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UPDATE ON SUBSONIC SINGLE AFT ENGINE (SUSAN) ELECTROFAN TRADE SPACE EXPLORATION

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Abstract

NASA is conducting an ongoing trade study analysis of the SUSAN Electrofan aircraft concept, which utilizes 20-MW-class electrified aircraft propulsion to enable propulsive, aerodynamic, and control benefits while retaining the range, speed, and size of typical narrow-body regional aircraft. The study is constrained by the ground rules of operating within the current airport and airspace infrastructure. This ongoing study seeks to find a configuration and combination of technologies that yield significant fuel burn and emissions benefits. Another key goal is to reduce cost per passenger mile. Currently, the study is focused on a configuration that utilizes jet A or sustainable aviation fuels, however, we plan to consider other fuel alternatives in the future. This paper describes the progress in defining the architecture of the aircraft, engine, power system, control system, and initial understandings of the sensitivity of the potential configurations to technology assumptions based on key performance parameters. Additionally, progress towards definition and refinement of driving operational, economic, infrastructure, certification, and technical requirements is discussed.

Keywords: Aircraft Concept, Electrified Aircraft Propulsion, Hybrid Electric, SUSAN Electrofan

1. Introduction

NASA is conducting a trade space exploration to develop the Subsonic Single Aft Engine (SUSAN) Electrofan aircraft concept [1]. The International Civil Aviation Organization has published emissions reduction roadmaps [2] that include aircraft technology improvements, operational improvements, and use of alternative fuels. The objective of the SUSAN study is to come up with a specific aircraft configuration and associated technology suite that results in significant energy use and emissions reductions. The SUSAN aircraft concept is intentionally constrained to operate within the existing airport infrastructure and airspace operational model to enable a path to product introduction. Cost requirements are being established for initial acquisition and maintenance costs to ensure that the per mile pricing is competitive. The target market is the regional low-cost carrier airline with mission specification: 180 passenger, design range of 2,500 miles, economic range of 750 miles, and speed of Mach 0.78.

The SUSAN Electrofan (uses a 20-MW-class electrified aircraft propulsion system to enable advanced propulsion airframe integration (PAI) in transport-category aircraft. By combining these features, there is the potential to significantly reduce aircraft emissions per passenger mile while retaining the size, speed, and range of large regional jets. A key feature of the SUSAN Electrofan is that energy is transferred onto the plane in the form of fuel at the airport like all existing aircraft. No airport battery charging or battery swapping is required. Instead, the power system and batteries are used to enable propulsive and thermal efficiencies on the aircraft to reduce energy used. Alternative fuels will be used to reduce the amount of emissions per energy used. The SUSAN trade study is a multiyear effort. Efforts so far have been focused on establishing an aircraft configuration and key performance parameters for required technologies. Future work will establish more detailed system requirements and explore alternative fuel configurations.

Figure 1 – Artist Rendering of SUSAN Electrofan Concept.

The challenge of reducing aviation energy use, cost, and emission while retaining the extreme level of aviation safety is a daunting one. SUSAN Electrofan is a concept to move up two technology S-curves. The first S-curve is the use of distributed propulsion on transport-category aircraft along with complementary innovations to reduce the amount of energy used per passenger mile while retaining the range, payload, and speed requirements of comparative aircraft. Recent innovations in the electric vertical take-off and landing (eVTOL) space illustrate the new aircraft design space options that can be explored when electrical systems are used to connect the power sources on an aircraft to the propulsors. SUSAN explores that design space in the transport-category aircraft. The second S-curve is the use of alternative fuels. At the time of writing, the alternative fuels options for SUSAN have not been traded yet, and the baseline assumption is that the alternative fuel is sustainable aviation fuels. In the future, we intend to consider liquid natural gas, hydrogen, and other options.

