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Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept and Trade Space Exploration

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A trade space exploration of a new NASA regional transport aircraft concept called the SUbsonic Single Aft eNgine (SUSAN) Electrofan is presented. The SUSAN concept uses a 20MW Electrified Aircraft Propulsion (EAP) system to enable advance Propulsion Airframe Integration (PAI) in transport category aircraft. Alternative fuels will be used to reduce the amount of emissions per energy used. By combining these features there is the potential to reduce aircraft emissions by 50% per passenger/mile while retaining the size, speed, and range of large regional jets. SUSAN has a 750 mile economic mission, a 2500 mile design range and a maximum capacity of 180 passengers. The SUSAN configuration utilizes a single aft mounted engine and distributed electric wing-mounted thrusters on a tube and wing arrangement with a T-tail empennage. The SUSAN Electrofan employs a hybrid powertrain to enable: single turbofan operation on a large transport category aircraft; increased aerodynamic and propulsive efficiency through placement of electric engines; optimized turbofan sizing and efficiency through control and electric boosting, reduced control surface sizing through thrust augmentation. A single use battery is employed as the power source in case of turbofan failure. The design study also considers the constraints of operating within the current airport, airspace and economic constraints. This paper presents the status of the trade space exploration; however the concept definition is not finished. Forward work includes optimizing the overall aircraft configuration and including certain hard to model features like boundary layer ingestion or natural laminar flow across all appliable subsystems. Additional work forward work is a more extensive analysis of the configuration using alternative fuels.

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I. Introduction

The International Civil Aviation Organization (ICAO) has established two aspirational goals for the international aviation sector: a 2% annual fuel efficiency improvement through 2050 and carbon neutral growth from 2020 onwards. Another driving factor in aviation is the reduction of cost while maintaining extremely high safety standards which combine to drive the continued growth. The SUSAN concept is intended to address both key drivers in aircraft design.

This paper outlines the ongoing trade space exploration of the SUbsonic Single Aft eNgine (SUSAN) Electrofan aircraft concept. The Subsonic Single Aft Engine (SUSAN) Electrofan is a 180 passenger regional aircraft concept with a design range of 2,500 nmi, an economic range of 750 nmi and a cruise Mach number and 0.785, respectively (Figure 1). SUSAN utilizes 20 MW Electrified Aircraft Propulsion (EAP) system to enable advanced Propulsion Airframe Integration (PAI) in transport category aircraft in order to reduce the amount of energy used per passenger mile. Alternative fuels will be used to reduce the amount of emissions per unit energy used. By combining these features there is the potential to reduce aircraft emissions by 50% per passenger/mile while retaining the size, speed, and range of large regional jets. Although the SUSAN Electrofan has the passenger capacity of a large single aisle aircraft, its range is similar to that of the latest regional jets, which is why it is categorized as a regional jet.

Figure 1 Artist Rendering of Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept (credit Eric S. Mindek.

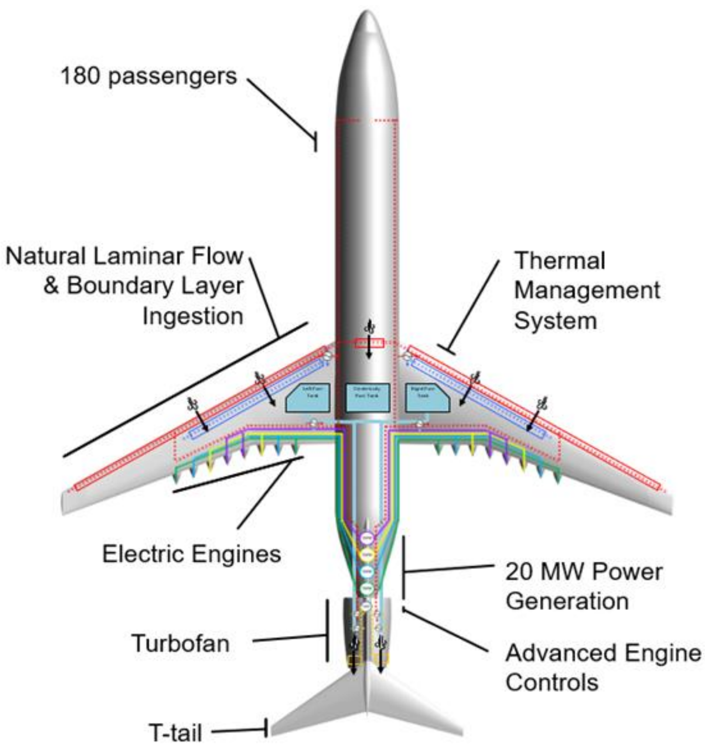
A. SUSAN Aircraft Concept

. The SUSAN trade space exploration intends to define an aircraft configuration that uses a combination of a hybrid EAP system, advanced propulsion aircraft integration (PAI), and alternative fuels to fulfill its mission (Figure 2). The target market application is the regional jet class of transport aircraft. The key performance metrics are total energy use, emissions, noise, and total cost of ownership. The current configuration is a tube and wing style aircraft with a single aft engine, a T-tail, and distributed electric propulsors (DEP) on the wings. Configurations using standard Jet-A fuel as well as alternative fuels are being traded. The aft, ducted turbofan produces thrust directly and drives four generators producing 20MW of electrical power for sixteen wing mounted electric engines. A relatively small rechargeable battery is used in combination with the EAP system to optimize the performance and sizing of the turbofan. A large single use battery is used only in engine out scenarios to power the propulsion system and allow the aircraft to safely conduct an emergency landing. The wing is a relatively conventional wing, however natural laminar flow techniques are implemented to reduce drag on a portion of it.

The SUSAN Electrofan employs a hybrid Electrified Aircraft Propulsion System to enable:

a) Single turbofan operation on a large transport category aircraft
b) Increased aerodynamic and propulsive efficiency through placement of electric engines
c) Optimized turbofan sizing and efficiency through control and electric boosting
d) Reduced control surface sizing through thrust augmentation

Trade studies are being conducted to determine if a significant reduction in energy use can be attained from the use of these features. One challenge of the trade studies is the highly coupled nature of airframe, wing, propulsion, and power system design. We are addressing the challenge by conducting parallel design studies and bringing them together through a methodology that links low fidelity analysis to medium fidelity computational fluid dynamics tools. The second challenge in analyzing this configuration is estimating future subsystem performance and understanding the sensitivity of the overall aircraft to that performance. We are addressing this challenge by using parametric design studies on a number of the subsystems. Forward work includes optimizing the overall aircraft configuration and including certain hard to model features like boundary layer ingestion or natural laminar flow across all applicable subsystems. Additional forward work includes analysis of a configuration using alternative fuels.



<u>Concept</u>

Regional Low-Cost Carrier Airliner
- Entry into Service 2040
- Hybrid Electric Distributed System
- 20MW Total Power
- Single Aft Mounted Turbogenerator

<u>Features</u>

Payload	180 passengers
Range (design/economic)	2500/750 miles
Speed	0.80 Mach
First Flight	TBD

<u>Key Technologies</u>

Electric Motor System, Drives, Cables
Advanced batteries: metal air and others

Emissions Reduction Objective: >50% with path to 100%

Noise Reduction: TBD

Figure 2 SUSAN Electrofan Features.

B. Historical Trend in Number of Engines on Transport Aircraft

Over the last 70 years the trend has been to reduce the number of engines on planes from four, to three, and now down to two. In general, the introduction of a system with fewer engines begins with shorter range applications before expanding to longer range markets as the capability evolves. Over the last few years electric and hybrid electric research aircraft have achieved flight, and small electric aircraft have been certified. The SUSAN concept was inspired by the idea that it may be possible to create a transport category aircraft with a single fuel burning engine if it is combined in a hybrid configuration with electric engines and an electrical power source. NASA commercial subsonic transport developments are guided by the objective of reducing energy use, emissions, and noise. Research activities across a range of technology readiness levels (TRL) are underway at NASA to meet this commitment. The SUSAN concept is aligned with the "Far Term" goals in the 2040-2045 timeframe.

Figure 3 shows the history of transport passenger introduction through time starting with the introduction of the turbojet and continuing with turbofan implementations. The most popular aircraft by production numbers are shown. The four jet engine passenger plane era began in 1949 with the de Havilland Comet. This was followed by the 707, DC-8, and 747 in 1968 with an ever-increasing range capability. The major three engine models were the 727, L-1011, and DC-10, with each growing in range. Since then, the prevalent configuration has been the two engine, with the capability of two engine aircraft growing tremendously over the last five decades in terms of both range and passenger count.

Reducing to a single fuel burning engine is the next step in the evolution of aircraft engine count. A hybrid system with both a fuel burning and an electrical power source has the potential to provide a path to a single engine propulsion system for a transport class aircraft that retains the range and speed of other aircraft in the category. Although it may be appealing to consider a reduction to zero fuel burning engines, with current technology levels, an all-electric aircraft is only possible for relatively for short-ranged low speed aircraft.

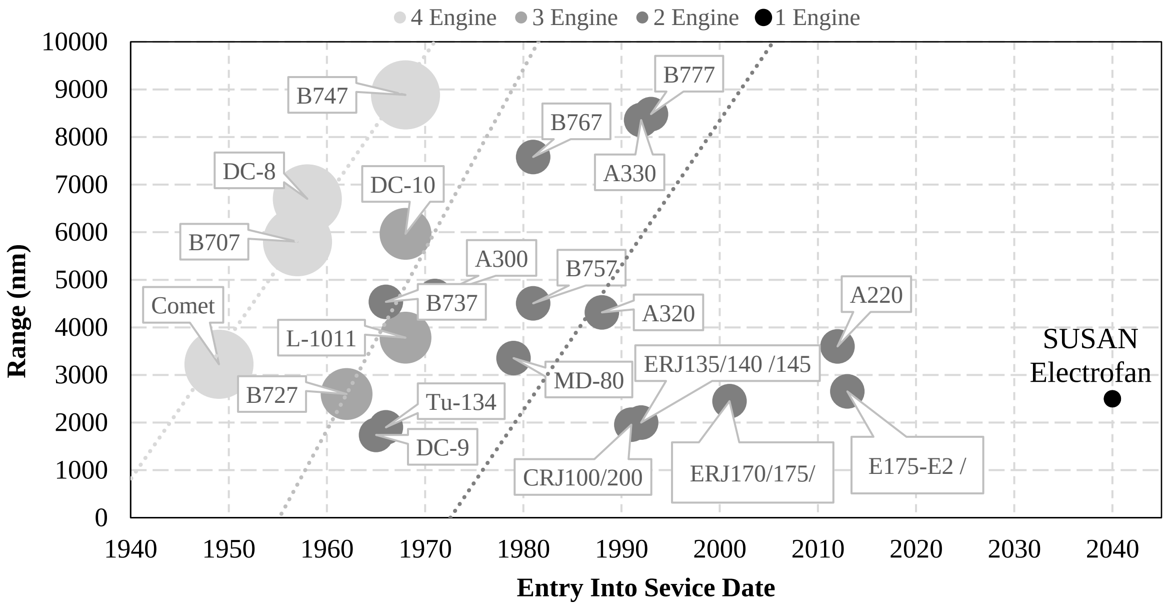


Figure 3 Number of Engines Through Time.

