Initial Regulatory and Certification Approach for the SUSAN Electrofan Concept

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New aircraft concepts and associated technologies are required to meet emerging environmental impact goals, while still meeting established airworthiness certification standards and regulations. The SUbsonic Single Aft eNgine (SUSAN) Electrofan is one of these concepts, utilizing a single aft-mounted engine, electrified aircraft propulsion, and an emergency backup battery. This paper explores the current certification and regulatory barriers to this novel aircraft design and the potential methods for adapting certification and regulatory requirements for the SUSAN Electrofan concept. Although some certification requirements, such as the Extended Operations regulations for continued operation after the loss of an engine, can be met with only minor changes, other requirements require modifications to the regulations or the aircraft concept for compliance. Early insight to the certification approach for the SUSAN concept, while the design is still undergoing trade space exploration, allows the development of the aircraft alongside any modifications to certification standards.

I. Introduction

Recent technological advancements will enable novel aircraft designs and configurations that were not feasible, or even imaginable, when many of today's airworthiness certification standards were established. One of the emerging technologies is Electrified Aircraft Propulsion (EAP), encompassing both hybrid-electric and fully electric propulsion, which enables a reduction in emissions as well as the potential for cost savings. However, many regulatory agencies are still adapting to these new technologies and do not yet provide a clear path to certification for these aircraft. This results in a need to investigate the regulatory and certification requirements for novel aircraft designs throughout the design process, starting at the trade space study and conceptual design level.

NASA's X-57 "Maxwell," a concept demonstrator for distributed electric propulsion, is an excellent example of how the technology and certification regulations can be developed side by side, leading to adoption of the technology by the broader aerospace community. The X-57 project developed a process for identifying the current standards and regulations that would apply to a conventional aircraft of the same type and then identified those that would require significant changes for the X-57 aircraft [1]. This process involved a coordinated effort with regulators to identify barriers and develop new regulatory standards to permit the use of innovative technologies [2, 3]. An additional goal of this work was to assist in the widespread and commercial adoption of these technologies within the aviation community [3].

Although there are many proposed concepts, no hybrid-electric transport category aircraft has been certified by the Federal Aviation Administration. Many of the certification and regulatory requirements for such an aircraft have not yet been developed, so each aircraft design team must investigate the regulatory barriers through a gap analysis and develop a certification and regulatory approach tailored to the specifics of their aircraft concept. As previously mentioned, this process should be iterative and developed alongside the aircraft concept. The objective of this work is to identify the initial regulatory and certification barriers for the SUbsonic Single Aft eNgine (SUSAN) Electrofan concept and provide preliminary approaches for how these requirements can be tailored for the design.

This paper will give an overview of the SUbsonic Single Aft eNgine (SUSAN) Electrofan concept, focusing on the aspects that make the aircraft unique from a regulatory and certification standpoint. The paper will then present the current barriers that prohibit or significantly restrict the certification or operation of this concept. Next, the paper will discuss the initial approach for how this aircraft concept will maintain the safety intent of these regulations. Finally,

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the paper will conclude with a summary of this work and the ongoing examination of the regulatory and certification approach as the SUSAN Electrofan concept continues its development.

II. SUSAN Electrofan Concept

The SUbsonic Single Aft eNgine (SUSAN) Electrofan concept, shown in Fig. 1, is designed to reduce cost, emissions, and fuel usage by utilizing EAP. The aircraft is designed to fit within the existing regional transport market, with 180 passengers and a range of 2500 nautical miles at a cruise altitude of 37,000 feet. An initial mission profile for the SUSAN concept is shown in Fig. 2, which illustrates initial timing estimates for multiple stages of flight as well as the 750 nautical mile range for the economic mission. Figure 3 reflects a common sizing mission profile, which includes additional reserve requirements for fuel allowance, missed approach, and additional cruise and descent segments. More detail about the current design and trade space is included in Ref. [4], this section will focus on the components of the design that make this concept unique from a certification standpoint.

Fig. 1 An artist's rendering of the SUSAN Electrofan concept, illustrating the T-tail, single aft turbofan, and the wing-mounted electric engines.

