decrease from 8 to 2 before increasing to 6 at the end of the Phase. The Goals for Phase B were initially reduced to 2 to better reflect that the Project was only approved through flight of the Mod III configuration at the time. By the end of Phase B, the Project had been approved to develop and fly the Mod IV configuration, and that is reflected in the expanded Objectives at the end of the Phase. It is notable that various Objectives such as measuring and demonstrating a noise reduction benefit came and went from the Project Objectives as NASA Stakeholder interest waxed and waned and the Project attempted to follow that lead to stay relevant to the NASA Stakeholders. Phase C saw the Project objectives updated to reflect a more formalized and traditional SE approach to NGOs, where the Objectives are set to achieve very specific targets, which map to the Project Goals.

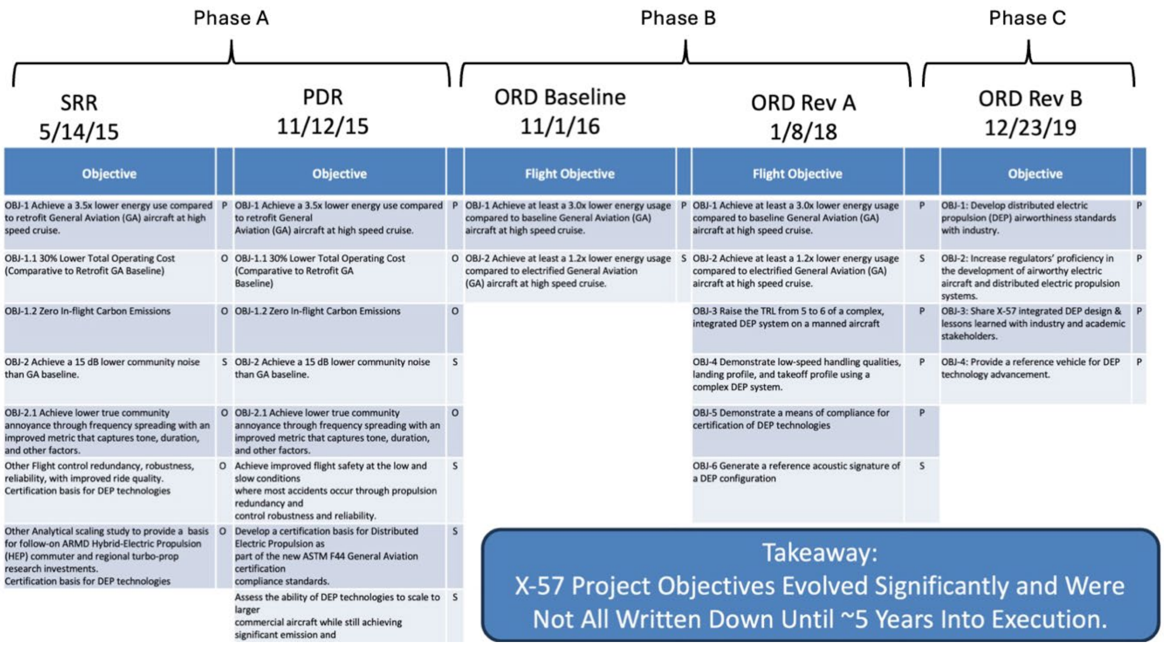

Figure 11: X-57 Project Objectives Evolution

In Phase C, the complete rewrite of the Project NGOs to better describe the Scope of the effort and match current Stakeholder expectations resulted in a breakdown in traceability from the Objectives to the System Level Requirements. The Project did not map the System Level Requirements to the Objectives; instead choosing to map the system level requirements to the Mod. In Phase C, the project understood the increasing breakdown in the traceability between the system requirements and the NGOs, but they did not have the resources or time to adequately address the issue under the pressure of always being “a year away from flight.” Instead, the concept of “Design Drivers” was introduced to map the Objectives to the Mods, which then allowed mapping to the System Level Requirements as shown in Figure 12.

Design Driver	Performance Target	Parent Project Objective
Mod II: Retrofit a baseline General Aviation aircraft with an electric propulsion system.	Optimize the design for cruise power consumption with a target of 3.3x reduction in energy from the baseline aircraft.	OBJ-1, 2, 3
Mod III: Modify the configuration with a cruise-optimized wing and provisions for a distributed electric propulsion system.	Optimize the design for improved cruise power consumption with a target of 1.5x reduction in energy from the Mod II configuration.	OBJ-1, 2, 3
Mod IV: Design for adequate low speed takeoff and landing characteristics with an integrated DEP system.	Design the integrated system to have a target minimum controlled flight speed of 58 KCAS or less while maintaining acceptable pilot workload and handling qualities.	OBJ-1, 2, 3, 4

Figure 12: X-57 Design Drivers

The significant evolution of the NGOs throughout the project lifecycle resulted in confusion within the project team and the stakeholders as to the scope and expectations for the Project. The PM and SE "light" approach essentially skipped the most fundamental stage of formulation, which is the development and documentation of NGOs that have the full support of stakeholders. The decision to buy American and the resulting assumptions about the TRL of the available electric aircraft subsystems both proved to have lasting and unintended impacts on the scope of the project, which affects both the actual NGOs and their planned completion. As a result, the project had to develop these subsystems instead of focusing solely on integration and flight-test of a DEP airframe.

The fluid nature of the Project NGOs resulted in a continual lowering of the technical performance objectives. When it would become clear that a subsystem would not meet a specified performance metric, the metric would be lowered or relaxed instead of attempting to address the subsystem challenges. For example, subsystem and vehicle weight were allowed to increase without penalty in part due to a lack of understanding of the impact on mission performance. This lack of weight control resulted in a much heavier vehicle than planned, which resulted in a continual worsening of climb performance and flight-time. During Phases A, B, and the first part of Phase C, lower climb performance and less flight-time was simply accepted as there was no written requirement for either. During Phase C, analyses were done to determine the minimum performance metrics required to achieve the mission objectives. Good, clear, stable NGOs would have aided the project by allowing for the development of good system and subsystem level requirements, including technical performance metrics.

In hindsight, the X-57 Project would have benefited greatly from following the standard PM formulation processes and the standard SE process for developing NGOS, which were intentionally deviated from as part of the PM and SE "light" approach. These approaches would have led to more detailed trade studies of the available technologies and their associated TRLs, which would have led to better understanding of the scope of the required effort. A better survey of the state of the art at the time coupled with the mandate to buy domestic hardware would have indicated that the real need for the project was not to demonstrate a specific performance level with a DEP airframe. The real need all along for the X-57 project has been to advance the nation's ability to design, test, and determine airworthiness of electric aircraft. This true need was not documented until mid-way through Phase C. An understanding of the true need for the project would have led the stakeholders to scope and structure the Project in an entirely different manner, which may have led to achieving the project objectives with fewer resources expended. For example, the project could have been structured to raise the TRL of electric aircraft subsystems instead of focusing on development of a DEP wing.

VI.2. Concept of Operations

A Concept of Operations (ConOps) provides guidance on how the vision from the NGOs is translated into hardware operations. A Concept of Operations is normally one of the first project documents developed and outlines the framework for how the envisioned system will operate during its mission and all phases of ground operations. It defines the scope of operations, including the dataflow, the operational environments, nominal and off-nominal scenarios, high-level and external interfaces, and the system constraints and assumptions. The ConOps facilitates requirement definition and decomposition, once the team agrees on what the system will be designed to accomplish. The ConOps is meant to be a living document that is updated to reflect the system state.