II. Market

A basic analysis of three large domestic carriers in the U.S. and two large European regional carriers was conducted to determine the aircraft passenger size, economic, and design range requirements.

Figure 4 shows the distribution of flights as a function of aircraft passenger capacity for three representative U.S. airlines during the period of 1990 to 2019 based on data from the U.S. Department of Transportation, Bureau of Transportation Statistics, Form 41 Traffic, Schedule T-100. It can be observed that 84% of the flights are serviced by aircraft with capacity 150 and 200 passengers. Analysis of two European regional carriers indicated the use of a limited number of aircraft models with seat counts between 156 and 189 passengers configured as a single economy seat class. The SUSAN aircraft capacity requirement was set at 180 passengers which covers more than 92% of the departures in the study.

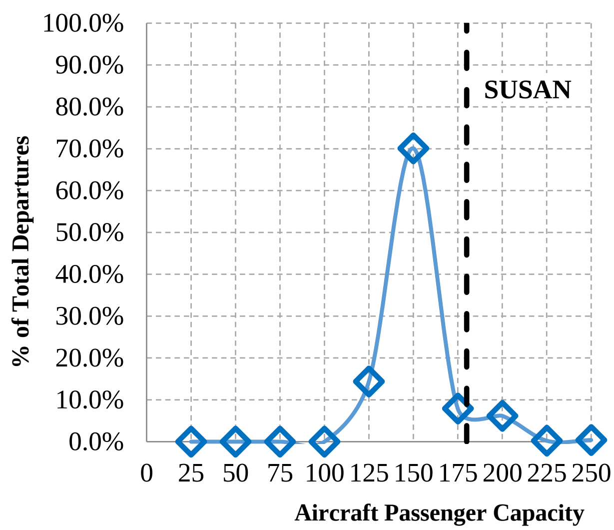


Figure 4 Aircraft Passenger Capacity Distribution.

Figure 5 shows the distribution of flights as a function of segment range for the same three representative U.S. airlines during the period of 1990 to 2019 based on the U.S. Department of Transportation data. It can be seen that the peak of the flight distribution is at 500 miles and number of segments above 1250 miles drops off rapidly. The two representative European airlines average sector length were 683 and 790 miles with longest route of 2,425 and 2,655 miles respectively. The SUSAN design range was set at 2500 miles which covers 99% of the segments flown by the U.S. carriers studied. The economic range was chosen at 750 miles which is covers 65% of the segments considered in this initial study.

Additional market studies are being conducted to include a broader set of representative data and better coverage of world wide utilization cases.

III. Concept of Operations

The SUSAN Electrofan is being designed to operate within the existing airport infrastructure and airspace operational constraints. Although these constraints make the problem of achieving significant energy benefits more challenging, they are critical to the likelihood of the idea developing beyond the study phase.

The limitation of using existing airports has a major impact when developing an aircraft that uses Electrified Aircraft Propulsion (EAP). The SUSAN aircraft only uses fuel as an energy source. **It has no plug in electrical charging or battery swapping requirements as part of the operational concept.** The 20MW EAP system is instead used to enable aero and propulsion benefits which concurrently reduce the fuel, energy, and emissions of the aircraft as enumerated above.

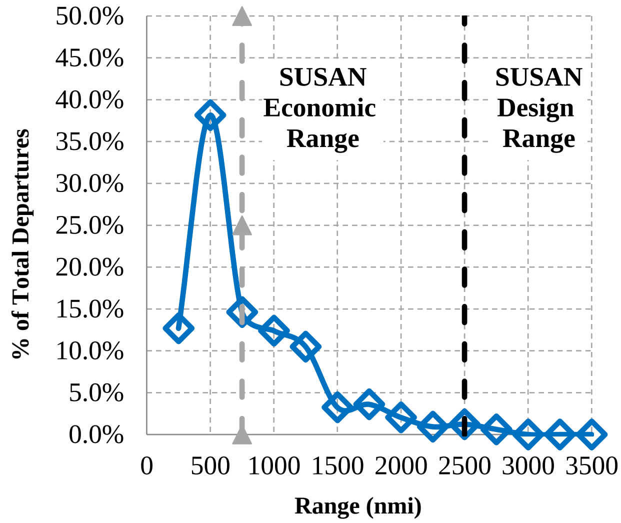


Figure 5 Range Distribution.

Operations within the current air traffic and airspace management system have been used to determine key requirements like cruise speed, minimum climb rates, and operating altitudes. Work is ongoing to define and understand the design implications of requirements like extended-range twin-engine operational performance standards (ETOPS) and one engine out takeoff in the context of an aircraft with one fuel burning and sixteen electric engines; however, the intent is to make the SUSAN aircraft performance similar to existing single aisle aircraft. The SUSAN Electrofan is focused on routes that do not fly for long periods across open oceans, because the range with the aft turbine engine failed is expected to be around 300 miles. These types of routes meet the needs of regional and domestic airlines, which are the target market for this concept.

Fuel selection is important for further definition of the SUSAN concept and the potential emissions benefits. The trade studies so far have focused on a variant which uses standard Jet-A fuel. Being able to operate on Jet-A is critical to introduction of a new aircraft in the near term because of the existing airport infrastructure capabilities. It is likely that sustainable aviation fuels will play a significant role in reducing aircraft emissions because of their ability to substitute for existing fuels and operate within the already existing fleet which increases the speed of their impact. The intent is that the SUSAN Electrofan will be compatible with sustainable aviation fuels (SAF). Studies that potentially will be conducted after the Jet-A and SAF concepts are will center on fuels that have the potential to reduce emissions to zero. It is likely that those fuels will require infrastructure and operational changes to introduce them into fleet use.

An initial mission profile for the SUSAN concept is shown in Figure 6, which illustrates initial timing estimates for multiple stages of flight; the 2500 nautical mile design and 750 nautical mile range for the economic mission; and additional reserve requirements for fuel allowance, missed approach, and additional cruise and descent segments.

A detailed concept of operations for the SUSAN Electrofan will be developed as the concept matures. Additional information on off nominal operation, maintenance constraints and operations using alternative fuels are key areas that need to be matured.

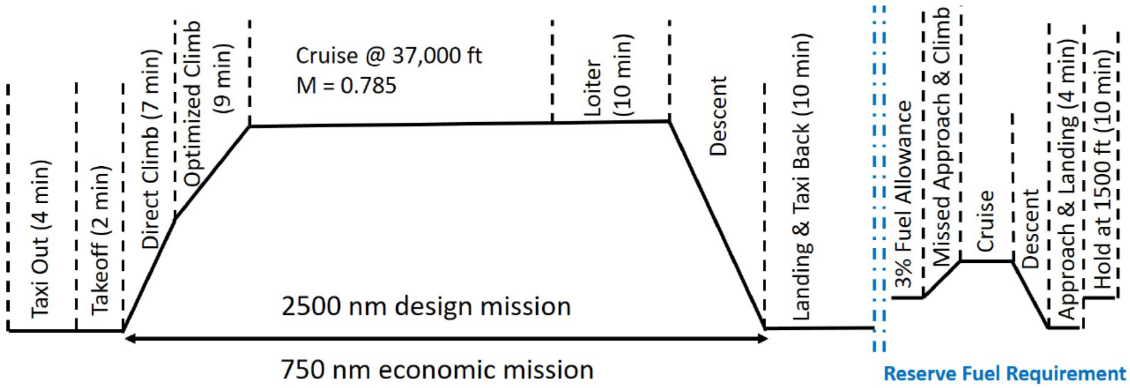


Figure 6 Nominal mission profile for the SUSAN Electrofan concept with included reserve fuel requirements.

IV. Regulations and Standards

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 current variant of SUSAN Electrofan has been conducted and subset of those results are presented by Denham et al. [1]. As the SUSAN concept matures the regulatory analysis will be conducted again to make sure any new features are captured.

Three categories of regulatory barriers to the introduction of the SUSAN aircraft are currently being evaluated:

a) Design and Production Certification – establishing 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.
b) Airspace Integration and Route Proofing - because the SUSAN concept relies on the single turbofan engine combined with a large backup battery to power the electric engines, compliance with ETOPS regulations will take some tailoring to the requirements and design.
c) Maintenance and Continued Airworthiness – training and maintenance procedures for any novel features including 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 must be defined and approved.

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. A subset of the certification requirements that are currently being addressed include: Airspace Integration, Climb and Takeoff, and Electrical and Battery. For example, we are evaluating how far the SUSAN aircraft should be able to fly on the backup battery in the case of turbofan engine failure by building maps of airspaces which are within ranges of suitable alternate airports where SUSAN could land. An example of the U.S. coverage with a 300 mile battery flight range is shown in Figure 7.

By concurrently conducting the regulatory barrier analysis and the conceptual design, we are able to consider the impact of design decisions on the difficulty of certification in search of the best combination of performance and practicality.