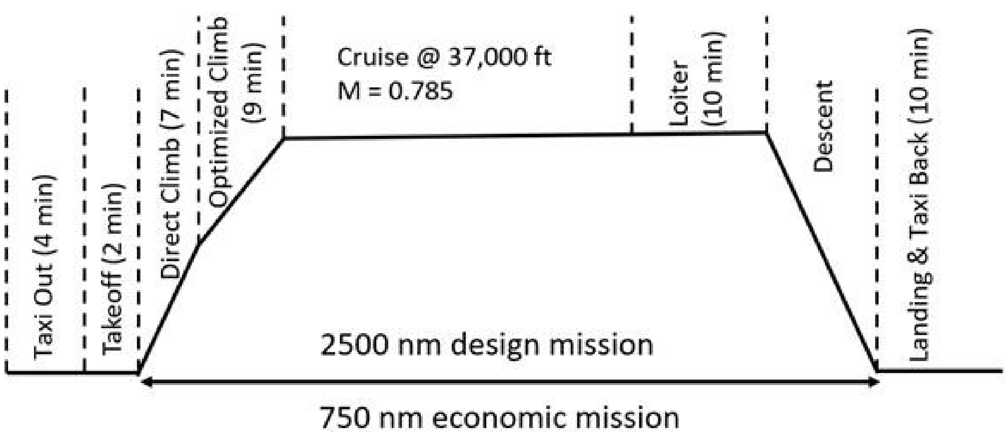

Fig. 2 Nominal mission profile for the SUSAN Electrofan concept.

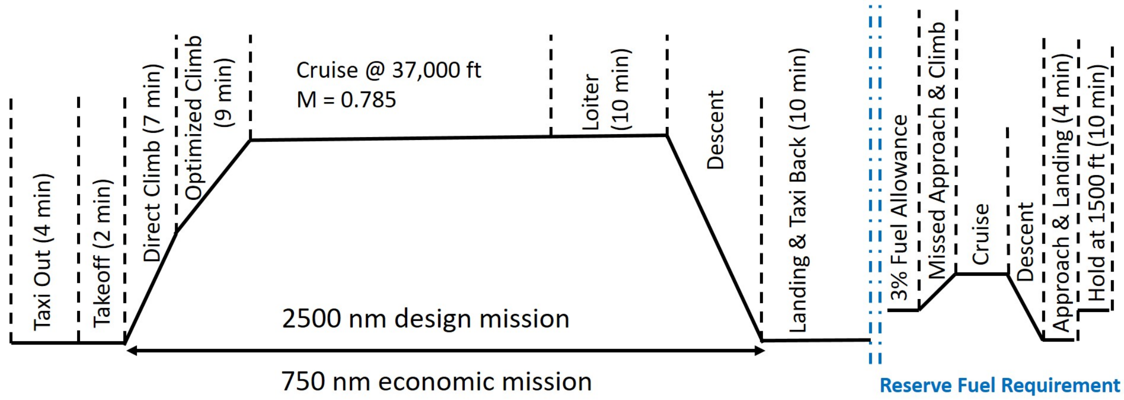

Fig. 3 Nominal mission profile for the SUSAN Electrofan concept with included reserve fuel requirements.

One of the unique aspects of the SUSAN Electrofan concept is the series/parallel hybrid EAP system with a turbogenerator. With this system electric power can be distributed and shared between the wing-mounted electric engines and the main turbofan. This hybrid system enables a single turbofan, reducing the amount of emissions-generating fuel required. In the case of turbofan failure, a dedicated backup battery capable of powering all of the electric engines and necessary electronic equipment is included, as shown in Fig. 4. The concept also includes a redundant wiring system, reducing the possibility of a single point electrical failure disabling all of the electric engines. More details about the hybrid-electric propulsion system can be found in Refs. [5], [6], and [7].