Following the high-risk, high-reward approach, the X-57 project never developed a ConOps, which eventually became a major problem. Well into the project there was a lack of clarity regarding how the full system operated as a whole, the design rationale for some of the system components, and disagreement on their usage across different discipline teams. This resulted in significant issues during testing and attempted operation of the aircraft and, in some cases, put hardware needlessly at risk due to a lack of understanding of how the system was designed and intended to function.

Lack of a ConOps and the resulting missed requirements led to a misunderstanding of how the Lock Out Tag Out (LOTO) component of the battery system was being used. This misunderstanding could have led to a failure of the battery system power convertors without warning. The LOTO component was originally designed as a method to control arc flash while connecting the battery modules together and to the Battery Control Module (BCM), which would only happen during system assembly or reconfiguration. In practice, the LOTO components were being used to "safe" the aircraft and disconnect the battery modules from the rest of the aircraft. This use of the LOTO component was a result of a requirement by the flight operations team to remove all power to the aircraft to perform maintenance or leave the aircraft unattended overnight. During the LOTO component design process, there was not a requirement for it to be used in this manner. Design choices were made with the BCM power convertors that resulted in frequent application of battery module power to the BCMs possibly leading to premature degradation of the power convertors, which did not have an indicator that could be monitored and that would show any potential issues. Use of the LOTO components every day to apply battery module power to the BCM power convertors placed the convertors at an elevated risk of failing. Without having this use-case documented, the requirements were not properly flowed to the team designing the BCM and LOTO components and resulted in a case where the flight operations team could not operate the aircraft in a safe manner.

The detailed Mod III cruise nacelle design was not briefed at the Mod III wing delta-CDR. The detailed design was developed and reviewed separately after the wing fabrication had already begun. During the design reviews for the Mod III cruise nacelle, an action was generated to evaluate the detailed design against the thermal analysis previously performed. Revisiting the analysis revealed the operational environment for the Mod III cruise nacelle had not been fully or accurately characterized. The lack of detailed ConOps along with an inaccurate understanding of the subsystem thermal performance and efficiencies led to an insufficient characterization of the needed system functionality and operational environment. The required analysis conditions were revised to ensure the thermal airworthiness of the Mod III cruise nacelle was fully assessed. The updated analysis results with revised conditions and updated subsystem performance numbers revealed the CMCs and aft bay electronics were generating more heat than could be dissipated with the current thermal management system design, necessitating the addition of flow paths to provide adequate cooling. Since the Mod III cruise nacelle had been subjected to an updated thermal analysis, it was deemed necessary to revisit the Mod II cruise nacelle and verify this design against the revised thermal analysis requirements. Where the Mod III cruise nacelle exhibited thermal issues with CMCs and aft bay electronics, the updated analysis indicated the Mod II cruise motor and CMC low voltage electronics would overheat. The Mod II cruise nacelle design also had to undergo design changes to manipulate the flow and extract excess heat. The need for this design change in the Mod II cruise nacelle was discovered during vehicle integration, and therefore, schedule and cost impacts were incurred to correct this technical issue. Figure 13 shows the final flow paths for the Mod II cruise nacelles.

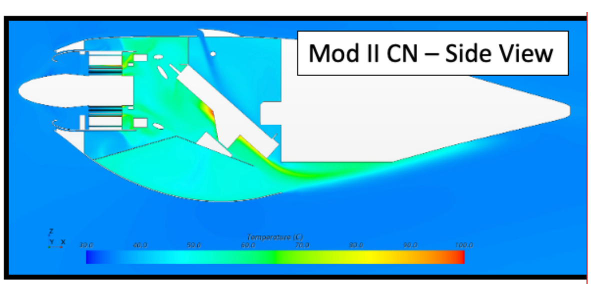

Figure 13: Final Flow paths for Mod II Cruise Nacelles

The lack of detailed ConOps also created issues with standard operating procedures performed in the hangar. For example, placing the aircraft on jacks to perform maintenance is a standard operation that was not accounted for with the increase in the aircraft weight. During hangar operations occurring in Phase C, it was discovered that the aircraft would require jacking at a weight that exceeded the OEM's limit for jacking of 2,711 lbs. The Mod II vehicle was estimated to reach 3,000 lbs. when fully populated, which exceeded the structural limits with the necessary safety factors. Upon this realization, the project structures and design engineers created a new jacking pad that enabled supporting the increased weight of the Mod II vehicle without modifying the fuselage. However, Mod III/IV was estimated to reach 3,400 lbs. The revised analysis revealed the fuselage could not support jacking operations without reinforcement. Reinforcing the fuselage for Mod III/IV jacking operations would require an invasive modification. Since the Mod II solution was less invasive and Mod III/IV flights were eventually descoped, modification of the fuselage was not required. Nonetheless, this impacted the Mod II integration efforts due to the design, analysis, and fabrication of the new jacking pads as well as having to update aircraft jacking procedures to include the new jacking pads. Discovering this issue related to jacking the aircraft late in the project resulted in time being taken away from integration and test activities. An issue such as this is best identified and addressed as part of the preliminary design phase of a project during formulation of the ConOps.

VI.3. Clear set of Requirements

After you have defined how the system operates through a detailed ConOps, the stakeholder needs are described in a series of requirements that further define the design and are flowed down from the high-level NGOs. For a system under design, requirements are usually captured in documents that are broken down along different product levels. All requirements should be clear, unambiguous, stand-alone, single-sentence statements that are verifiable. They need to address the specific system, subsystem, or component at the appropriate level. Requirements must define the functions or constraints without designing the product. An easy way to check if one has written a good requirement is by simultaneously coming up with a testing/verification plan when requirements are being developed. It is important to ensure that all derived requirements trace clearly to parent requirements, and to the overall NGOs. The expected verification of each requirement must be kept in mind, and documented, to ensure that each is verifiable, and that the verification method is appropriate.

Specifications are lower-level requirements documents that describe a more specific design implementation. Specifications are generally used when the end-product is well-defined and does not involve development; one should be able to pick up a specification and build to print. Interface Control Documents are documents that help manage and control the interfaces or connections between different subsystems so that subsystems and/or components can be designed to the same boundary. They are used to gain a common understanding of the "touchpoint" between two disparate systems/subsystems/components that are usually under different design authority. They can be thought of as a very specific type of requirements document. It is important to develop Interface Control Diagrams (ICDs) as early as practical and keep them up to date. As components and subsystems evolve, it is important to have all interfaces defined, and make changes as necessary, so all affected parties are working with the same assumptions. Common ICDs can be either subsystem specific, or broken down further into electrical, mechanical, thermal, etc. ICDs. As lower-level components are designed and built, their requirements must first be verified before integration and testing at the next higher level of assembly.