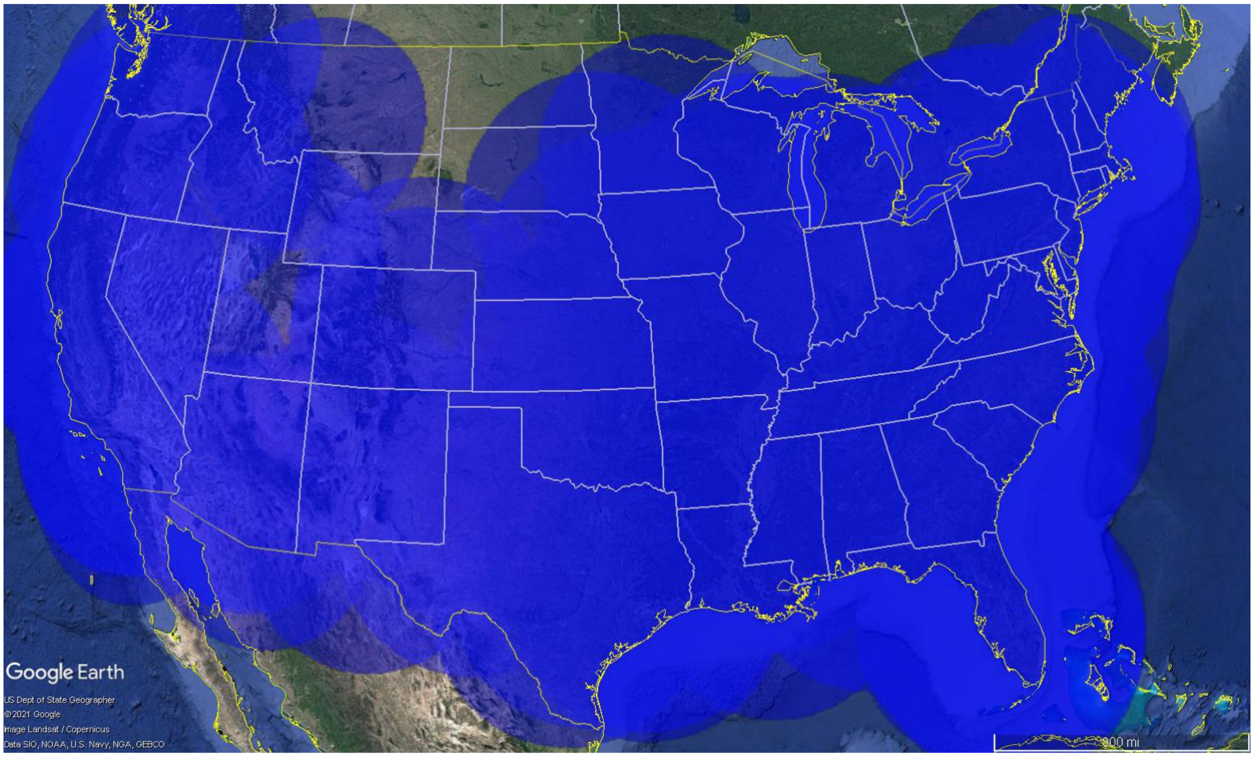


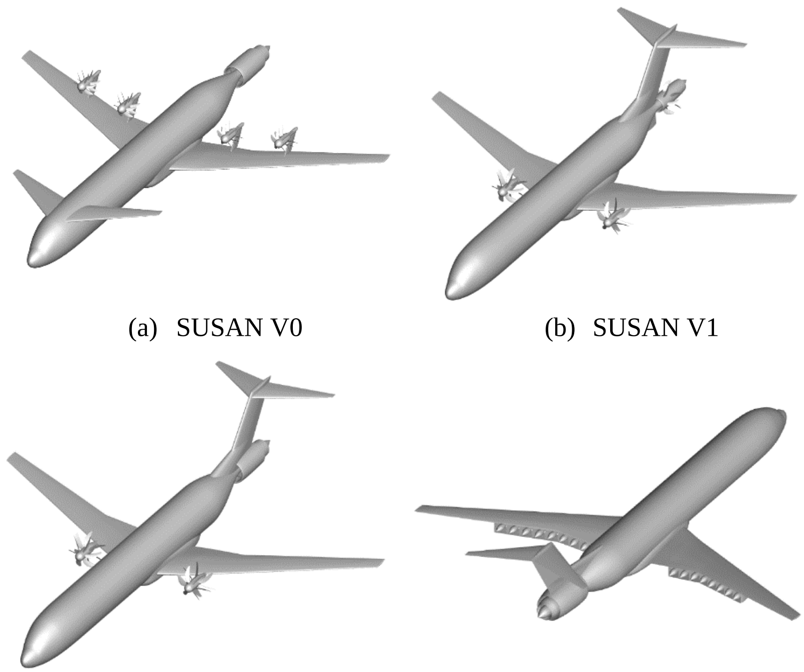
Figure 7 Area covered by 300 nautical mile radius from US Primary Airports, equivalent to 30 minutes flying time at Mach 0.785, shown in blue shading.

V. Conceptual Exploration of Aircraft and Subsystem Configurations

A trade space exploration for the SUSAN Electrofan concept was performed through both conceptual-level and detailed design methodologies.

A. Aircraft Conceptual Design

For the conceptual exploration of the aircraft configuration trade space, several concepts were considered with different combinations of hydrocarbon fuel-consuming tail-cone thrusters, electric wing-mounted propulsors, and horizontal and vertical stability and control surfaces as described by Chau et al. [2]. Each concept was evaluated based on their fuel burn performance, as well as their capacity for satisfying a set of top-level aircraft requirements. These included ducted turbofan and open rotor tail-cone thrusters with boundary-layer ingestion, over-wing and front-of-wing electric counter-rotating propfans, a distributed electric propulsion system, and canard and T-tail systems as shown in **Error! Reference source not found.Error! Reference source not found.**.



(a) SUSAN V0 (b) SUSAN V1

(c) SUSAN V2 (d) SUSAN V3

Figure 8 The evolution of the SUSAN Electrofan aircraft configuration.

The sizing and analysis of each aircraft configuration was performed through a conceptual design environment called Faber, which includes capabilities for multidisciplinary design and analysis. These capabilities are provided by low- and medium-fidelity disciplinary analysis modules, consisting of low-order models for aerodynamics, weight and balance, structures, propulsion, and performance. In order to provide a means for handling hybrid electric aircraft concepts, these disciplinary analysis modules are supplemented by propulsion system models developed through NASA's Numerical Propulsion System Simulation (NPSS) framework [3] and NASA's Weight Analysis of Turbine Engines (WATE++) code [4], as well as first-order estimates for the sizing of the electrified aircraft propulsion systems. A flow chart of Faber's sizing and analysis routine is shown in Figure 9Figure 9.

In addition to performing an initial sizing of the SUSAN Electrofan concept, the conceptual design environment also serves as a platform for synthesizing and combining the performance characteristics of the various aircraft components and subsystems, which are independently developed by the various subject matter expert teams. This enables the translation of individual performance improvements to aircraft level performance gains in the form of design weight improvements and overall fuel burn savings.

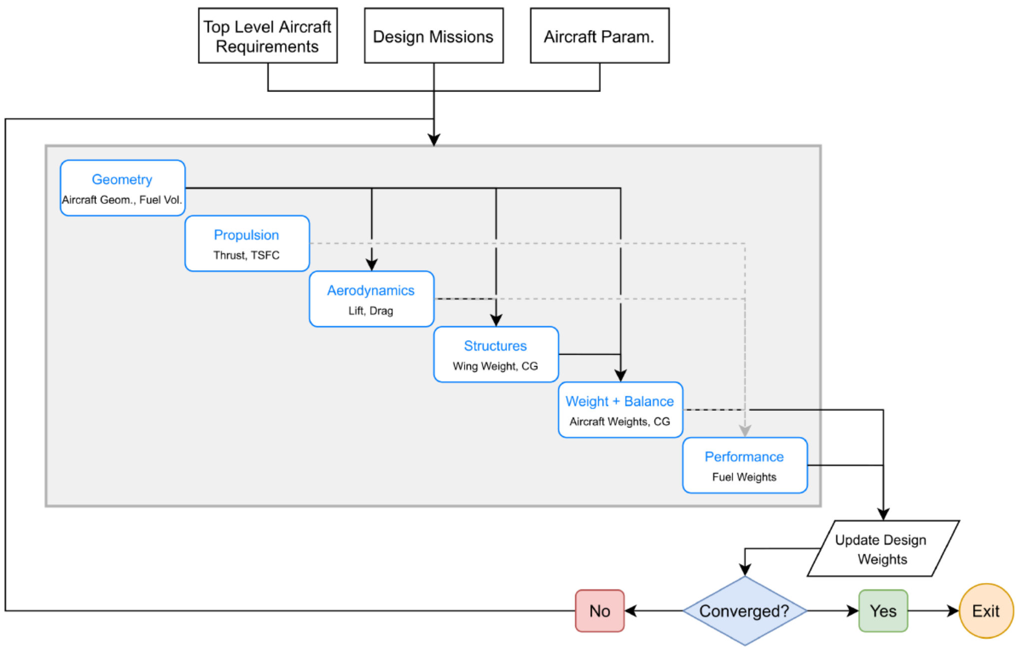


Figure 9 A flow chart of Faber's sizing and analysis routine

The fourth and current variant of the SUSAN Electrofan, as shown in **Error! Reference source not found.Error! Reference source not found.**, features a boundary-layer ingesting geared turbofan tail-cone thruster, along with an under-wing distributed electric propulsion system with sixteen low pressure ratio ducted counter rotating fan pairs in a mail-slot nacelle configuration. A T-tail configuration is also included, whose primary load paths are shared with those of the tail-cone thruster through a novel integrated structural design. This enables an extension of the tail moment arm for maintaining reasonable horizontal and vertical tail planform areas, despite the aft-positioned wing system, landing gear, and hence center of gravity location necessary for avoiding tail strike during takeoff. Initial performance estimates, which include only first-order effects and a subset of the advanced technologies being considered for the SUSAN Electrofan, are presented in **Error! Reference source not found.**. These results indicate that SUSAN V3 offers a 26.8% reduction in economy mission block fuel relative to a year 2005 baseline aircraft. This is largely due to the 29.1%

Table 1 - Conceptual analysis results for SUSAN V3

Parameter	Baseline	SUSAN V3	Δ [%]
MRW [lb]	175,020	173,260	−1.0
OEW [lb]	92,810	109,260	+17.7
MZFW [lb]	139,810	155,260	+11.1
MFW [lb]	43,980	28,370	−35.5
Weight [lb]	141,850	153,960	+8.5
Drag [lb]	8,738	8,080	−7.5
TSFC [lb/lbf/hr]	0.621	0.440	−29.1
Block fuel (750 nmi) [lb]	10,680	7,813	−26.8

Weight, Drag, and TSFC are defined with respect to the start of cruise.

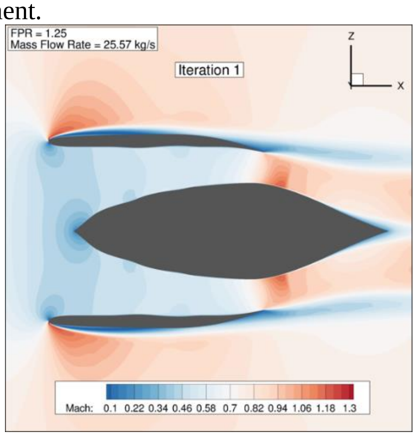
lower thrust specific fuel consumption of the propulsion system and a 7.5% reduction in drag at the start of cruise, despite an 8.5% higher weight as a result of the electrified aircraft propulsion systems and batteries.