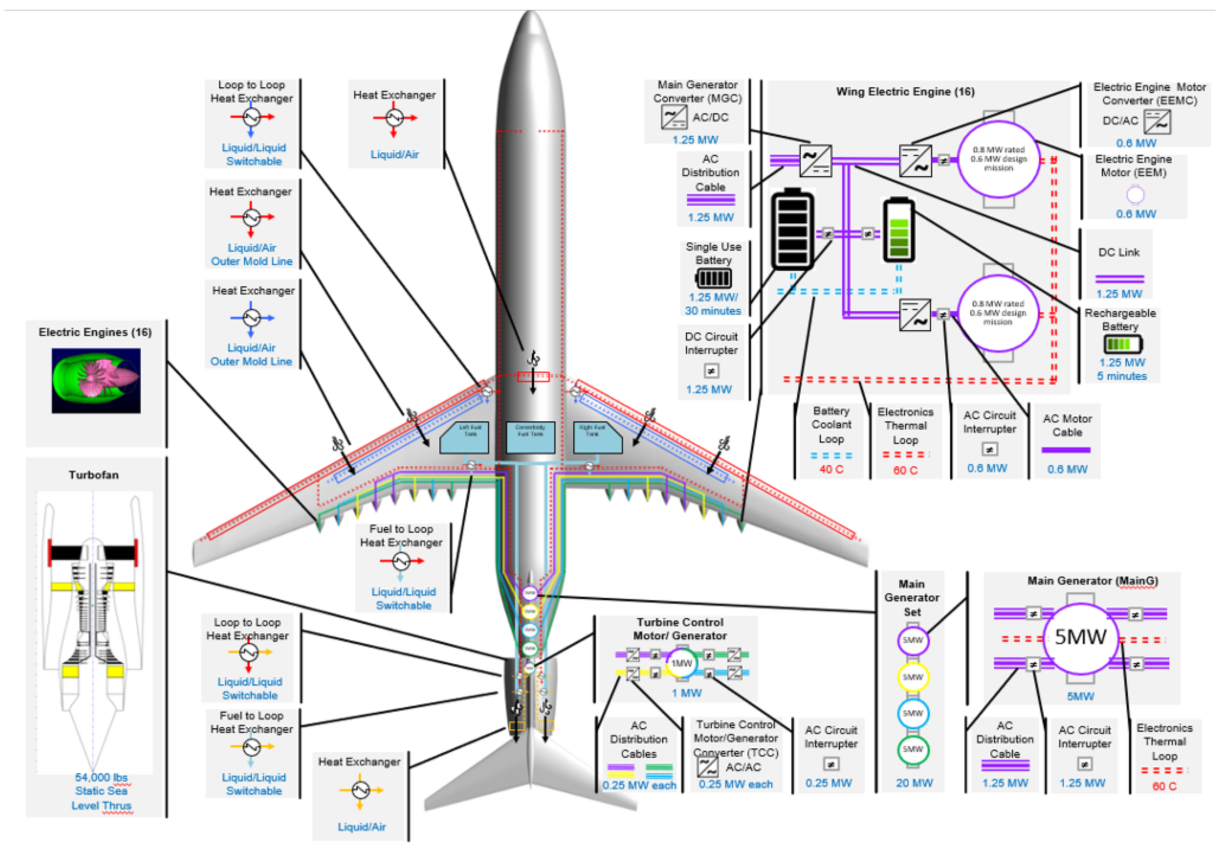

Fig. 4 An initial internal system layout diagram for the SUSAN Electrofan concept, showing the single aft turbofan, the wing-mounted electric engines, the emergency backup battery, and the redundant wiring system.

III. Current Regulatory Barriers

Transport category aircraft are generally certified under Title 14 Code of Federal Regulations (CFR) Part 25, with engines certified under 14 CFR Part 33. These aircraft are typically operated per the rules under 14 CFR Part 121 and the aforementioned rules tend to reflect the traditional "tube and wing" designs in use for decades. However, just as the transition from propeller to turbojet propulsion significantly impacted the aviation industry and certification requirements, the transition to electric propulsion requires modifications to these standards. A full regulatory gap analysis for the SUSAN Electrofan has been conducted - this paper will focus on a subset of those results [8]. Further analysis will be performed throughout the remainder of the design and implementation process.

A. Design and Production Certification

As with any large aircraft designed for commercial transport, the SUSAN concept must obtain type design and approval for the aircraft using 14 CFR Part 25 for Transport Category Airplanes. The technologies and operational concepts embodied by the SUSAN concept necessitate significant changes to the requirements or means of compliance to enable certification [8]. As updated standards are being developed for energy generation and storage, the SUSAN concept must remain aligned with the revised standards. Means of compliance for demonstrating the continued safe operation of the hybrid-electric turbofan and the distributed electric propulsion system must be developed to align with 14 CFR Part 25 Subpart E [9].