Initially in Phases A and B, the project started out with their design objectives written in a series of specifications, and the ICDs were captured in a series of PowerPoint presentations with minimal detail. Since the project was initially formed as a COTS integration effort and not a detailed design effort, this initial approach was thought to be adequate. On X-57, specifications were meant as "guides" as to what performance was desired and to provide guidance to the contractor team regarding best practices regarding design, analysis, and operation. Frequently when the hardware was found to not meet the specs, the team would work to "sharpen the pencil" and descope the performance needs instead of building to what was required to meet the current mission needs. This was problematic since the team did not yet have well-defined performance requirements and stable NGOs. Additionally, instead of fixing detailed issues in the ICDs and keeping them up to date, the ICDs were consolidated into an overall Cockpit ICD which described the cockpit systems and an Electrical ICD which described the entire electrical architecture on the aircraft. These documents were usually revised well after changes were made on the aircraft in many cases, documenting the as-built system rather than used as the design blueprint, which led to differences in what was installed on the aircraft and what was supposed to be on the aircraft. These configuration management issues lead to issues in subsequent on-aircraft testing and troubleshooting.

During Phase C, an effort was undertaken to address the inadequate specifications by creating subsystem requirement documents, which fully described the required performance for the hardware and software elements of a subsystem. This unfortunately resulted in a very confusing requirements hierarchy/architecture in which multiple documents had to be consulted to get a full picture of the functionality of a component. The subsystem requirements documents allowed for clear direction to be provided to the subsystem teams on what products were needed but did not end up mapping well to parent requirements or objectives. For example, the X-57 project ORD was flowed down into Integrated Product Team (IPT) documents that contained higher-level requirements. Following a specific example as shown in Figure 14, the Power and Command IPT Requirements were then flowed down into a single specification that combined the desired design implementation for the controller hardware and software. This was eventually found to be inadequate to describe the system and was replaced with a series of requirements documents that split the functionality of the power and command system into its constituent components, with separate requirements documents for the motor and the motor controller, which was further separated into hardware and software requirements. While this approach helped clean up many of the inconsistencies in the approach laid out above and further defined the system in a way multiple design solutions could fit the requirement, not all the higher-level parent requirements were updated in conjunction. This led to child requirements that when fully verified did not satisfy, and in some cases directly contradicted, their parent requirements. One other challenge in Phase C was the different levels of maturity across subsystems as multiple components failed their verifications and were forced to be redesigned. This also contributed to the disconnects in the various requirements documents. This led to a much larger scope of work for the Systems Engineering team as the number of requirements documented, tracked, managed, verified and reverified, greatly increased in number.

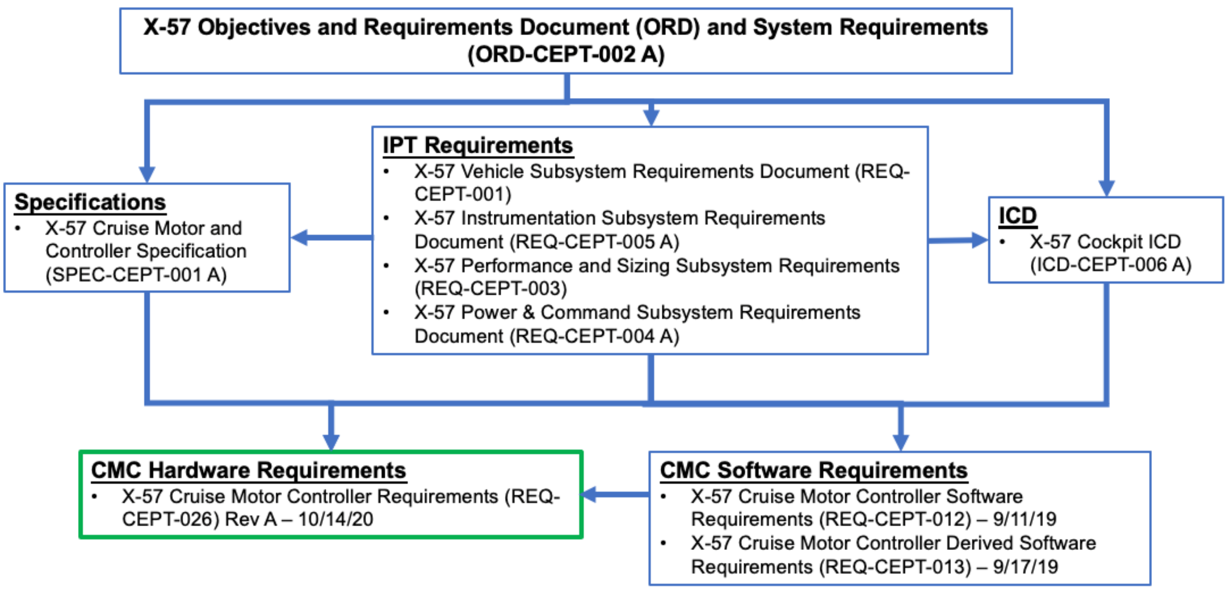

Figure 14: Phase C CMC Requirements Flow Example for CMC Software and Hardware Requirements

Towards the end of Phase C, as verification of lower-level requirements was ongoing, a robust process for deviations and exceptions was developed by the Systems Engineering Team to document the relationship between the conflicting requirements and specifications and their traceability. This process evolved and became more rigorous as the aircraft started integration and issues were found. This allowed the project to document those requirements that had been overcome by events, or were poorly written, years before, and document why it was acceptable that they were not met. The project defined deviations as a verification that met the intent of the requirement, whereas an exception did not meet the requirement. For a deviation or an exception to be approved, a justification was required that explained why it was acceptable to deviate from, or except, a specific requirement. This was done through an ERB led by the Chief Engineer and comprised of members of the technical team, including the Lead Operations Engineer for required concurrence. However, specification deviations could be approved solely at the discretion of the IPT or subsystem Lead, since items developed to a specification, as opposed to a requirements document, were considered 'best effort' from early in the project and therefore unenforceable. In hindsight, the X-57 could have benefited greatly from developing detailed requirements once the realized TRL of the components changed and it was no longer a COTs integration effort and rather a detailed subsystem design effort.

Early in Phase C, the project team wrestled with attempting to integrate hardware that either did not function as needed or was not able to be integrated in the aircraft. The BCMs and CMCs are just two examples of subsystems for which the project stepped back to the requirements development phase for both the hardware and software elements for these subsystems. The new BCM hardware and software requirements documents were flowed to the contractor team and resulted in hardware and software that was able to be integrated and operated on the Mod II aircraft. The CMC hardware requirements resulted in the combined NASA-contractor team developing airworthy CMCs that met the required performance needs and worked well with the integrated systems on the aircraft. The CMC software requirements resulted in the NASA team delivering safety critical software that demonstrated the required level of performance on-aircraft during ground testing. The project team continued to experience challenges with the development and integration of these subsystems, but with an adequate set of requirements, the team had a common understanding and framework from which to tackle the inevitable issues that arise during any developmental activity. With the successful operation of the aircraft for over 2 hours with no heating issues and minimal EMI, Phase C proved that the project was on the right track to develop and integrate airworthy electric aircraft technologies for flight, they just needed to first have a good understanding of the requirements.

VI.4. Verification & Validation Test Approach

Verification and Validation (V&V) activities are where the project verifies that the realized product meets the requirements and validates that the system meets the mission objectives. It is important to document and prove how requirements are met. This ensures any required activities for verification are planned for as part of project formulation; verification documentation is expected for each component and subsystem. The end-item data package upon component delivery should consist of all documentation for a component or subsystem. It should contain all design drawings, verification results, and any non-conformances. Verification ensures the system is built per the requirements ('did the product meet the requirements'). Validation ensures the system meets the customer's needs ('did we write the right requirements').