Although preliminary assessments are promising, substantial work is required to better understand the impact of the integrated propulsion systems on aerodynamics, propulsion, and weight. The impact of other advanced technologies being considered for the SUSAN Electrofan, such as natural-laminar-flow wings, must also be quantified. Incorporating these effects into the aircraft level trades will be necessary for making a final assessment of the benefits. In addition to evaluations based on fuel burn, energy usage, and emissions for the current Jet A version of the SUSAN Electrofan, further work will also be required for evaluating the total emissions reductions offered by alternative fuels, which have the potential to reduce the quantity of emissions per unit energy usage.

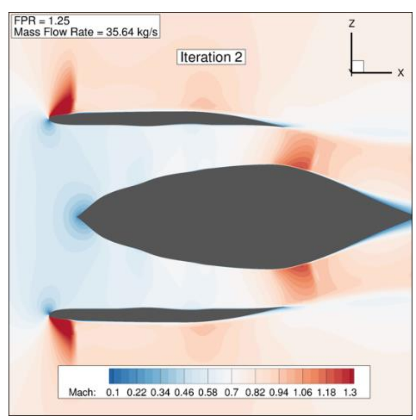
B. Propulsion and Airframe Integration Aerodynamics

Once a suitable candidate configuration was identified, the initial SUSAN Electrofan concept was subjected to more detailed aerodynamic analysis methodologies involving computational fluid dynamics (CFD) in order to verify and update the first-order estimates for system-level performance; identify integration challenges that could be addressed through the application of high-fidelity aerodynamic shape optimization tools; and to facilitate detailed component design which can have a strong dependence on the flow behavior surrounding the airframe. In this work, CFD based on the Reynolds-averaged Navier-Stokes (RANS) equations with the Spalart-Allmaras turbulence model is applied to provide accurate simulations of the flow phenomena surrounding the airframe, with particular focus on the integration challenges surrounding the boundary-layer ingesting tail-cone thruster, as well as the wing-mounted distributed electric propulsion system. In order to provide realistic flow conditions to support the development of the propulsion system, this work includes actuator zone models to simulate the effects of fan operation. More details on these studies are provided by Machado et al. [5]. Future work will include the application of adjoint-based aerodynamic shape optimization methodologies to address the challenges surrounding the propulsion and airframe integration of each subsystem.

The development of the electric engine internal flow path and the optimal method of integrating the electric engines with the wing is a complex trade between aerodynamics, propulsive efficiency, and structural considerations. Two steps in that optimization have been conducted. The first, focused on maturing a single propulsor design that could meet system level requirements which are based on a preliminary SUSAN Electrofan concept with sixteen electric engines and present overall satisfactory aerodynamic performance, by resizing and refining the outer mold line design. Examples of a subset of the free stream electric engine design iterations are shown in Figure 10. The second step addressed the airframe integration by integrating the propulsor onto a simplified wing model, in order to perform trade studies and further understanding of the coupled propulsion aerodynamic problems posed by such an architecture. Overwing, underwing, and trailing edge locations on an infinite wing section have been evaluated thus far (Figure 11) Mach contours, velocity profiles, and total pressure results at the nominal cruise condition are shown in Figure 12. Significant forward work is required to optimize the integrated electric engine / wing configuration in order to maximize the aircraft benefit over the total mission including takeoff, climb, cruise, decent, and landing. The interrelated nature of the wing shape optimization with both traditional and natural laminar flow objectives combined with propulsor optimization including disturbed flow and boundary layer ingestion, requires a complex collaboration between multiple groups using tools that typically operate independently in the preliminary phases of aircraft concept development.

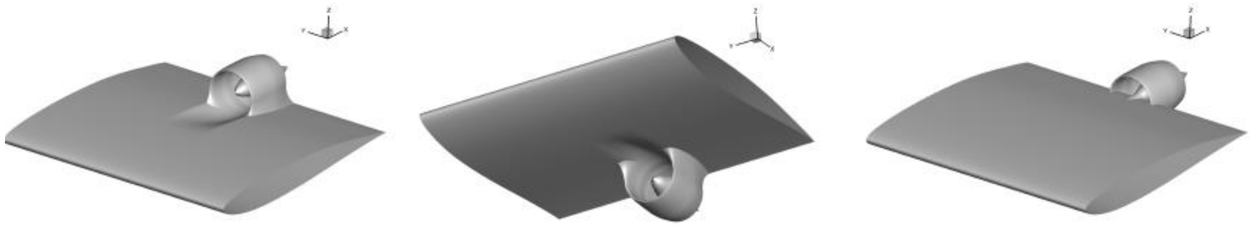


a) DEP Design Iteration 1



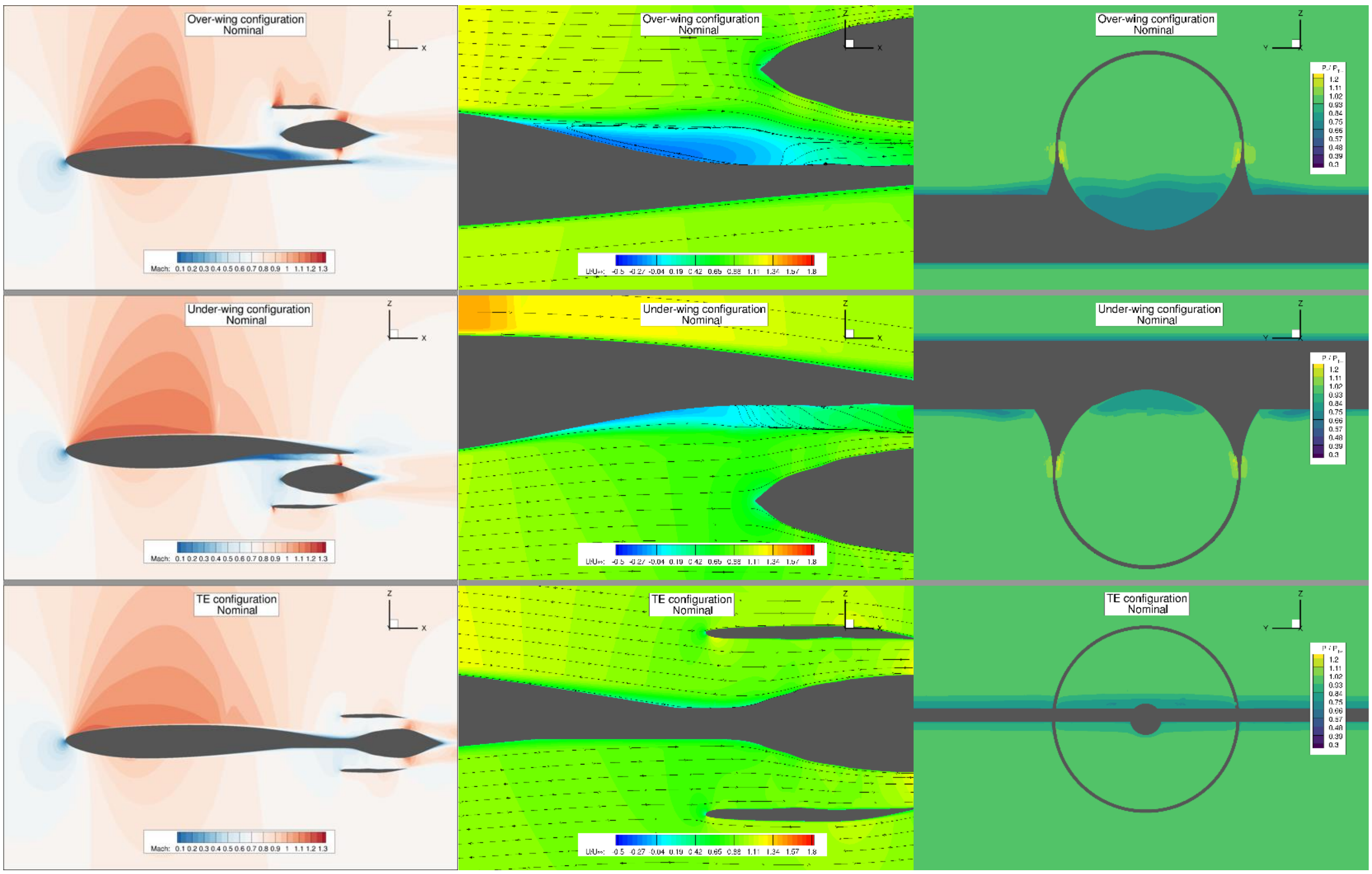
b) DEP Design Iteration 2

Figure 10 Representative iterations of the Electric Engine flow design



(a) Over-wing configuration (b) Under-wing configuration (c) TE configuration

Figure 11 Electric Engine / Wing Location Configurations

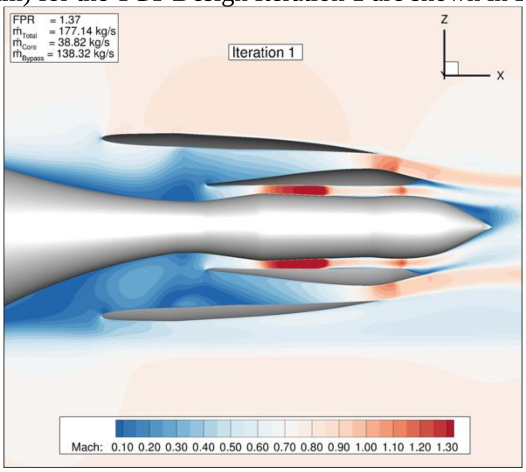


a) Mach contours at center plane **b) U-velocity contours at center plane at nacelle inlet** **c) Total pressure ratio contours at nacelle inlet**

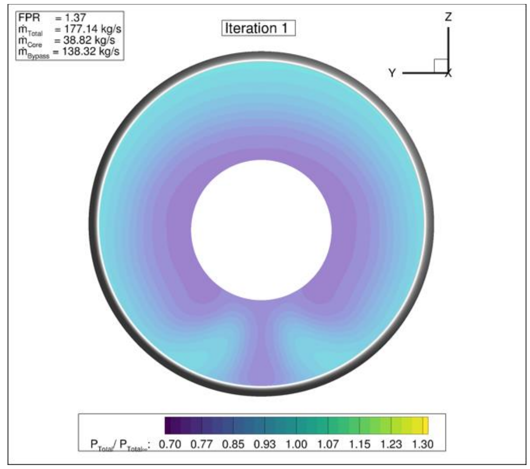
Figure 12 Integrated Wing / Electric Engine Results at Nominal Condition

The second significant propulsion / airframe integration problem on the SUSAN Electrofan aircraft is the rear fuselage integration with the aft turbofan. Similar to the DEP analysis, the high-fidelity analysis of the tail cone thruster (TCT) aimed to accomplish two main objectives. The first objective was to benchmark engine performance and inform design sizing in order to obtain a TCT model that could attain system level requirements set by conceptual models. This data will also inform the propulsion team, contributing to updated engine models and the design of the engine turbomachinery. These updated models could then be used to provide core inflow and outflow boundary conditions that would improve the accuracy of the CFD simulations presented. The second objective was to characterize the distortion profile at the nacelle, enhancing the group's understanding of the fan working conditions and the performance penalties BLI entails. In an effort to minimize these penalties, aerodynamic shape optimization was employed to reduce the distortion intensity captured by the fan by modifying the aft fuselage contours.