Aircraft engines must obtain approval under 14 CFR Part 33. However, although there are Subparts for both reciprocating and turbine engines, there are not yet regulations in place for electric propulsion systems. A special condition for the type certification of an electric engine under Part 33, recently released by the FAA, provides insights to future regulations for electric aircraft [10]. The European Union Aviation Safety Administration (EASA) has released a proposed special condition for Electric and Hybrid Propulsion Systems, which proposes similar requirements [11]. Although both of these special conditions are focused on current electric engine designs, the future of electric engine regulations to address SUSAN-class electric engines is promising.

B. Airspace Integration and Route Proofing

As a transport category aircraft, the SUSAN Electrofan concept is designed to operate under 14 CFR Part 121. Although the name - SUbsonic Single Aft eNgine - may raise concerns that the aircraft is not in compliance with §121.159, which states "single engine airplanes are prohibited," the concept also contains 16 wing-mounted electric engines. One important consideration is how this unique configuration interacts with various operational requirements, particularly those defined by engine inoperative conditions.

Another operating regulation, ETOPS (ExTended OPerationS, formerly Extended Twin-engine OPerationS), determines acceptable flight paths for multi-engine passenger-carrying aircraft in the event of a loss of engine power[12]. Importantly, this requirement only considers the acceptable flight areas and is separate from any reserve fuel requirements, which provide additional range past the desired landing airport. Because the SUSAN concept relies on the single turbofan to power the electric engines, compliance with ETOPS regulations will take some tailoring to the requirements and design.

C. Maintenance and Continued Airworthiness

Alongside the type certification process, there are specific requirements for the maintenance and continued operation process for transport class aircraft. Many components are covered by existing 14 CFR Part 43 standards, but training and maintenance procedures for any novel features must be defined and approved. For the SUSAN aircraft, this includes the electric engines, the unique aft-mounted turbofan, the rechargeable multi-use battery, the single use backup battery, and the extensive electrical and control systems used to power and operate the aircraft. Throughout the development of the concept, the ease of access for maintenance, the frequency of repairs or replacement for individual parts, and the overall system reliability must be considered.

IV. Regulatory and Certification Approach

Although the SUSAN Electrofan concept is still early in the trade space and conceptual design process, the regulations and gaps identified in Section III can already be applied to the design. This regulatory identification and certification approach assessment will be an iterative cycle that is performed many times as the aircraft concept is further developed. The items included in this paper are not a final comprehensive list, rather they are a sampling of the certification requirements that are currently being addressed.

A. Airspace Integration Requirements

The ETOPS requirement was designed with twin turbine engines in mind and has been updated as more engines were added and engine reliability increased. As of 2007, ETOPS regulations for passenger aircraft only apply to two-engine airplanes more than 60 minutes of one-engine-inoperative flying time away from a suitable airport or airplanes with more than two engines operating more than 180 minutes of one-engine-inoperative flying time away from a suitable airport [12]. Because the SUSAN Electrofan concept has a single turbine engine and 16 electric engines, how ETOPS would be applied for this novel configuration is unclear. However, establishing the range that the aircraft could fly on the backup battery system in the event of failure of the turbofan is important. This range, similar to ETOPS requirements, would determine the allowable flight paths for the aircraft, influencing its operational area. Figure 5 shows the operational area for the SUSAN concept, assuming a battery sized to provide 30 minutes of flying time at Mach 0.785 (approximately 300 nautical miles), while Fig. 6 shows the equivalent operational area for 15 minutes of flying time at Mach 0.785 (approximately 150 nautical miles). In both figures, the shaded blue areas indicate the area within the given flying time of a suitable airport - defined in this preliminary analysis as any US Primary Airport designated by the FAA as Large, Medium, or Small by passenger metrics. For the 30 minutes of flying time scenario, the covered area includes almost all of the contiguous United States, with only small areas in the Northern Plains and Maine not included. The shorter flying time of 15 minutes covers significantly less geographical area, but still includes the travel heavy corridors along the East Coast and West Coast. Although the exact flight time and range are still to be determined, the ETOPS-like requirement allows the SUSAN Electrofan concept to fulfill its intended role as a regional transport aircraft.