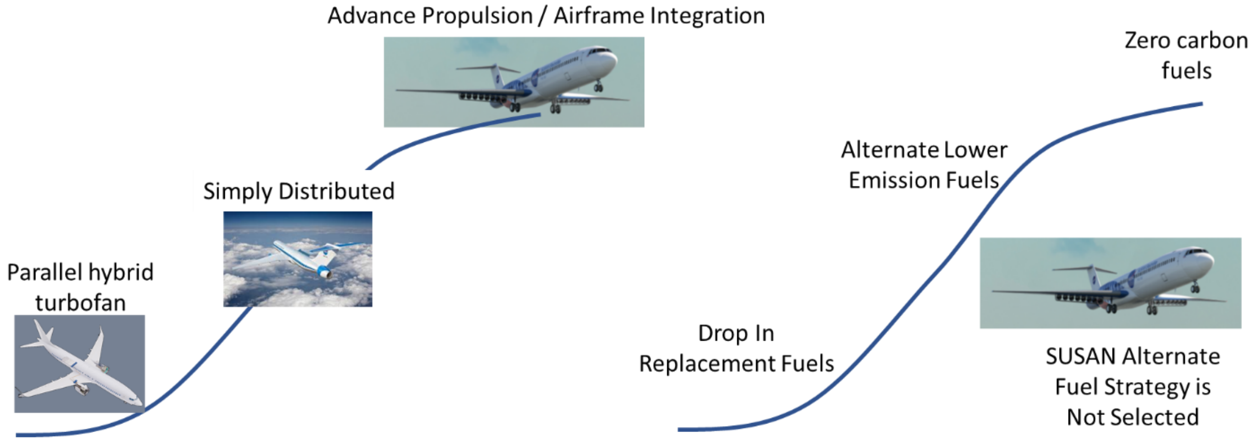

Figure 2 – SUSAN Electrofan is a concept to move up two technology S-curves.

2. Basis of Key Requirements

2.1 Passenger Size/Range

The U.S Department of Transportation is in the process of conducting an assessment to determine the fraction of the U.S. domestic market that could be serviced by the SUSAN aircraft. The assessment includes an analysis of historical and future range and passenger count distributions.

Over the course of the past 30 years, narrow-body aircraft have made up most passenger enplanements and revenue passenger miles (RPMs) in the domestic market. Recent trends in the domestic U.S. aviation market have also seen robust growth in the overall capacity and range capabilities in narrow-body aircraft. A comparison of seat capacity (weighted by operations) between 1990 and 2019 (Figure *3*) shows a significant shift in the distribution to larger aircraft, with the average number of seats increasing from 138 to 162 over this period. A similar change occurred in the distribution for distance flown in miles (weighted by operations, Figure *4*), where the average distance flown for narrow-body aircraft increased from 532 to 867 miles. Data is sourced from the U.S. Department of Transportation Bureau of Transportation Statistics, Form 41 Traffic Schedule T-100 [3]. Aircraft categories are defined by regional aircraft with up to 100 seats, wide-body (twin aisle) aircraft and four separate narrow-body categories divided into 25 seat increments.

The Federal Aviation Administration (FAA) publishes official annual domestic forecasts of U.S. airports under the Terminal Area Forecast (TAF) program. This model was enhanced in 2015 (TAF-Modernization or TAF-M, [4] to include origin-destination (OD) pair modeling of passenger demand and produces forecasts of enplanements and commercial operations for airports with over 100,000 total annual enplanements (99% of all commercial traffic domestically). The most recent publication of the TAF-M's long-term forecasts was released in 2021 and estimated out to 2050. The TAF-M forecasts at the OD pair level by airframe type.