Initial iterations on the fuselage / aft turbine engine integration did not consider the tail, however they did provide a means to perform initial shaping of the engine duct, and in collaboration with the propulsion team, the internal flow paths. Example Mach contours and distortion profiles (total pressure is normalized by the total pressure in the free-stream) for the TCT Design Iteration 1 are shown in Figure 13.



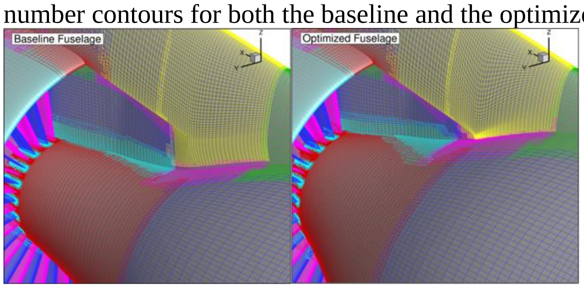
a) Mach number contours at the symmetry plane



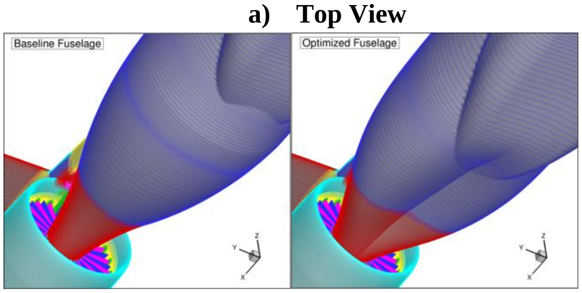
b) Inlet distortion profile at the nacelle highlight

Figure 13 Example Aft Engine Flow Design Iteration.

After finding an initial engine configuration that met the performance requirements, the focus shifted to minimizing the flow distortion ingested by the fan through the employment of aerodynamic shape optimization tools. Once an optimized satisfactory design was attained, the vertical tail and Inlet Guide Vanes (IGVs) were integrated onto the model. The former features an innovative design where the structure is partially integrated on to the engine, where the primary loads are shared between both the tail and the engine, as visible in Figure 14. Furthermore, it also enables a design which minimizes engine flow blockage, since the vertical tail skin merges into the IGV shape. Finally, the IGVs, which in the current iteration consist of a uniform circumferential distribution of symmetric airfoils, were included as a measure to further reduce the flow distortion captured by the fan. A comparison between the Mach number contours for both the baseline and the optimized fuselage are shown in Figure 15.



a) Top View



b) Bottom View

Figure 14 Vertical tail and IGV fuselage integration for both initial and optimized fuselage

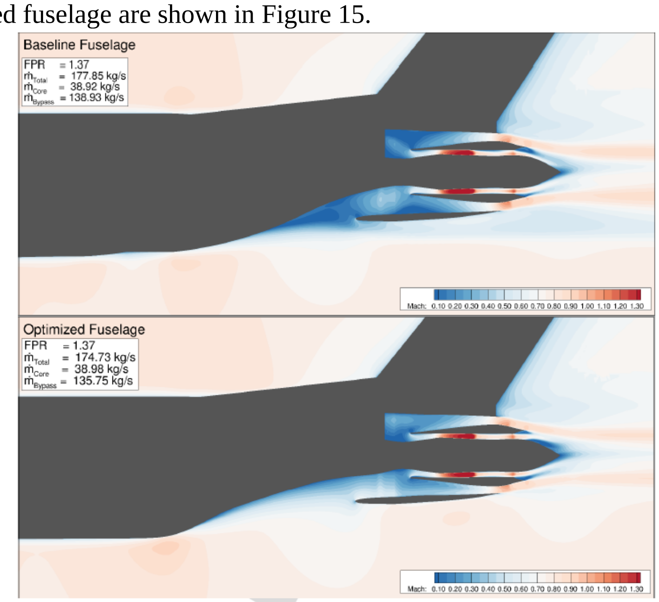


Figure 15 Mach number contours comparing the initial and optimized SUSAN aircraft

C. Natural-Laminar-Flow Wing Technology

The SUSAN Electrofan project is also investigating the application of Natural Laminar Flow (NLF) to the aerodynamic design of the wing system. Supporting laminar flow provides a performance improvement through the reduction of skin friction and profile drag. Laminar flow on the main wing upper surface offers the largest potential for drag reduction due to the higher skin friction levels in that region. However, the main wings of transport vehicles have historically posed a challenge to maintaining laminar flow because of the presence of crossflow instabilities that are amplified with wing sweep and higher Reynolds numbers. Lynde et al. [6] documents the exploration of the Crossflow Attenuated Natural Laminar Flow (CATNLF) method to the SUSAN Electrofan configuration, with emphasis on the aerodynamic design and performance characteristics of the wing.

To obtain laminar flow on the main wing, the CATNLF method was employed. This method uses airfoil shaping to obtain pressure distributions known to control the crossflow growth at the leading edge of components with high sweep and high Reynolds number, such as the main wing of the vehicle. For this study, laminar flow is only targeted on the wing upper surface because this provides the greatest drag reduction while still leaving the lower surface available for items such as leading edge high lift devices and maintenance access panels. To quantify the performance potential of laminar flow, two wing designs were conducted: a fully-turbulent design to represent the standard transonic cruise wing and a laminar design utilizing the CATNLF method. Figure 17 shows the lift to drag performance curves for the Turbulent Design , the Laminar Design (LA), and the Laminar Design operating in a turbulent condition (TA); with the Laminar Design providing the highest efficiency across the Mach range. The laminar design supported laminar flow on 53% of surface area on the upper surface Figure 16, which resulted in a 19-count (8.8%) drag reduction compared to the turbulent design. The laminar design performance benefit was maintained across near cruise off-design conditions.

The high-fidelity designs presented in this paper are meant to serve as representations of the performance characteristics of the SUSAN Electrofan configuration if laminar flow is a final technology selected for the main wing. The final design would need to be performed on the full configuration with the wing-mounted distributed electric propulsion included, which is expected to have significant aerodynamic interference on the wing pressures. While these designs are on a simplified geometry, the effect of laminar flow on the performance of the vehicle has been effectively studied, and proved to be a promising technology to help the SUSAN Electrofan configuration meet its performance objectives.

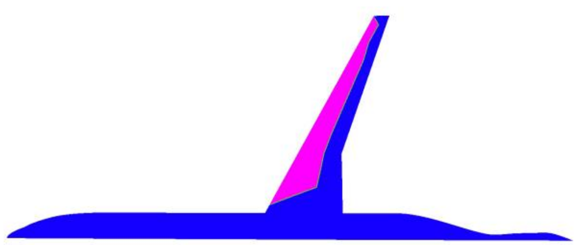


Figure 16 Planform view of the laminar design wing showing the predicted transition front at the design condition

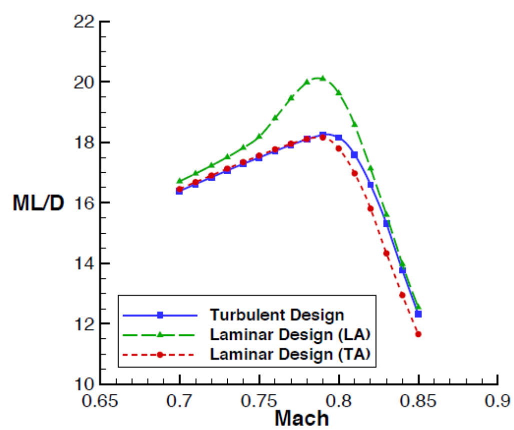
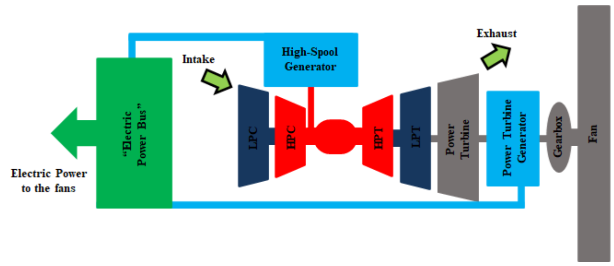


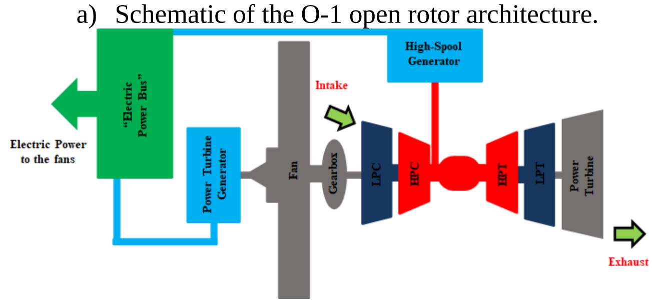
Figure 17 - ML/D curve comparing the designed configurations

D. Turbofan Conceptual Design

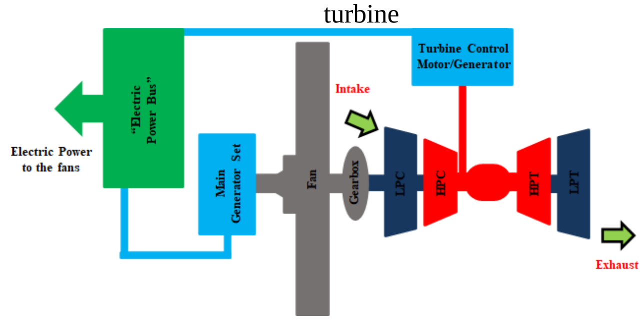
There are two fundamental challenges in designing the turbofan engine for this application. The first challenge is the engine's atypical operation wherein a large fraction of the total power is used to drive a generator. Approximately 35% of the available core power (20MW) is converted to electrical energy in order to drive the wing mounted propulsors at take off. At cruise, approximately 65% of the available core power is converted to electrical energy. The power lapse with altitude which mostly impacts the turbomachinery is the cause of the difference in power split. This led to a design complexity which is not analogous to typical turboprop, turbofan, or turbo-generator designs. The second challenge is to address operation of an aircraft with a single engine. The SUSAN concept relies on a battery backup system to provide emergency power to as many of the propulsors as possible in case of an engine failure. Additionally, the 20MW electric machine which is typically utilized as a generator will be employed as a motor to drive the fan of the tail-mounted engine in case of an engine failure. Certain mechanical disconnects and design features need to be considered in order to implement the power switch for the electric machines and the turbofan engine. The design point for this phase of the study was selected as 0.79 Mach number at 37000 ft, with a total system thrust of 11500 lbf (4025 lbf generated by the direct drive fan and 7475 lbf generated by the electrically driven fans). Complete information on the engine trade space exploration is provided by Mirhashemi et al. [7].



a) Schematic of the O-1 open rotor architecture.



b) Schematic of the D-1 ducted fan architecture with power turbine



c) Schematic of the D-2 current geared ducted fan architecture.