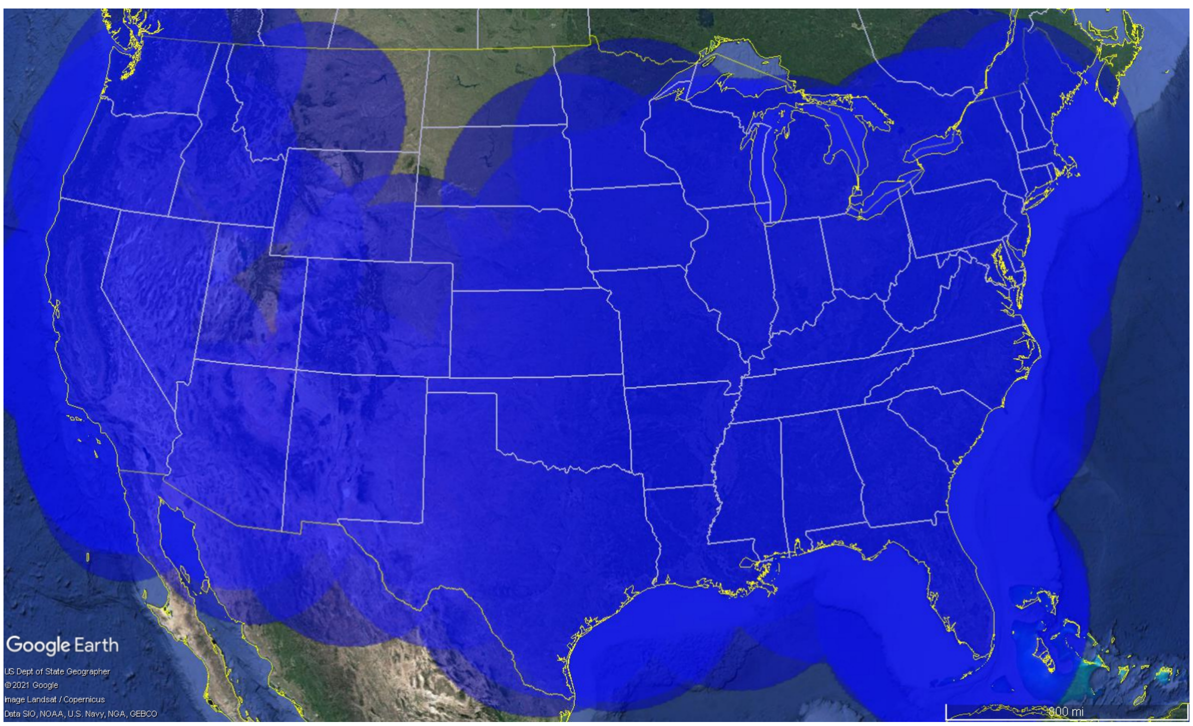

Fig. 5 Area covered by 300 nautical mile radius from US Primary Airports, equivalent to 30 minutes flying time at Mach 0.785, shown in blue shading.

B. Takeoff and Climb Requirements

As mentioned in Section III.A, the unique hybrid-electric propulsion included in the SUSAN concept, which consists of a single traditional fuel-burning turbofan and 16 wing-mounted electric engines, will require adaptation of the current regulations. A prime example of this is the engine out takeoff requirements, detailed in §25.105-25.115 [9]. For a