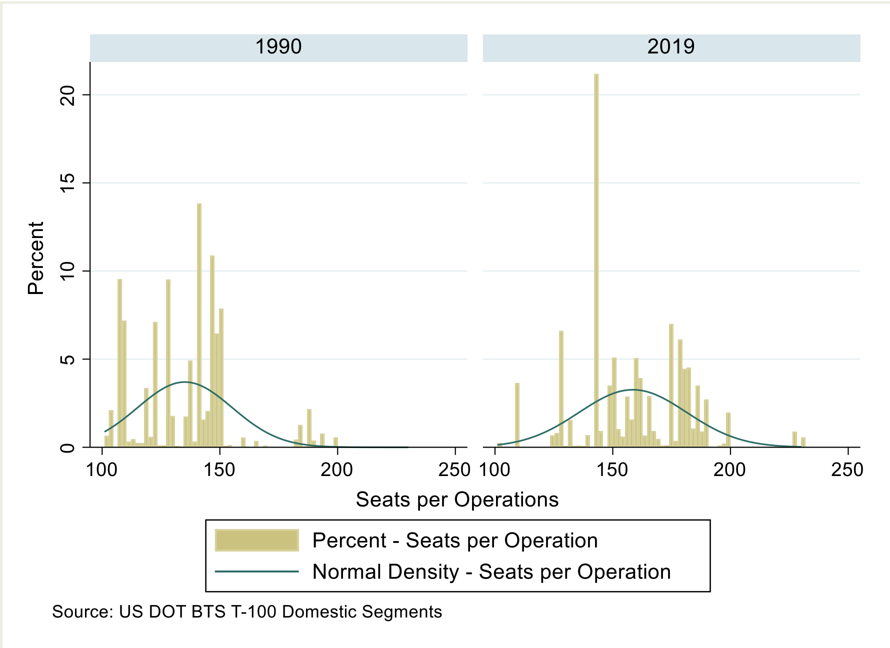

Figure 3 – Distribution of average narrow-body capacity in 1990 and 2019.

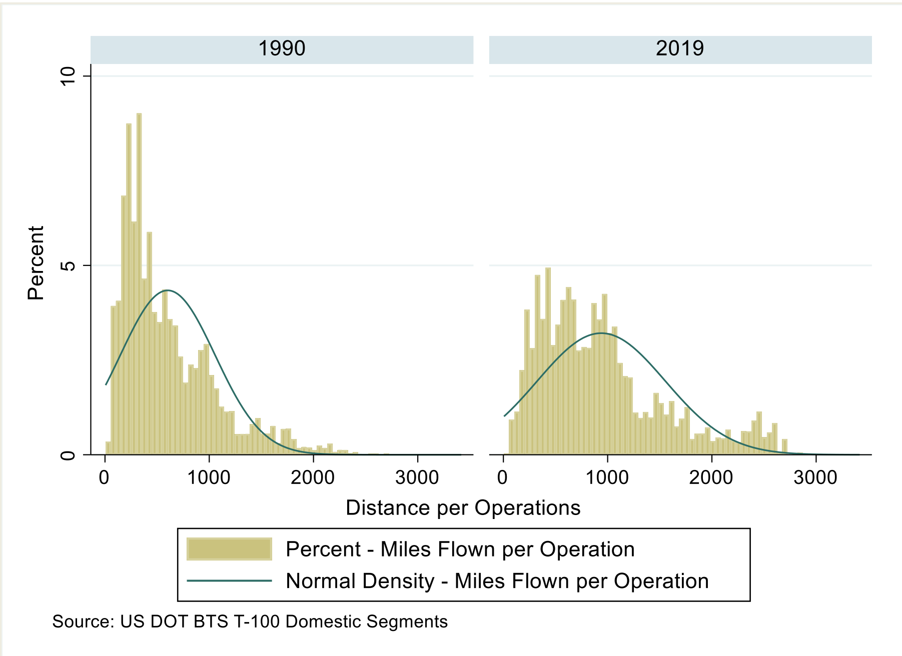

Figure 4 – Distribution of average narrow-body miles flown in 1990 and 2019.

The future traffic projections are being done using a multinomial logit (MNL) regression analysis, where the dependent variable contains multiple categories that are considered mutually exclusive from each other. For this analysis, the aircraft size defined by seat ranges and type is the categorical (dependent) variable of interest (Table *1*). These type of discrete choice models have been utilized extensively in previous transportation research [5], [6] and specifically in the case of predicting aircraft type and size in the U.S. domestic market [7]. The modeling effort undertaken here extends this framework to predict and forecast the future fleet size using historical BTS T-100 data in combination with the TAF-M as the exogenous forecast traffic demand input.

Table 1 – Seat Class Category Definitions

Seat Class Category	Seat Class Definition	Example Aircraft Types
1	Piston/Turbo Prop ≤ 100 Seats	ATR42/7, CNA280, Q400
2	Regional Jets 25-100 Seats	CRJ200/700, ERJ145/175
3	Narrow Bodies 101-125 Seats	A220-100, ERJ195
4	Narrow Bodies 126-150 Seats	A220-200, A319, B737-7
5	Narrow Bodies 151-175 Seats	A320, B373-8
6	Narrow Bodies 176+ Seats	A321, B737-9
7	Wide Bodies	A330, B787

The TAF-M OD pair RPM forecast values were used as inputs to predict the future distribution of aircraft categories, measured by total passengers, with results from the forecasting process presented in Figure *5*. These results show significant growth in the two largest narrow-body categories in the outer years, accounting for 86% of total passengers by 2050, up from 49% in 2019. The model predicts that while all other categories will experience declining passenger growth, the two largest narrow-body categories are predicted to grow at an annualized rate of 3.6% over the 32-year period.