As part of the PM- and SE-light approach in Phases A and B, there was a general lack of insight and oversight of subsystem and component development. The normal approach to SE insight and oversight follows a "trust but verify" approach where the onus is on the subsystem developer to provide sufficient evidence that the subsystem components delivered have been fully verified before integration into the aircraft. However, due to the multiple technical issues described in the previous sections with the subsystems and components, verifications were completed after NASA accepted delivery of parts, instead of coming as a complete package. This resulted in components that were specifically designed for the X-57 aircraft being sent back to vendors for re-work, or redesign. Having different parts of the aircraft at different TRLs led to many discrepancy reports being written against systems that ended up being under-designed for an integrated system application. Many projects at NASA adopt Design Analysis Cycles for continuous improvement during a project. Had the project known it was going to be necessary to plan for multiple design cycles up front, as is typically done prior to a CDR, to find problems and finalize designs, the component TRLs could have been matured under more realistic schedules prior to integration onto the aircraft for system level verification testing.

Another consequence of incomplete verification at the appropriate level means that lower-level components were tested after integration on the aircraft. For example, the CMCs and BCMs were not fully tested prior to the initial attempted integration, and they were found to be either non-functional or not compatible with the rest of the vehicle. It is important to fully verify all lower-level components prior to integration at the next higher level. It is generally understood that the cost of fixing problems grows exponentially, the later or higher the integration level. For example, finding and fixing low-level issues at the component and box-level helps to prevent a standing army while an issue is being debugged at the system level when the team should be focused on integration and system-level testing. There are many ways to accomplish this depending on the scope of the project, but the general principles remain the same: test early, test often, and "test like you fly, and fly like you test." Unfortunately, this best practice was not able to be followed as more and more problems with lower-level hardware components and subsystems were found during the integration of the Mod II vehicle.

It is also important to have a functional duplicate, or partial duplicate, of the system (iron bird, flat-sat, etc.) for integrating and testing components early. COTS assumptions along with the limited CAS-size budget and schedule resulted in an "expedited" hardware development approach that did not provide for prototyping or an iron bird. This situation caused problems later during integration. On X-57, the aircraft was under configuration control while being used as a test bed, due to lack of adequate off-aircraft test systems/hardware. An iron bird, or lab equivalent, would have allowed many of the subsystem issues and integration related issues such as EMI to be discovered, and debugged in parallel, prior to installation on the aircraft. Instead, many issues were discovered when items were already integrated on the aircraft, which led to more overhead from a configuration management standpoint.

Due to lack of good requirements and a V&V approach that was not developed in conjunction with the requirements, the project ended up developing a series of ad hoc test setups to complete hardware and software development efforts and complete these tests off the aircraft. These ad hoc test stands ended up only partially replicating the on-aircraft flight conditions. For example, the CMC SW development team used a setup with an unloaded motor in a lab to work through their initial SW development activities, but they required the full aircraft to conduct their final SW V&V since they needed access to a loaded motor along with the rest of the aircraft interfaces. A dynamometer test-stand was available for CMC HW development activities, but due to various reasons including scheduling, the dynamometer test-stand was only used minimally to aid in SW development. In addition, the dynamometer test-stand was developed separately from the project and only became available during the middle of Phase C. The project would have benefited tremendously from a loaded motor test setup, like the dynamometer, as early as during Phase A of the project. However, this was not identified until verification activities began due to lack of a detailed V&V approach development as part of formulation.

In hindsight, the testing approach was never a comprehensive full system test approach and was instead undertaken from the point of view of individual subsystem functionality, where each subsystem was tested individually for what it needed to do, as opposed to a "system-level" viewpoint where the subsystems are tested within the larger aircraft system in order to meet operational and performance targets. In general, the testing approach should fall out of the ConOps and requirements; if a ConOps and complete set of requirements has been written, a test plan can start with verification of the requirements in a "test like you fly" manner. If an additional test needs to be added, there is a good chance a requirement was missed. On X-57, the subsystem testing plan was never fully written down and, in some instances, overlooked the needed verification of the requirements until the LSE became involved. This lack of complete subsystem testing led to additional testing needed at the aircraft level, which was not planned for. The system-level Verification and Validation testing plan also did not trace to the IPT- and system-level requirements and had to be substantially revised to include verification of these requirements that should have been included from the beginning. Additionally, each system-level test was treated separately, meaning that there were multiple duplications in testing across the aircraft. This led to an inefficient approach, with much duplication of exact or almost identical test points across different individual system-level tests. Since the subsystem verifications were behind and requirements were neglected when developing the test plan, there was little separation between subsystem and system-level testing, with the subsystem-level testing pushed to aircraft level testing for the reasons described above.

VI.5. Configuration Management

Configuration Management is a process that ensures that all components, subsystems, and documents that are affected by any single configuration change are identified, communicated, and implemented. It is not good enough to document the change if affected groups, subsystems, or documents are not identified and notified of the changes. Configuration control is typically applied when design iterations are near completion and a baseline is established. The X-57 project was challenged with maintaining configuration control in Phases A and B due to a number of related factors. The small size of the team and the lack of experience with the configuration management processes were shown in incomplete application of changes across the full system, resulting in conflicting documentation. The PM and SE "light" approaches led to minimal to no documentation, which meant in some cases changes were not captured at all. Additionally, during Phase C the Project team wrestled with an unknown configuration and the impact of placing the aircraft under configuration control while the subsystems were still being designed and developed, which led to a continually changing aircraft configuration that was hard to keep up with.

A significant configuration management challenge that the project never fully addressed was having accurate drawings of the aircraft wiring and subsystems. When technicians attempted to install the CMCs, they immediately ran into issues trying to follow the existing drawings. Drawings were not adequate to explain how the CMC connections should be made, and the hardware was not labeled. When NASA received the aircraft, the team received an aircraft with inaccurate drawings and incomplete labeling of the wiring and components. The operations, maintenance, and instrumentation teams worked to address the drawing issues, but they would occasionally still be surprised when they would attempt to make a change based off the drawings and discover an issue. It was not unusual for the team to find the drawing did not match the aircraft and that neither the drawing nor the aircraft wiring had been kept up to date with the changes that had to be implemented to account for design deficiencies. This lack of complete understanding of the configuration of the aircraft was a continual problem both before and after delivery of the aircraft and stemmed from a lack of drawing and configuration control that was the norm in Phase A as part of the CAS approach to projects.

When originally delivered to NASA, the X-57 aircraft was put under configuration control immediately since it was intended as an airworthy aircraft operated by the AFRC operations team. The team took this approach because they did not understand the full extent of the work required to make the aircraft airworthy, which only came to light as ground testing commenced and tests and components began to fail. Detailed tracking of hardware and knowing the exact configuration of the aircraft is a necessity for an aircraft to be airworthy. As the aircraft was inspected and NASA began to operate it, the team discovered that engineering best practices were not followed, such as adequate separation of signal and power electrical systems and shielding for Electromagnetic Interference (EMI). The aircraft subsystems were not ready for flight and needed extensive development before they could be considered airworthy. In hindsight, the aircraft should have been treated as an iron-bird with informal configuration control in place to allow the engineers and technicians to quickly identify issues and address them, then placed under configuration control once development was complete. Placing the aircraft under configuration control before subsystem development had completed added a significant burden on the project by requiring the operations team treat the aircraft as airworthy, which required a higher standard of workmanship and documentation than is used on either an iron-bird testbed or in systems development.