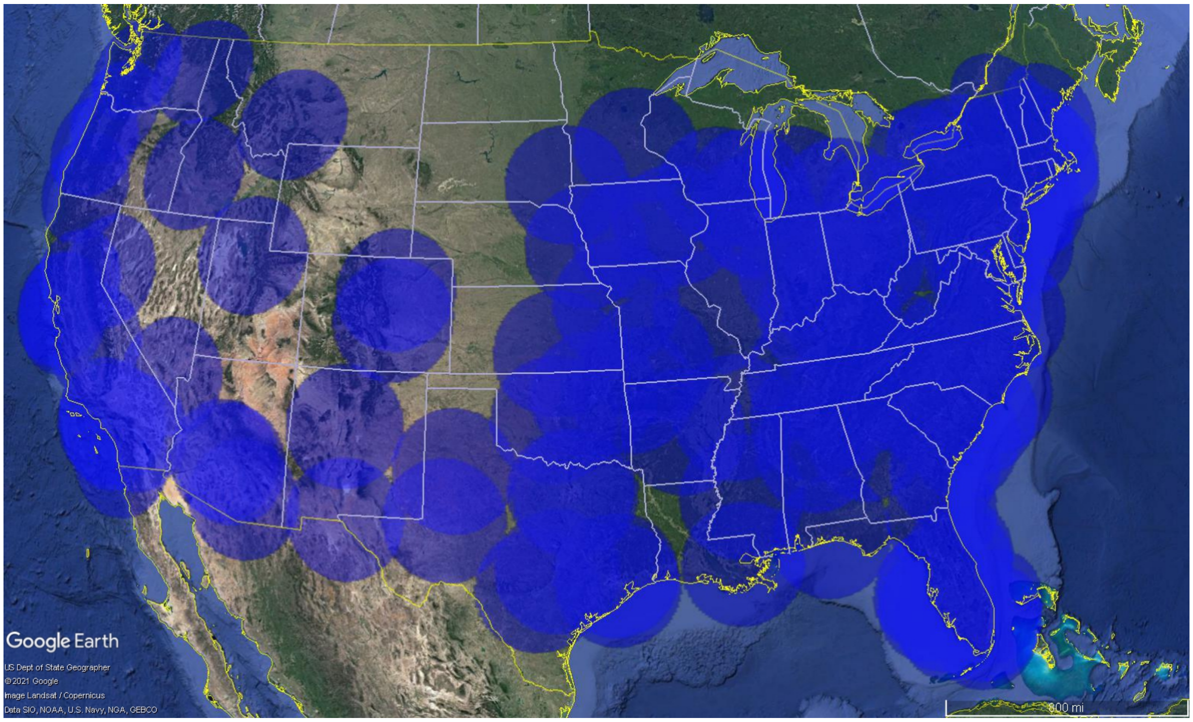

Fig. 6 Area covered by 150 nautical mile radius from US Primary Airports, equivalent to 15 minutes flying time at Mach 0.785, shown in blue shading.

multi-engine aircraft, after a failure of the critical engine at or above the final takeoff velocity, the aircraft must still be able to complete the takeoff, maintain adequate speed, and meet a specified climb gradient. After the loss of the single turbofan, the aircraft operates entirely under electrical power using the backup battery, which is sized to support the power requirements of takeoff. The aircraft is designed to enable climb at a reduced rate compared to the nominal case and cruise at a reduced altitude and speed, allowing the aircraft suitable time to execute a safe landing with a maximum flight range of 300 nautical miles.

Although the loss of a single electric engine would have a smaller effect on the overall performance of the aircraft, a good practice is to design for this failure and ensure regulatory requirements are met. As shown in Fig. 7, in the event of a loss of a single electric engine above the final takeoff velocity, the SUSAN concept is designed to still be able to climb normally and reach the nominal cruise altitude and speed. However, to minimize the risk of additional failures, the maximum flight time will be limited post-failure (initially set as 1 hour), as shown in green. With the design cruise Mach of 0.785, this is approximately equivalent to 600 nautical miles, almost the entirety of the assumed economic mission. Because of the redundancy in electric engines, the SUSAN aircraft could potentially still complete the intended mission, even in the event of an electric engine failure.

C. Electrical and Battery Requirements

Because of the unique hybrid-electric propulsion system included in the SUSAN Electrofan concept, many of the relevant regulations and requirements have not been fully developed. Compared to other existing distributed electric propulsion concepts, including the X-57 and NASA's Electrified Powertrain Flight Demonstration, the SUSAN aircraft requires a much larger power draw, on the order of 10s of megawatts. The power requirements and the infrastructure to safely and consistently maintain operation are an area of continued research and development. As mentioned in Section II and Fig. 4, the wing-mounted electric engines are configured in a redundant manner which reduces the likelihood of a single point failure rendering all electric engines inoperable. Although the design is still in the early stages, the turbofan is designed to provide consistent and distributed power to the 16 electric engines.