The SUSAN Electrofan is sized for a maximum passenger load of 180 passengers, a nominal load of 167 passengers. The SUSAN Electrofan range is set to 2,500 miles with an economic range of 750 miles.

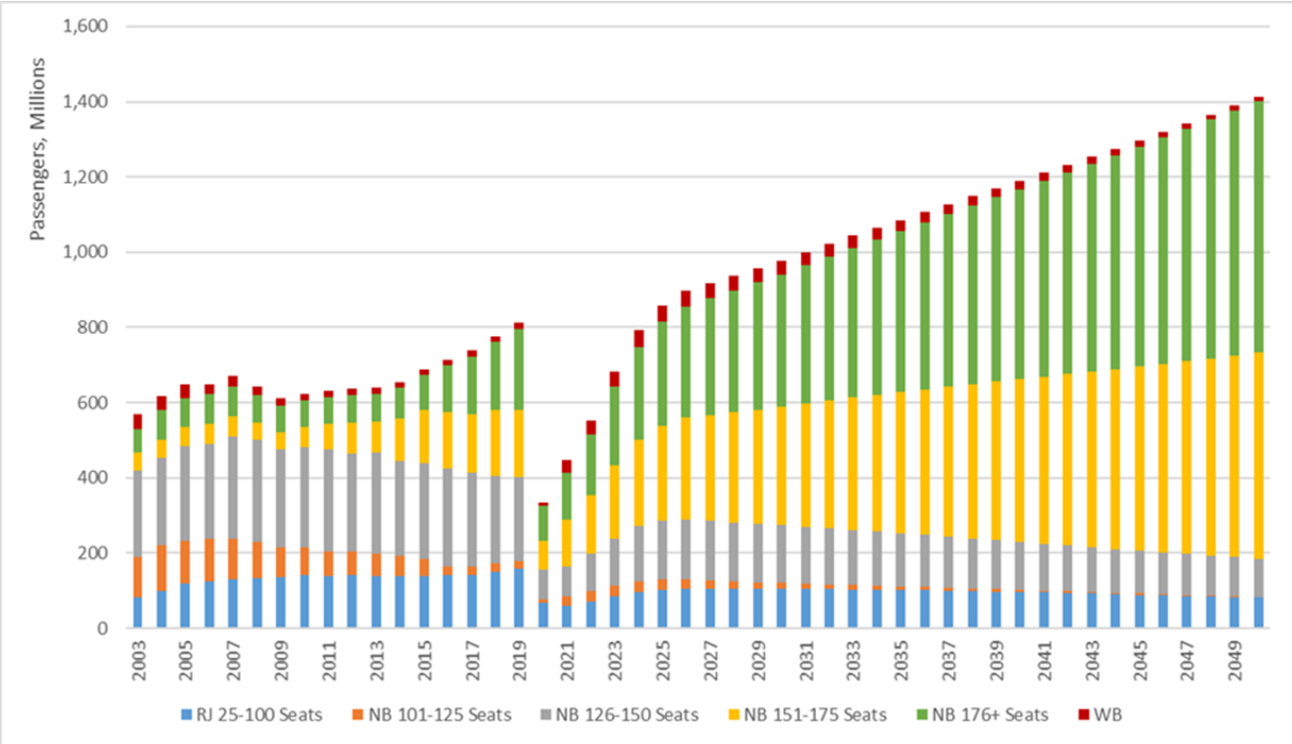

Figure 5 – Fleet size category forecast output to 2050 from the MNL model.

The fleet forecast predicted from the MNL model suggests significant gains for the two largest narrow-body-size categories the SUSAN aircraft is expected to compete in, making up over 86% of total passenger enplanements by 2050. Second, this analysis provided insight into the future composition of the fleet through a detailed fleet evolution model to compare differing fleet mixes with and without the SUSAN aircraft.

2.2 Mission Definition

An initial mission profile for the SUSAN concept is shown in Figure 6, which illustrates the timing estimates for multiple stages of flight for the 2,500 nmi design mission and the 750 nmi economic mission. Figure 6 reflects a common sizing mission profile, which includes additional reserve requirements for fuel allowance, missed approach, and additional cruise and descent segments.