VI.6. Technical Decision-Making Process

The process for making decisions on the X-57 project and the information used to make those decisions did not follow a typical approach for a project of this size until partway through Phase C. Following the CAS approach to technical leadership, during Phase A, the project team was relatively small with the PI setting the project overall technical and airworthiness approaches and leading the technical decision-making process instead of the Chief Engineer and the Lead Operations Engineer. In part, this led the project to focus on a DEP wing structure and the research outcomes that the aircraft would be used for once it was designed and built instead of what needed to be done to design an aircraft capable of meeting those objectives. On a typical flight project, PIs work closely with the CE to ensure the system developed can meet the research objectives. This coordination between the PI and CE should result in a healthy tension between the competing needs of meeting the research objectives while also meeting the airworthiness requirements. During Phase A, this balance was weighted heavily towards meeting the research objectives instead of integrating an airworthy system that could meet those research objectives. An additional complication for the X-57 project was that the PIs would also serve as IPT leads. The IPT leads typically report to the CE who works closely with the PI to ensure the research objectives are met by designing an airworthy vehicle. Having personnel fulfill the dual role of PI and IPT lead caused confusion as to whether a decision was being made for technical or research reasons and resulted in an unclear technical decision process. This focus on the research needs reflects the PM and SE "light" approaches used by the project. The result was that insufficient attention was paid to the overall vehicle design, airworthiness requirements and formal review process during Phase A of the project, as shown through the issues described previously.

During Phase B of the project, the decision-making approach for the project shifted towards the IPT leads with the Vehicle IPT being the forum for most technical decisions. In this phase, the project worked to finish the design work started in Phase A and begin to build and test hardware. The increased workload was coordinated at the IPT level by the individual leads. The Vehicle IPT served as an informal ERB where the individual IPT leads, and team members would discuss matters and make decisions. Each IPT meeting was attended by many personnel from multiple disciplines and by the contractor team, and the IPTs had no clear decision-making process. The result was that the IPTs would make consensus-based decisions, which would then become further consensus-based decisions in the vehicle IPT. The engineering technical decision path became even more obscure in Phase B with the PIs and IPT leads all making final technical decisions. The need for consensus across distributed technical leadership led to lack of a clear decision path which affected the team's ability to develop a functional airworthy vehicle. This again resulted in insufficient attention being paid to airworthiness requirements, analysis results, and hardware development.

Phase C started in early 2018 with a shift in the technical decision-making process towards the CEs, with the shift completed in mid-2020. This shift was necessary to refocus the team on identifying and addressing the numerous challenges and airworthiness deficiencies that the project team faced and to start integration and ground testing. The CEs worked to bring a disciplined, systems engineering based approach to first identify the driving requirements and then to take a systematic, detailed technical approach to resolving technical issues and ensuring the hardware met the driving requirements. Too often, the team did not understand the Concept of Operations or the associated functional subsystem requirements, especially since they were not documented.

The shift towards a system-based decision-making process accelerated in early 2020 with the CEs working with the IPT leads to formulate systematic approaches to address the project challenges. The decision-making process was formalized in the Fall of 2020 with the chartering of a Weight ERB and with the chartering of the project ERB in the Spring of 2021. The ERB was co-chaired by the two project Engineering TAs, which are the CE and the Operations

Engineering Lead. ERB decisions were made by agreement of the co-chairs with the PI's agreement required for matters which affected research objectives, as shown in Figure 15. The ERB served the project well as a forum to address the most challenging technical issues.

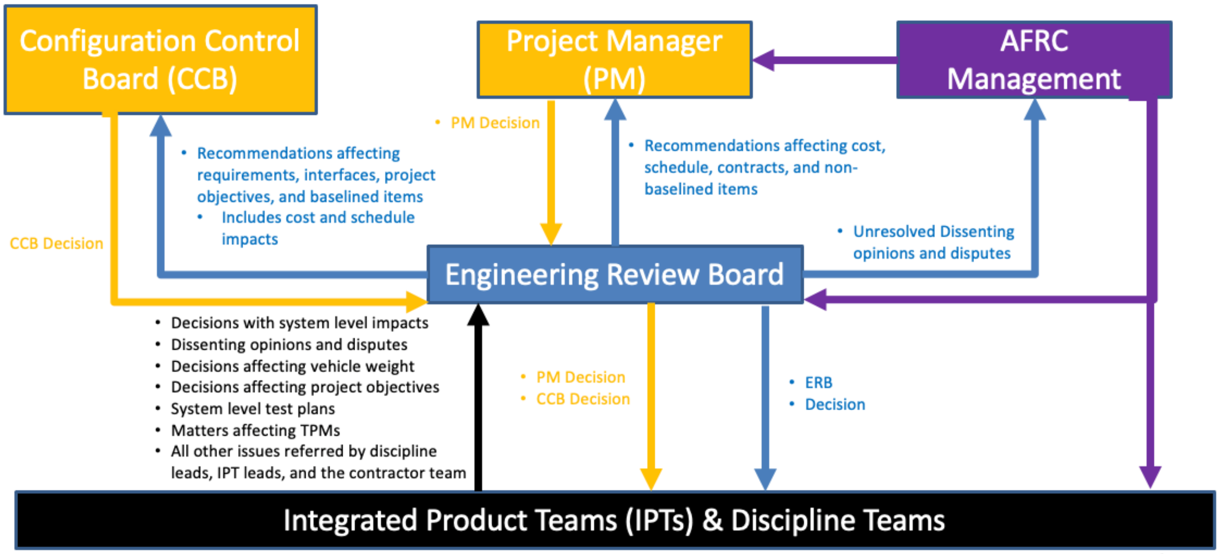

Figure 15: X-57 Technical Decision Process

As a result of shifting the technical decision-making process towards a system-based approach, the project's approach to design reviews changed significantly during Phase C. The expanded Project CE team made extensive use of NPR 7120.5 [8], that provides clear guidance for review entry & exit criteria. This process required each hardware and software subsystem element being redesigned undergo formal design reviews.

The project was continuously moving from one technical challenge to the next. In order to address each technical challenge, the team had to focus on the challenge and deprioritize other technical work. Additionally, due to the small project team size, the team's focus was continuously divided across the three different project Mods based on what was going on within each Mod. As a result, the project made risk-informed decisions utilizing technical and programmatic information available with each emerging technical challenge by weighing the options for resolution against the schedule and budget of the project in an effort to continue making progress toward milestones.
For example, the Mod III configuration is considered a high-risk configuration because failure of a single cruise motor located at a wingtip will result in a large yawing moment that cannot be quickly or easily overcome at low speeds and low altitudes. Initial incomplete analysis of this failure scenario indicated that a subsystem to reduce power on the remaining good cruise motor was required to maintain control. The analysis was initially incomplete due to a lack of resources and the team's focus being diluted across Mods II, III, and IV. The decision to pursue development of an Asymmetric Thrust Inhibitor (ATI) subsystem was made via a largely consensus-based process made at the IPT level. With the advent of Mod IV, the team revisited the analysis to assess the impacts of introducing the High Lift System, and the IPTs attacked the problem with the appropriate rigor. The result indicated the ATI subsystem would place the pilots in a more hazardous situation with further reduced thrust at low altitude. In this instance, the most effective solution was to train the test pilots how to respond to an "motor out" situation. The ATI subsystem is an example of how a more rigorous decision-making process that required the need for detailed technical information could have resulted in significant savings to the project.