Figure 18 - Engine Architectures

Three engine architectures have been considered so far: the O-1, the D-1, and the D-2. The O-1 architecture is an open rotor counter rotating design with a power turbine. The D-1 design is a ducted fan turbofan design where the fan ingests boundary layer flow; the D-1 design has a power turbine in the back of the engine, but the main electric generators were moved to the front of the engine in the aircraft's fuselage to avoid structural issues from the engine's hanging weight. The current design choice, denoted by architecture D-2, is a geared turbofan design with a ducted fan similar to the D-1 architecture, but the power turbine was removed in this design iteration. Schematics are shown in Figure 18. Weight was estimated using NASA's Weight Analysis of Turbine Engines (WATE) code.

A comparative study was performed on the D-1 design to assess its performance with traditional jet fuel and natural gas fuel. A 3% reduction in the overall weight of the engine was observed, as the higher energy content of the natural gas fuel allowed for a smaller engine core.

A notional cross section of the D-2 variant is shown in Figure 19. The engine has an overall Operating Pressure Ratio (OPR) of 76 and a bypass Ratio of 5.38 at the top of the climb. The low speed shaft rotates at a speed of 5417 rpm and the high speed shaft rotates at a speed of 14175 rpm. The gearbox provides a gear ratio of 1.55. The total engine weight for the current D-2 design is 8816 lbm,

The effects of BLI are not considered in the current analysis of the engine. An important point of focus for future work is to add a distortion tolerant fan to the current analysis and to account for the effect of BLI on the flow field entering the engine core. This will likely reduce the size of the core and increase the overall efficiency of the propulsion system. Future study work includes optimizing the thrust split between the turbofan and electrical engines; more detailed engine out sizing with an eye to regulatory studies; and further alternative fuel studies.

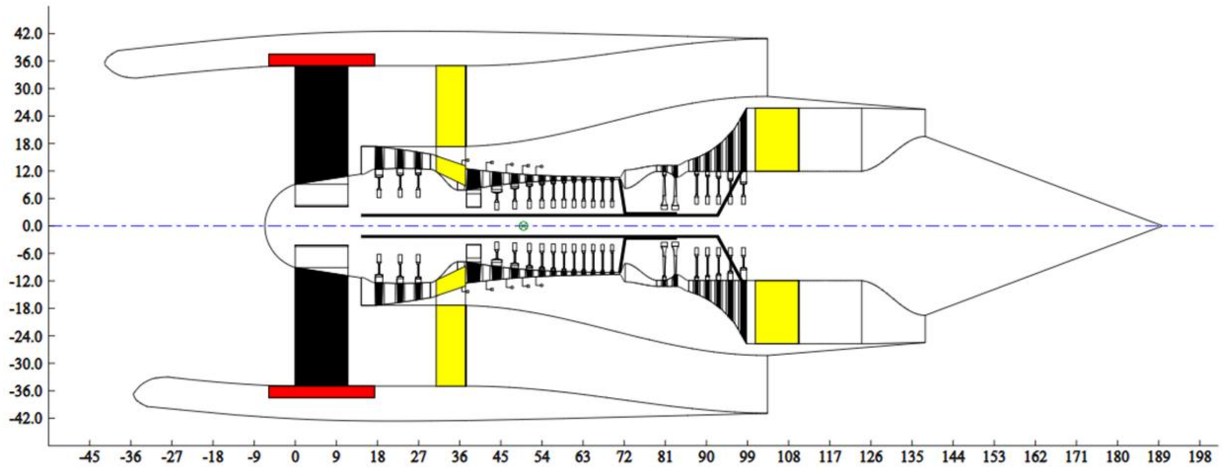
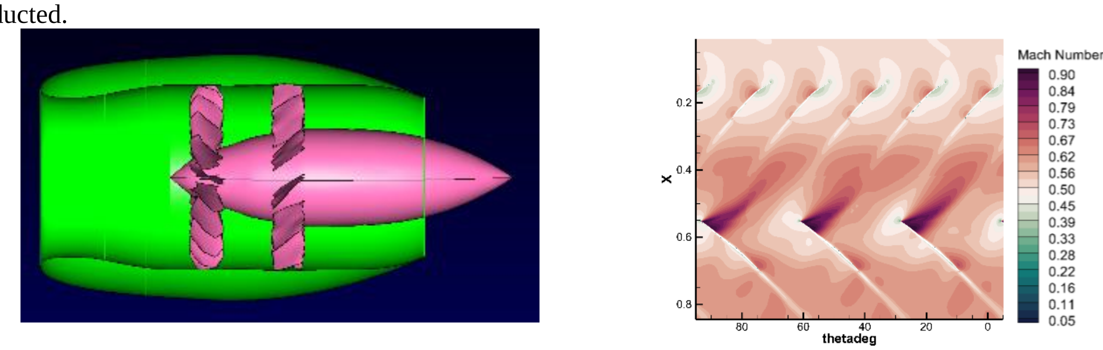


Figure 19 - Schematic of the D-2 ducted fan architecture derived from the WATE code

E. Propulsion System Development

The SUSAN Electro-fan uses a combination of an aft mounted turbofan engine with boundary-layer ingestion and distributed electric engines on the wings (Figure 1). The current trade study by Lee et al. [8] addresses the performance aspects of the distributed electric systems along with the BLI benefits, and considers adopting low speed/low pressure counter rotating fans as a part of the effort to increase the distortion tolerance of the fan stage. One advantageous feature of the distributed electric propulsion system is that the bypass ducts are decoupled from the core and electrically powered. As a result, the system designer has more flexibility in the choice of the concepts and location of the propulsors.

The wing mounted distributed propulsion system has evolved as the aircraft has concept matured. An initial trade between eight and sixteen electric engines led to focusing on a sixteen-engine configuration. Initially, a single transonic fan stage was used. Currently the electric engines utilize lower pressure, lower speed, counter rotating fans. Individual engine pods have evolved to a mail-slot installation configuration. A recent electric engine configuration with flow Mach contours is shown in Figure 20. Because the shape factor of the incoming boundary layer changes, and the inlet profile is 2-Dimensional (non-axisymmetric), the performance cannot be analyzed nor designed by one of the traditional 0-D, 1-D, or 2-D system design tools. Hence, a relatively high fidelity 3-D CFD model (in terms of external flow-field) is used predict the inlet profile into the nacelle, and understanding the interaction between the external potential flow field and the suction effect from the operation of the fan stage is essential in the design of the BLI propulsors. Since there are significant changes in the operating conditions and the performance of the fan stage depending on the relative size and location of the nacelle with respect to the airframe, and its shape changes depending on the relationship between the nacelle and airframe geometries, concurrent external and internal CFD studies are conducted.



(a) Electric Engine Cross Section **(b) Mach Contours**

Figure 20 Electric Engine configuration with Counterrotating fans

The tail-mounted engine combines a traditional gas turbine with BLI concept, and is dubbed the tail-cone thrustor (TCT). The concept takes advantage of the boundary layer ingestion due to its high propulsive efficiency and reduced wake dissipation of the vehicle. Unlike conventional turbo-jet engines, the tail-mounted TCT incurs a flow distortion and flow blockage from the vertical tail at the inlet. Figure 21 illustrates the aft turbofan mounting approach using a primary beam and limited mounting points to facilitate engine maintenance. The flow into the turbofan engine is strongly coupled with the airframe, and the trailing edge of the vertical tail is extended into the nacelle and aligned with the IGV (inlet guide vane) row. Given a target thrust, the tasks involved in the conceptual design are the fan sizing, inlet guided van (IGV) inclusion to avert the distortion, defining the appropriate bypass ratio, and selecting nozzle design. Aspects of the design process include nacelle sizing optimized for the flight missions, and design of the inlet guide vanes (IGVs) rotor, bypass duct, flow-path, and nozzle shapes. A representative engine pressure distribution is shown in Figure 22.

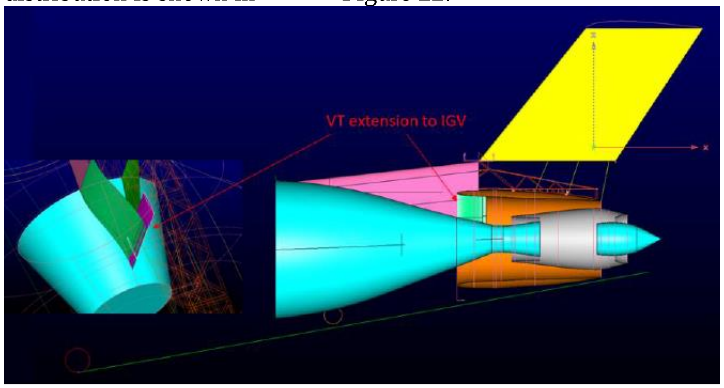


Figure 21 Overview of tail-mounted engine installation with vertical tail

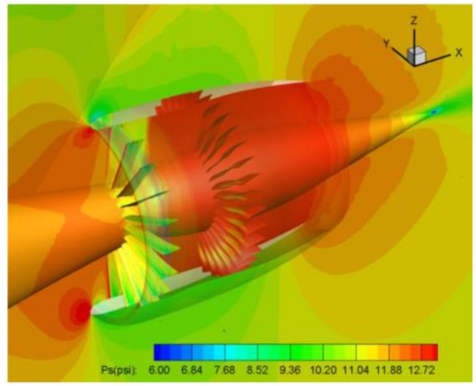


Figure 22 Engine Pressure distribution

In order to maximize propulsive efficiency several design aspects are being investigated [8]. The flow split between the bypass and core air must be carefully considered given the distorted inlet flow. The inlet guide vanes are being optimized to reduce the impact of distorted flows into the low-pressure compressor (LPC) and the bypass fan. A distortion tolerant fan is being designed. Currently the distortion penalty generated by non-axisymmetric flow profile is approximately -2.2% compared to the axisymmetric flow profile, and the choking mass flow rate is about 2% less than the axisymmetric profile results.

F. Electrical Power System (EPS)

The Electrical Power System (EPS) must be capable of generating and distributing roughly 20MW of electrical power, while also being extremely light and efficient. If the system is too heavy or inefficient, the penalties of the electrical power system will offset the benefits listed above. The efficiency also has a second impact in that the waste heat from the electrical system impacts the size of the thermal system, which adds additional mass, power, and drag losses. The SUSAN EPS Trade study is described by Haglage et al. [9].