The SUSAN Electrofan concept contains two batteries - a small, rechargeable battery that is used to temporarily power the electric engines and maintain even voltage, and a larger, single use battery that is used only in the event of turbofan failure. The backup battery was sized to minimize overall aircraft weight while still allowing for continued

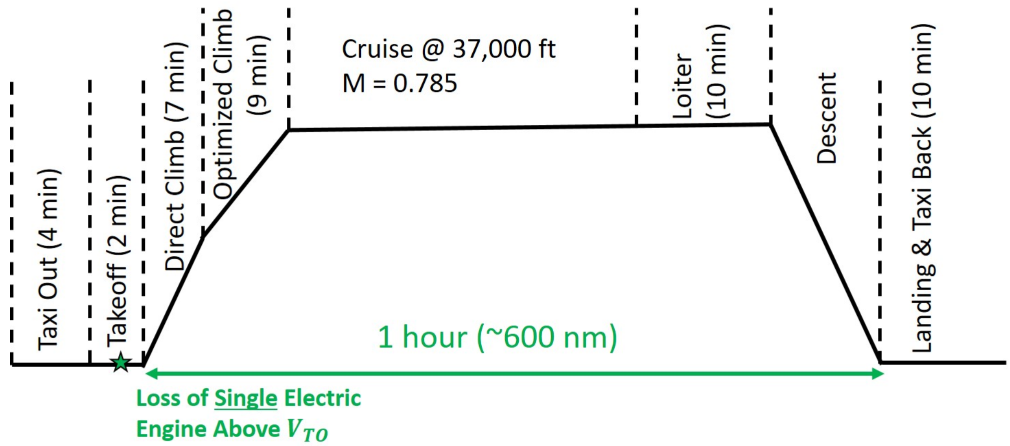

Fig. 7 Mission profile for the SUSAN Electrofan concept in the event of loss of a single electric engine at or above final takeoff velocity.

flight after turbofan failure. The sizing results in a backup battery that is capable of powering the electric engines for approximately 30 minutes, allowing sufficient time for the aircraft to reach a suitable alternate airport and land. Turbofan failure during cruise, resulting in the loss of both thrust and electric power, is illustrated in the modified mission profile shown in Fig. 8, where the portions of flight under electric power only are indicated in orange. Due to the significant portion of the aircraft thrust from the turbofan, the aircraft would perform an emergency descent, allowing the aircraft to fly at the optimal altitude and velocity to an alternate airport. Based on the maximum electric-only operation Mach of 0.785, the 30 minutes of flying time equates to a maximum of 300 nautical miles in range, although the exact range will be determined in further analysis.

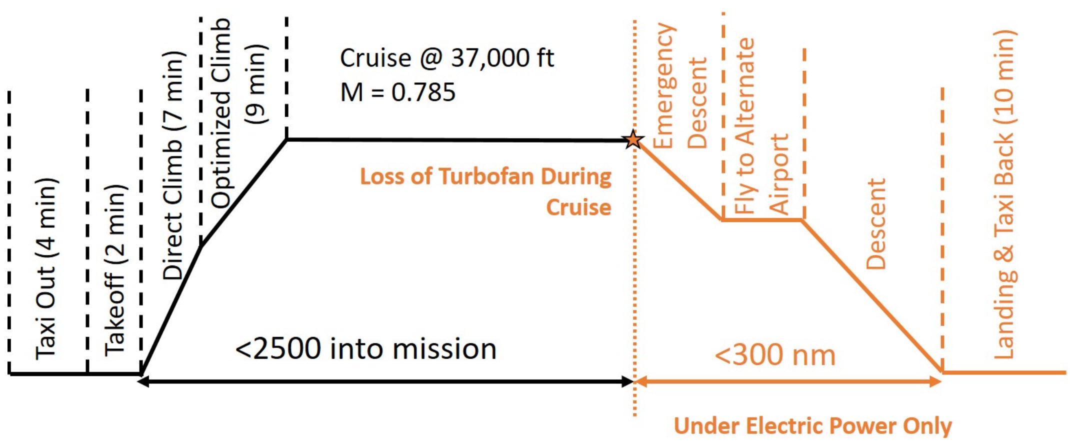

Fig. 8 Mission profile for the SUSAN Electrofan concept in the event of loss of the turbofan during cruise, illustrating the emergency descent to allow for optimum cruise to an alternate airport for descent and landing under electric power only, indicated in orange.