Technical Performance Measures (TPMs) can be used by the decision-making authorities to identify and address issues early on. The proper use of TPMs requires proper selection and tracking of TPMs along with a rigorous decision-making progress. As part of the PM and SE "light" approach, only weight and telemetry bandwidth were regularly tracked as TPMs at the system level and reported to management. Upon reexamination, more TPMs, such as motor and controller efficiency, could have been identified early in the project and tracked. The project's responses to changes in the TPMs was also non-optimal. When weight increased, the project team would simply accept reduced climb performance or flight-time since the PIs and IPT leads assessed that the project had margin. Although a common practice is to address this issue operationally and reduce climb performance or flight time, the project took this approach without a clear understanding of the margin. During Phase C, to resolve this moving forward, a weight ERB was chartered to address the weight challenges that the Mod III and IV configurations were experiencing. The improper use of TPMs is another example of how a more rigorous decision-making process that required the need for detailed technical information could have resulted in significant savings to the project.

In Phase C, the project encountered several unique challenges due to the project's "SE light" approach. When an aircraft is nearing integration, most of the subsystem development risk should be retired, which was not the case with X-57. The Mod II aircraft was undergoing integration and test at the same time as several subsystems were being redeveloped. A more rigorous systems engineering process could have identified and addressed the issues prior to integration. On X-57, the project would make a risk-based decision on how to proceed when the subsystem developments ran into the inevitable problems. Throughout Phase C, the project operated under schedule pressures to fly or risk cancellation of first Mod IV then Mods III and II. The project was up against a hard deadline of September 30, 2023, for completion and Mod II was continually operating in the mindset of being a year away from flight. Due to this pressure, the project would broadly accept more subsystem development risk than would typically be desired for a project at this stage of its lifecycle. For example, after the aircraft had been delivered, it was discovered that the BM2 CMCs that were delivered with the aircraft were not airworthy for several reasons, such as inability to pass environmental vibration tests and electrical deficiencies that rendered them inoperable. The project had to go back to requirements development to redesign the CMCs for flight, which led to development of the XM3 CMCs. With the understanding of schedule and budget, the project followed a risked-based decision to move forward and continue on-aircraft testing utilizing the BM2 CMCs in parallel with the XM3 CMC development in an effort to continue integrated testing. This split the attention of the small team, delaying redesign efforts. With the XM3 CMCs, the project team made several technical decisions to reuse components instead of designing new, more suitable parts. This turned out to be a relatively high-risk decision as the integration of these re-used components caused several issues during environmental testing. The assembly of the XM3 CMCs was also delayed, which resulted in the project assuming further risk and integrating the hardware onto the aircraft to begin system integration testing before the subsystem testing had completed. In all instances, the team made the best decisions they could to maintain schedule with the issues known at the time, but in all cases, they accepted increased risk during the integration stage. If the project had followed a more rigorous SE approach from the beginning, these technical challenges with the CMCs could have been identified much earlier in the project lifecycle and could have been easier addressed as part of the preliminary or critical design phases. The use of the "SE light" approach pushed technical issues that should have been identified early into significant programmatic risks during the aircraft integration phase, which is when the project should be retiring, not accepting, risk.

With the shift in technical leadership towards a system-based approach, the project began to systematically work through technical issues that had been discovered. Technical decisions were now made with the proper amount of rigor and clearly communicated and enforced. This approach also allowed the technical standards to be raised and provided clear guidance on expectations by focusing on a clearly documented process. Unfortunately, this shift occurred too late in the project to result in an airworthy vehicle within the final project schedule and budget.

VI.7. Independent Review Process

The X-57 Maxwell project implemented a review approach that was meant to meet the intent of the standard systems engineering review approach prescribed in the AFRC CE Handbook. This approach included the standard use of pre-defined Entry and Exit criteria and an Independent Review Team (IRT). The project began with the standard initial reviews, which included a Mission Concept Review (MCR), System Requirements Review (SRR), and a Preliminary Design Review (PDR). The PDR IRT identified a list of Requests for Action (RFAs) for the project to respond to by a Critical Design Review (CDR). The IRT recommended a series of informal peer design reviews in addition to the large design reviews, but they also explicitly recommended peer review of the following subsystems: Power and Command, Instrumentation, Performance and Sizing, and Wing. The project held four Subsystem Tabletop Reviews (STTR) for the areas of Instrumentation, Airframe, Traction Battery, and Cockpit Hardware. The project proceeded to hold a CDR, where the team at the time briefed the plan to hold a delta-CDR to cover the Wing detailed design, analyses, and fabrication plans later. The CDR presented the Mod II and III systems at a high level but did not include detailed subsystem design information since the project planned to procure subsystems that were ready to integrate. The project then held two additional STTRs between the project CDR and the Wing delta-CDR. After the Wing delta-CDR, two additional STTRs were held to cover the Battery module redesign and the use of vibration isolators in the Mod II configuration. The Mod IV configuration was formally introduced into the Program of Record in August of 2017. As a result, the High Lift Motor Controller (HLMC) team held a PDR and CDR in advance of the Mod IV system level PDR. A Mod IV system-level CDR was held with the goal of obtaining approval to proceed to fabrication of the High Lift subsystem hardware. However, the team was directed by the IRT to reconvene when the high-lift subsystems were at a more mature state to meet CDR-level Entry and Exit criteria. The team proceeded to hold a series of Mod III and IV STTRs to prepare for a Mod IV delta-CDR. Several of these Mod IV STTRs served as release approval for the contractor to begin fabrication of a subset of the required hardware. Ultimately, the Mod IV flights were descoped in July of 2021. The X-57 reviews described are shown in Figure 16.