The SUSAN electrical power system trade is being conducted at a nominal size of 20MW, with a sensitivity exploration between 10 and 30 MW. Electrical power systems of this size on an aircraft necessitate higher voltage operation and advanced thermal management, which are significant barriers to overcome in the environmental, flight, and operational conditions of an aircraft application. Safety and reliability requirements are also extremely stringent, since the power system is required for propulsion.

The SUSAN electrical architecture concept has features that are meant to help meet the efficiency and emission requirements, while providing the redundancy required for a single turbofan aircraft. An overview of the electrical system architecture is shown in Figure 23.

The bottom-right section of Figure 23 shows the generation portions of the electrical system. The main source of electrical power is the Main Generator (MG), driven by the low pressure spool (LPS) of the turbofan engine. 20MW of electrical power is generated via (4) 5MW machines. In addition to the 20MW generated power on the LPS, a single 1MW generator (the turbine control motor-generator) is driven by the high pressure spool (HPS), the output of which is connected to (4) AC/AC converters that enable the outputs of the main and turbine control generators to be electrically connected. The purpose of this generator on the HPS is to achieve the benefits of the TEEM concept discussed by Litt et al. [10].

The top-right section of Figure 23 shows the battery and wing propulsor portions of the electrical system. There are two sets of batteries that serve two different purposes within the architecture concept. The primary batteries are single-use, non-rechargeable batteries that are to be used in the event of a turbofan engine failure. In the event of such a failure, the primary batteries will provide electrical power to the wing propulsors and allow the aircraft to continue flight for approximately thirty minutes. The secondary batteries are rechargeable and will be used during normal flight. These batteries provide both electrical power to the wing propulsors, and the energy storage mechanism to enable the TEEM concept discussed above.

On the wings, an AC/DC-link/AC converter combines the AC power from the generators with the DC power from the rechargeable batteries, and feeds each of the sixteen propulsors, eight on each wing. Each propulsor consists of two counter-rotating electric engine motors (EEM), each driven by an electric engine motor controller (EEMC).

The paper by Haglage [9] describes the current status of the bus architecture, voltage, and AC/DC trades. The range of component level performance parameters and related component research to reach the needed performance metrics is also given. The power system trade studies continue in conjunction with the engine studies, with the goal of optimizing the mass and thrust specific fuel consumption of the integrated propulsion and power system.

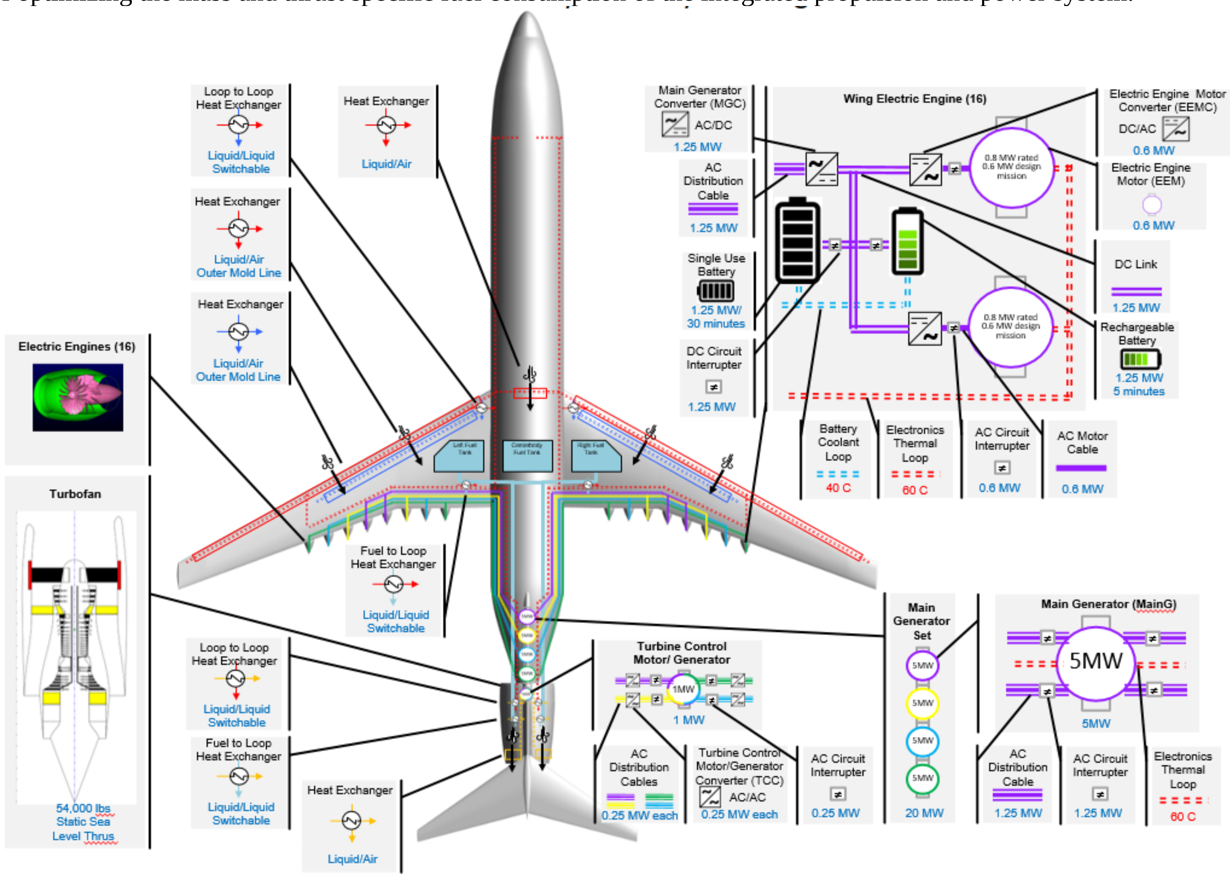


Figure 23 Electrical Power System Architecture

G. Thermal Management System

One of the barriers to achieving the full benefits of EAP is the thermal management of the electrical components. The thermal management challenge for the SUSAN Electrofan aircraft concept is particularly challenging because the amount of low-grade waste heat generated by the electronics is an order of magnitude higher than that of any existing aircraft. The largest electrical power systems in operation on commercial transport aircraft utilize approximately 1 MW of electrical power for secondary systems, and generate roughly 150 kW of waste heat, assuming 85% end-to-end power system efficiency. The SUSAN Electrofan aircraft concept uses 20 MW of electrical power, generating waste heat on the order of 1 MW. The temperature limits of most electric components require the waste heat to be rejected at relatively-low temperatures between 30 and 200 °C. Rejecting such low-grade waste heat using traditional methods, such as passively-cooled finned heat sinks and liquid-based pumped cooling loops with conventional heat-air exchangers, would incur significant weight, drag, and power penalties. Heersema [11] provides an overview of the SUSAN thermal system design studies conducted at this time.

The current approach for thermal management on the SUSAN aircraft concept consists of five elements: minimization of heat loads; use of three different thermal management loops operating at temperatures appropriate for their thermal loads; use of waste heat from the engine to warm electrical systems on cold day conditions; management of transient heat loads through heat capacitance of the fuel; and transfer of excess heat to the surrounding air stream through a combination of traditional heat exchangers and outer mold line cooling. The basic layout of the thermal system is shown in Figure 24**.**

Our current thermal management approach is described in this paragraph, however it will evolve as trade studies continue. Heat loads for the SUSAN concept primarily consist of the waste heat from the 20 MW power system and the aft turbofan. The turbofan heat load is expected to be typical of a large modern turbofan. The minimization of the heat load through use of high efficiency components and topologies will be a driving requirement for the power system because of its direct fuel burn benefit, and indirect benefit of reducing the heat load. The current plan is to have three different thermal management loops that operate at temperatures appropriate for their thermal loads. The battery management thermal loop will operate at a nominal temperature of 40 °C, the second loop will service the electrical machines, converters, and other power components at a nominal temperature of 60 °C. The third loop will service the turbofan engine. The aircraft will use waste heat from the engine to warm critical components when operating in cold conditions, thereby eliminating the need for additional heaters. To reduce the impact of thermal transient conditions, the heat capacitance of the fuel will be used to level the load on the thermal systems. Ultimately, all excess heat needs to be transferred off the aircraft to the airstream using heat exchangers through a combination of traditional heat exchangers and outer mold line cooling.

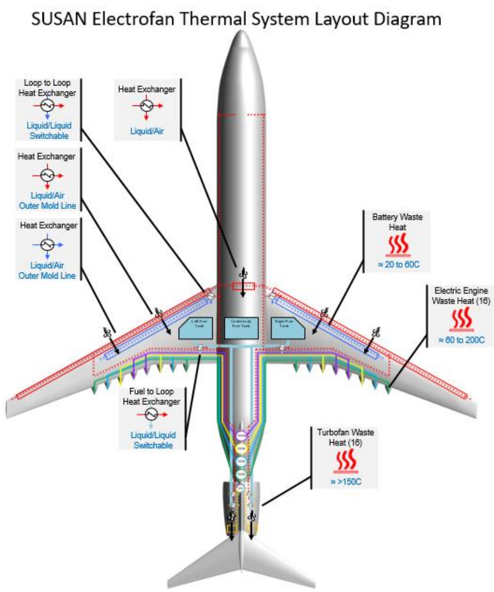


Figure 24 SUbsonic Single Aft eNgine (SUSAN) Thermal System.

H. Structural Integration of the Aft Engine and Empennage System

A trade space exploration and concept development is being conducted for the mounting system of the aft SUSAN engine. Key structural requirements were defined and adhered to for ensuring the design of a structure which can be maintained and made accessible for maintenance. The intent is to maintain commonality between other commercial aircraft designs and components used, while meeting requirements such as tail-strike avoidance, ground accessibility for maintenance, maintenance of continuous air flow, mounting via pylon, and location as close to the aft pressure dome as possible while still including sufficient space to mount the electric motor.

The structural mounting concept focuses on utilizing a commercial engine mounting approach which has been modified to allow inline power transmission to the auxiliary motor. The secondary objective here is to use a standard pylon approach in mounting the T-tail and engine, while also maintaining serviceability as described in the Requirements section above. The preliminary concept is sized for an assumed engine thrust of 30,000 lbf – an approximate equivalent to that of a Boeing 737-800 aircraft.