Similar to the reduced effects seen when a single electric engine is lost during takeoff, the loss of a single electric engine during cruise does not have as dramatic of an effect as the loss of the turbofan. Figure 9 shows this effect - although there is the loss of a single electric engine, the aircraft is designed to be able to continue cruise at the nominal mission altitude and speed, for no longer than one hour, as indicated in green. With a nominal mission cruise Mach of 0.785, one hour of flight time is equivalent to approximately 600 nautical miles, which almost all of the economic mission range of 750 nautical miles. In most cases, the SUSAN concept is expected to be capable of completing the intended mission in the event of a loss of a single electric engine during cruise.

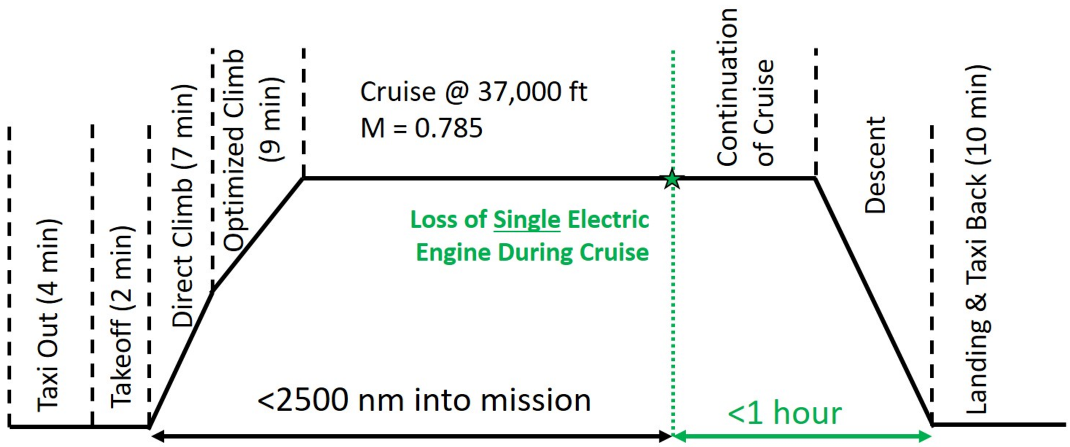

Fig. 9 Mission profile for the SUSAN Electrofan concept in the event of loss of a single electric engine during cruise, illustrating the continued cruise at nominal altitude and velocity with a maximum flight time after failure of one hour, as shown in green.

V. Summary and Conclusions

A summary of the key regulatory and certification barriers has been presented for the SUSAN Electrofan concept as well as initial thoughts on how these barriers can be addressed for this aircraft. Due to the unconventional nature of the SUSAN concept, including the novel hybrid-electric distributed electric propulsion system, some current regulations cannot be directly applied and must be revised to accommodate this design. The intent behind other regulations, such as the Extended Operations (ETOPS) requirement, can be met with minor changes to the existing standards or the design. This early insight to the certification approach for the SUSAN concept, while the design is still undergoing trade space exploration, allows the development of the aircraft alongside any modifications to certification standards. An example benefit of this timing is the aircraft sizing, which is able to account for aerodynamic and inertial requirements as well as the regulatory requirements. Coordinating these processes will ideally reduce the time needed to develop new regulatory standards and ease the approval process for novel hybrid-electric aircraft designs.

To further develop the design, establish the performance of the aircraft, and assist in the development of potential means of compliance methods for the SUSAN Electrofan concept, a series of subscale flight research aircraft are planned. The smallest, a 5% scale, radio-controlled aircraft, will demonstrate basic thrust augmented steering functions. The second, a 25% scale aircraft, will be used to develop and demonstrate integrated flight, propulsion, and power system control algorithms. These subscale concepts, crucial to the development of the aircraft, provide a significant benefit to the certification and regulatory approach as a test case for the requirements and performance-based means of compliance. Performance-based means of compliance have previously been used for smaller aircraft but have not yet been used for passenger-carrying transport class aircraft.

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