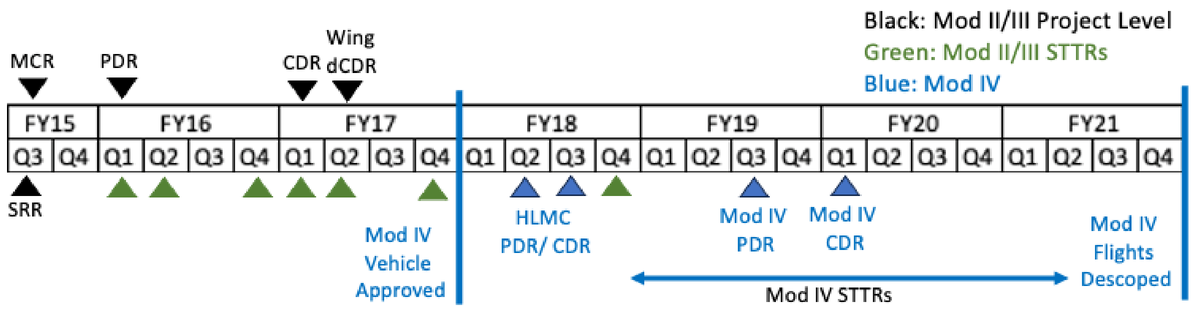

Figure 16: Project Design Reviews

During Phase A, the project outlined a standard review approach as part of project formulation, but there were deficiencies in how the approach was tailored, implemented, and executed, which came to fruition when the project began to encounter technical issues during Mod II system integration. The Entry and Exit criteria as presented in the AFRC CE Handbook was highly tailored on X-57 because of the SE "light" foundation laid for the project along with the assumption that the subsystems were at a higher assessed TRL than they were. The level of tailoring applied proved to be inadequate as components began to demonstrate a TRL that was less than assumed and required for successful system integration. During Phase C, technical discoveries indicated the true state of the hardware was assessed to be at a point where the project was forced to regress to an earlier point in the project lifecycle of requirement development. In addition, the project PDR and CDR did not cover all the planned project modifications. The project assessed the Mod III wing design and integration as the only complex portion of the project, and therefore the focus of both PDR and CDR was the Mod III wing. The Mod IV vehicle configuration was not yet approved, so it was addressed at a conceptual level, but the detailed design would not be briefed until years later. Since Mod II was assumed to be a straightforward, minimally invasive modification from an airworthiness perspective, the Mod II vehicle configuration was never subjected to a formal, dedicated design review. The IRT noted this observation in both Final Reports delivered to the project. Consequently, CDR RFA2 required the project team to hold a peer review, or document the risk for lack thereof, for the detailed analysis, fabrication, assembly, and integration of Mod II. However, the project team determined several recommendations by the IRT were not required including the Mod II peer review, but instead the project introduced the utility of the STTR and/or Technical Interchange Meetings (TIM). The STTRs and TIMs utilized in Phases A and B to review the Mod II subsystems and components did not follow a formal review process. No Entry and Exit criteria were defined to lay out expectations or to assign a level of rigor to this informal review tactic. No RFAs were collected or tracked; instead, an informal list of actions was generated to document concerns were identified as part of the briefings. None of the STTRs nor TIMs resulted in a final assessment report to document the subsystem/component maturity and readiness to proceed to fabrication, procurement, or integration, as they case might have been. The STTR board members consisted of project team members, which eliminated a critical aspect of design reviews, which is the independent perspective. The project team did not deem these standard review characteristics as required due to the initial assumption that subsystems/components were at the COTS level of integration readiness.

Following the same CAS operating principles, the review process external to the project team also operated under the SE "light" approach during Phases A and B along with the assumption that the required subsystems were at a sufficiently high TRL that minimal review was required. Mirroring the impacts on the project side, this assumption impacted the level of rigor applied by the IRT. During Phases A and B, the IRT was chartered with a membership that reflected the COTS assumption. As a result, the review team did not include the skill sets or experience that would have identified the technical issues that were uncovered during system integration (Phase C). For example, since the cruise motors were assumed at a TRL high enough to be ready to integrate without further development activities, there was no mechanical system expertise represented in the IRT. In hindsight, having a mechanical system SME on the IRT would have led to the identification of fundamental issues with the cruise motor design, which were not uncovered by the project until the end of Phase C.

Since the Mod IV vehicle configuration was not approved until the Mod II and Mod III efforts were well underway in Phase B, the Mod IV system development and review followed a path decoupled from Mods II and III. The Mod IV PDR applied greater rigor than the initial project design reviews. The Entry and Exit criteria implemented were taken from the AFRC CE Handbook and exhibited minimum tailoring when compared to the project level reviews. The Mod IV CDR attempted to follow the same rigor as the Mod IV PDR. However, the system and subsystem designs were found to be immature against expectations for a system level CDR. The IRT documented the shortcomings of the review in the Final Report and did not grant the authority to proceed to fabrication without repeating a CDR when the system could demonstrate a maturity commensurate with a system ready to proceed to fabrication, integration, and test. In the interest of minimizing schedule impacts caused by the need for a delta-CDR, the project team tailored a series of Mod III/IV fabrication and integration readiness reviews to continue progressing components and subsystems to fabrication or procurement as deemed ready. Flight of the Mod IV vehicle configuration was descoped in 2021 and the Mod IV CDR was left incomplete.

In Phase C, the Chief Engineers oversaw the preparation and execution of all design reviews, including the subsystem/component level. Shifting the project's oversight of the review process to the chief engineers ensured a technically sound narrative that demonstrated the technical issue at hand, and the impacts of the path forward across the rest of the system were understood since the Chief Engineers, like Systems Engineers must maintain a system level view of all decisions. The fruits of this revised approach were further validated as the aircraft slowly approached a fully functional system by the resolution of the technical issues discovered. Table 1 and Figure 17 list the reviews that employed the revised review approach as part of Phase C.

Table 1: Phase C Design Reviews

No.	**Mod II Reviews**	**Date**
1	XM3 CMC SW Requirements Review	8/8/19
2	XM3 CMC SW Baseline Review	11/21/19
3	BCM CDR	6/30/20
4	BMS Software CDR	7/17/20
5	XM3 CMC CDR	10/22/20
6	XM3 CMC Implementation Readiness Review	11/16/21
7	XM3 CMC HW Review	12/8/21
8	EMI Filter Design Review	5/25/22
9	Mod Z CDR	6/8/23
No.	**Mod IV Reviews**	**Date**
1	HLMC SW Requirements Review	5/14/20
2	HLMC SW PDR	2/2/21
3	HLMC SW CDR	10/18/22

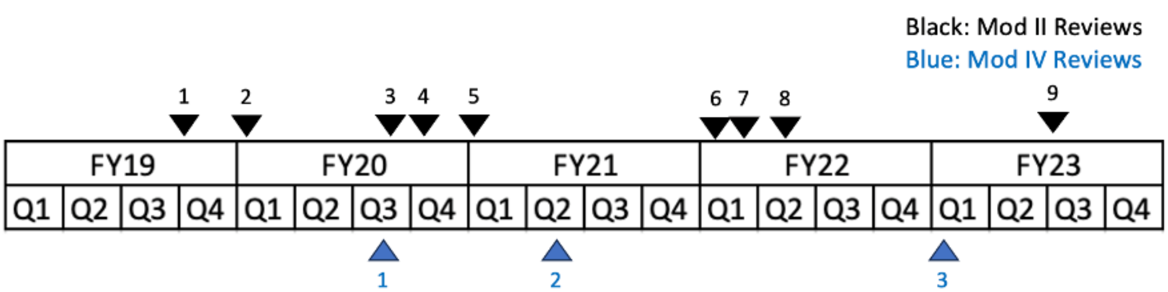

Figure 17: Timeline of Phase C Design Reviews

VII. Best Practices- the Art and science of Systems Engineering

Hindsight is always 20/20, and the recommendations for future projects should not be taken as criticism of the X-57 project team. The team worked diligently to execute the mission under the assumptions, direction, and constraints under which the project began and in light of the increasing challenges. In hindsight, the project team and the stakeholders did not have a clear understanding of the risks and implications of the decisions that were made at the beginning of the project. This section provides recommendations as to how future projects could tailor the art and science aspects of systems engineering to avoid some of the challenges faced by the X-57 project team.