The tail beam and skin structure are designed to be failsafe. If a failure of the outer skins were to occur, the tail beam can handle all engine loads and environments without a physical loss of motor. The inner fuselage beam is responsible for sustaining main engine thrust, startup dynamics, and containing failure modes. The outer skin on the beam adds stiffness and is responsible for carrying aerodynamic loads from tail control surfaces and assisting in transferring load into the tail cone structure. The tail cone/structure attachment is located at the aft pressure dome aft of the aircraft. The geometry will include the tail cone, generator mount, fuselage beam, tail skins, control surfaces, engine, and engine pylon. Figure 25 below depicts the tail cone/fuselage mount minus the aerodynamic covers and tail surfaces.

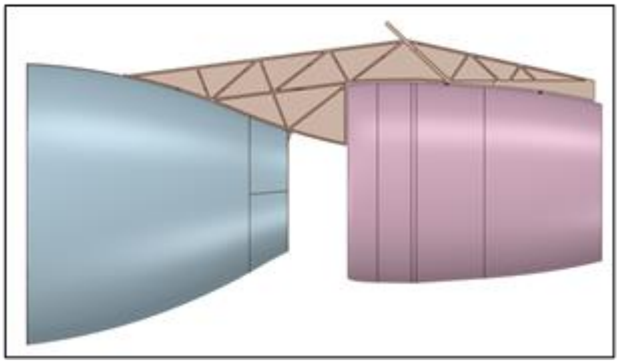


Figure 25 Geometric representation of tail cone/fuselage mount

VI. Cockpit Design and Flight Simulator

A flight simulation system for the SUSAN Electofan is being developed for two purposes: to mature the integrated flight, propulsion, and power control design; and to develop a cockpit design and receive pilot feedback and inputs on improving the human interfaces for the SUSAN aircraft. Litt provides an overview of progress so far [10]. As the SUSAN concept is refined, preparations are underway simultaneously to create the capability to evaluate its performance and handling in a flight simulator. Modular programming approaches and parameterizable modeling tools simplify the initial model integration, and provide the ability to update the models as necessary.

The plant and control system model of the integrated airframe, turbofan, electric engines, powertrain, and flight elements will be developed using a combination of development environments and toolboxes. Initially low fidelity models will be created to ensure the proper model interfaces and functions are established; fidelity will be increased as the SUSAN concept matures. The parts of the overall dynamic powertrain model described above are created using the Matlab/Simulink based tools, Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS), and Electrical Modeling and Thermal Analysis Toolbox (EMTAT). To implement the aircraft model in a flight simulator, it is interfaced with the X-Plane commercial software package, overriding the internally generated flight dynamics in X-plane.

The process, which involves the integration of independently developed models and their subsequent implementation in a flight simulator, is general and can be applied to a variety of aircraft types. However, the use of electrified propulsion architectures has the potential to add complexity beyond that of a traditional aircraft, related to the pilot interface. The way the pilot interacts with the thrust producing components could vary significantly between architectures, and the information displayed to the pilot will necessarily include additional variables beyond what is normally displayed in a traditional cockpit. Reference [10] describes the integration in general, as well as specific accommodations made for the architecture under consideration.

The pilot interface is an important feature in cockpit design, and new concepts related to EAP will require new displays, showing information such as battery state of charge, etc. Furthermore, the concept of operations related to thrust generation needs to be defined. Considerations such as fraction of thrust produced by the turbofan engine versus that produced by the electric engines, fraction of power produced by the batteries versus the turbofan engine during takeoff, etc., must be coordinated and optimized as a function of flight condition. Appropriate displays and control knobs must be designed. Private industry as well as NASA are starting to develop all-electric vehicles, but there is little precedent for cockpit displays in vehicles with hybrid electric propulsion. Conceptually, the SUSAN display should represent a futuristic aircraft for the 2040 timeframe. The type of information displayed will depend on the pilot's ability to act on it, which in turn relates to the level of automation.

The initial attempt described below owes much to standard cockpit displays, augmented with corresponding information related to the power system. The flight simulator implementation is limited by the capabilities of customization in the Modular Fight Deck and X-Plane. The inclusion of a Head-Up Display (HUD), implemented either on a separate see-through dashboard-mounted display or directly superimposed on the out-the-window scenery;

and a multi-page touchscreen, perhaps implemented on a tablet, will give a hint of a futuristic, information rich cockpit. The throttle quadrant will probably be limited to four or fewer throttles, and certain other details will probably be ignored for now to further simplify the implementation. These relate to as yet unanswered questions; for instance, about the existence and/or operation of thrust reversers.

An early SUSAN display concept, designed to be fairly complete yet fit into the relatively small instrumentation screen in the dashboard, is shown in Figure 26. The designers' objective was to compartmentalize information while keeping the overall layout simple. This compartmentalization serves to organize the display and facilitates a clear understanding of what information is being presented. Displays and fonts follow readability standards. In future iterations the pilot and copilot side of the cockpit will most likely differ in information. Flight status, position, and urgent messages should populate the pilot side; diagnostics and subsystem details should be placed on the copilot side. Splitting up indicators between both sides of the cockpit will decongest the displays.

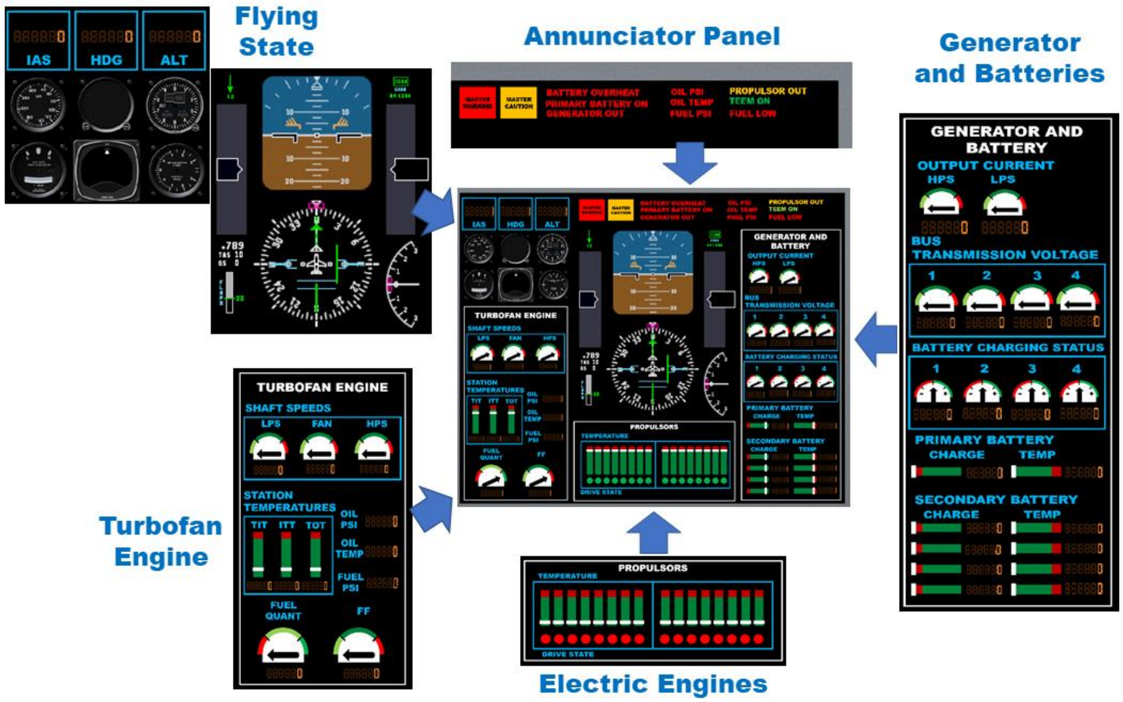


Figure 26 Exploded view of an early SUSAN pilot display. The central section shows the traditional pilot display as implemented with the surrounding sections comprising the individual components.

VII. Conclusion

A trade space exploration of a new NASA regional transport aircraft concept called the SUbsonic Single Aft eNgine (SUSAN) Electrofan is presented. The SUSAN concept uses a 20MW Electrified Aircraft Propulsion (EAP) system to enable advance Propulsion Airframe Integration (PAI) in transport category aircraft. Alternative fuels will be used to reduce the amount of emissions per energy used. By combining these features there is the potential to reduce aircraft emissions by 50% per passenger/mile while retaining the size, speed, and range of large regional jets. SUSAN is has a 750 mile economic mission, a 2500 mile design range and a maximum capacity of 180 passengers. The SUSAN configuration utilizes a single aft mounted engine and distributed electric wing-mounted thrusters on a tube and wing arrangement with a T-tail empennage. The SUSAN Electrofan employs a hybrid powertrain to enable: single turbofan operation on a large transport category aircraft; increased aerodynamic and propulsive efficiency through placement of electric engines; optimized turbofan sizing and efficiency through control and electric boosting, reduced control surface sizing through thrust augmentation. A single use battery is employed as the power source in case of turbofan failure. The design study also considers the constraints of operating within the current airport, airspace and economic constraints. This paper presents the status of the trade space exploration; however the concept definition is not finished.

Potential future work is described in this section of the conclusion. Market studies could be to include a broader set of representative data and better coverage of world wide utilization cases. Regulatory analysis both drives the concept development and requires reassessment as the aircraft concept matures. To stay true to the economic, airport, and airspace constraints the operational concept needs to be matured. A flight simulation system is being developed to ensure pilot considerations are addressed for the concept. A better understand the impact of the integrated propulsion systems on aerodynamics, propulsion, and weight. The impact of other advanced technologies being considered for the SUSAN Electrofan, such as natural-laminar-flow wings, must also be quantified. Incorporating these effects into the aircraft level trades will be necessary for making a final assessment of the benefits. The effects of BLI are not considered in the current analysis of the engine which will likely reduce the size of the core and increase the overall efficiency of the propulsion system. Optimizing the thrust split between the turbofan and electrical engines and more detailed engine out sizing with an eye to regulatory studies and impacts on power system sizing needs to be done. The power system trade studies continue in conjunction with the engine studies, with the goal of optimizing the mass and thrust specific fuel consumption of the integrated propulsion and power system. The thermal management system for the power system needs to be optimized such that it's weight and drag don't offset the benefits of the concept. Finally, future work will also be required for evaluating the total emissions reductions offered by alternative fuels, which have the potential to reduce the quantity of emissions per unit energy usage.

Although preliminary assessments are promising, substantial work is required to complete a closed concept with an understanding of benefits. One of the challenges to completing the SUSAN Electrofan concept and benefit analysis is the highly interrelated nature of the design when airframe, engine, power system, and control challenges are so tightly coupled within the aircraft. Bringing regulatory, economic, operational, and human factors in at the very beginning of a concept requires substantial interaction across a diverse set of skills. Despite these challenges we believe that the comprehensive approach we are using will lead to a more robust concept study.

Acknowledgments

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