A project should spend enough time in formulation to ensure a clear understanding of the Need, Goals, and Objectives for the project. This understanding needs to include a thorough assessment of the required technologies to understand what development efforts are needed. For a project of the complexity of X-57, which was developing three separate aircraft configurations simultaneously, the authors recommend sufficient time be spent in formulation to ensure a solid understanding of the technology maturation required and how that is mapped to a tailored SE process for which sufficient programmatic resources exist. In addition, the formulation team should include experienced personnel in the key roles of project manager, technical leadership, and lead systems engineer along with experienced technical personnel. Experienced project leadership is needed to ensure the project's programmatic and systems engineering approach is artfully tailored to ensure the proper rigor and implementation. An initial ConOps is a vital product for the formulation phase as it serves to inform the follow-on requirements phase and ensures that the stakeholders all agree to the mission that the realized product is to meet. If the X-57 project team had spent an extended time in formulation with the aid of experienced project leadership or had gone through a replan after given the direction to only buy American components, the project may have identified that the TRL of the required technologies was not high enough to accomplish the goals and objectives at the time. This discovery would have led to a rescoping of the project's initial efforts to focus instead on developing specific technologies instead of focusing on an integration effort.

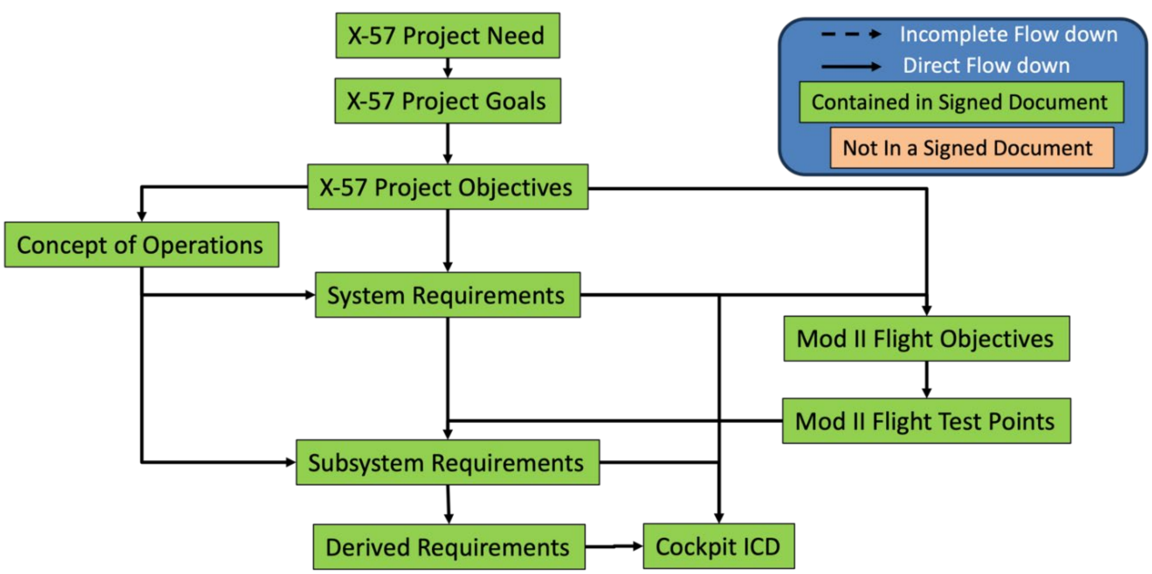

Figure 18: Recommended NGO to Requirements Flow for a Project such as X-57

Following formulation, the NGO and ConOps should be flowed down into a good set of system, subsystem, and derived requirements. At the same time, the flight test plan needs to be drafted to inform the requirements development process and ensure the flight research objectives will be met. Figure 18 illustrates how the X-57 requirements flow down could have been structured to implement this recommendation. The subsystem development and requirement verification approach also must be defined during this phase. Again, experienced project leadership is a tremendous asset as they can aid the project in determining how to tailor the development and verification approaches. An important aspect of this tailoring is an understanding of the level of risk being accepted. The X-57 project was instructed to accept a high level of risk to accomplish the mission on an expedited timeline with limited resources. If more focus had been spent on developing a ConOps, requirements, and a flight test plan at an early stage of the project then the project team would have had a much better understanding of the scale of the technical challenges in front of them. This better understanding of the technical challenges would have led the team to advocate for additional subsystem development and testing, including an iron-bird testbed on which to test the new subsystems prior to aircraft integration.

During implementation, the authors recommend striking a balance between meeting the airworthiness requirements and research objectives of a project. In order to strike this balance, a good set of requirements and objectives is first needed. Once that common understanding is obtained, it is vital that the engineering technical authority (typically the project CE or LSE) and the owner of the research objectives (typically the PI) work closely together to ensure they are met. A clear process for making and documenting engineering technical decisions is critical to ensure disagreements and issues are addressed quickly. For this process to work well, the project technical authority and the project engineering technical authority need to ensure the team is asking and answering the correct questions. These personnel must also ensure that the configuration of the system being developed is well understood. If the necessary rigor is not present in the analysis or there is an incomplete understanding of the hardware configuration, then the results will be non-optimal and may result in component rework later in the project lifecycle.

One last consideration that the authors recommend is that everyone involved realize that no project team is infallible no matter how well experienced, staffed, or well led. An independent review process is a vital tool for the project to aid in assessing progress and providing suggestions with the development effort. The authors recommend implementing a rigorous independent review process that in this case would have aided the project in identifying gaps in their understanding earlier in the project and potentially led to the project team addressing technical challenges at an earlier stage. An independent review process works best when conducted by a team of experienced discipline SMEs who are given clear, thorough criteria on which to objectively evaluate a project team. Management's role as part of this review process should be to evaluate the reviewer's feedback and work with the project team to provide course corrections as necessary. Informal tabletop reviews can be useful, but they are no substitute for the rigor that comes with a formal system-level design review with clear criteria evaluated by experienced discipline SMEs.

VIII. Conclusion

This paper described how the X-57 Project's Systems Engineering approach evolved through three distinct functional phases from an initial SE "light" approach to one that was more typical of a large aeronautics flight project at NASA. It cannot be emphasized enough that in Phase A and Phase B, the project team believed their primary mission was to develop a DEP wing, integrate high TRL COTS subsystems into the DEP wing, and demonstrate the benefits of DEP technology in-flight. This belief along with the SE "light" approach led the team to not place the required emphasis on ensuring the subsystems were mature enough to support the project. The integration and development challenges experienced by the project in Phase C were an indication of the realization of the technical risk seeded in Phase A as a result of the PM and SE "light" approaches along with the overestimation of the subsystem TRL. A disciplined systems engineering approach would have aided the project by challenging these beliefs in formulation and throughout the project lifecycle. SE is the most useful when it is applied early in the project lifecycle and declines in utility as the project solidifies the technical approach early in execution. A more robust decision-making and review process would have also benefited the project by identifying and resolving issues earlier in the lifecycle. The X-57 project began experiencing success in developing and integrating subsystems towards the end of the project, once systems engineering principles were applied. The application of systems engineering principles began to bear fruit, which culminated in the successful operation of the aircraft on battery power with no heating or EMI issues demonstrating that properly implemented SE practices can go a long way to producing a system that functions as needed to achieve a goal, thus showing that even NASA projects classified as high-risk, high-reward can benefit from upfront inclusion of Systems Engineering practices.

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