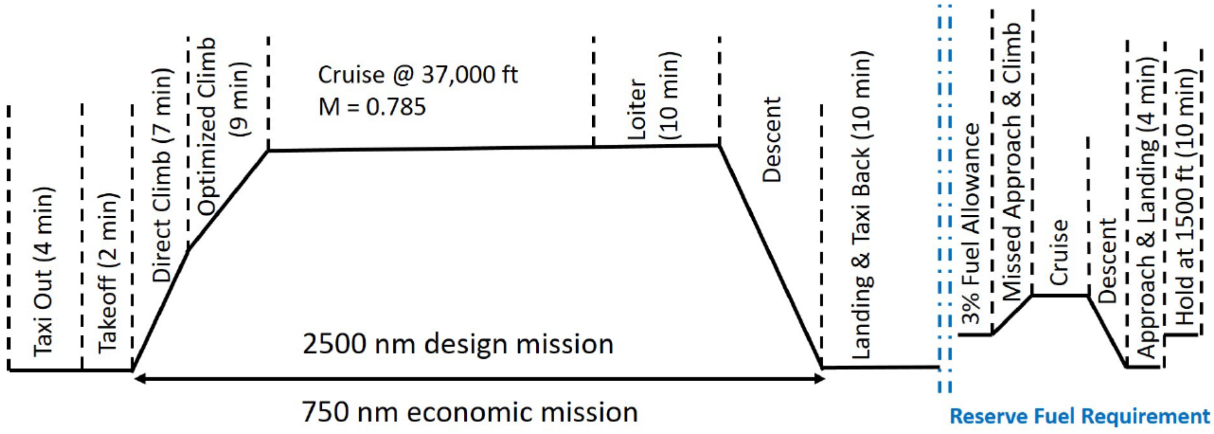

Figure 6 – Nominal mission profile for the SUSAN Electrofan concept with included reserve fuel requirements [8].

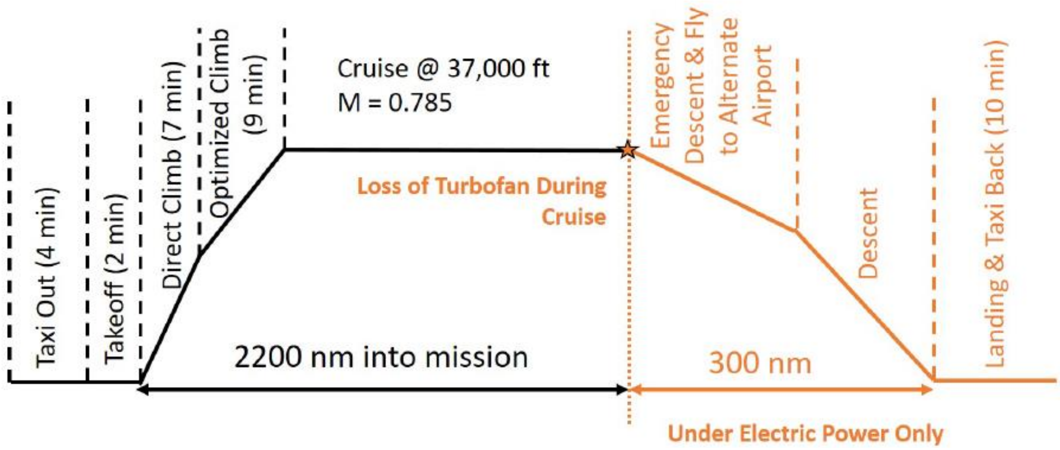

Figure 7 – Mission profile for the SUSAN Electrofan concept in the event of loss of the turbofan during cruise.

Turbofan failure during cruise will result in loss of thrust from the turbine as well as loss of the primary source of electrical power to run the electric engines on the wings. In this case, the electric engines will switch to power provided by the single-use backup battery that is only employed when the turbofan fails. The electric engines will be able to run at full power on the backup battery, however only 65% of the total thrust is nominally provided by the electric engine so the aircraft will fly at a reduced velocity. 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 reduced electric-only velocity, the 30 min of flying time equates to a maximum of around 300 nautical miles in range, although the exact range will be determined in further analysis. The mission profile with turbofan failure is shown in Figure 7, where the portions of flight under electric power only are indicated in orange. Additional mission profiles are being developed for a range of electric engine failure scenarios.

2.3 Airport Infrastructure/Airspace Operations

Although the SUSAN Electrofan introduces many novel technologies, it must still be able to utilize existing airport infrastructure. By maintaining a similar size, wingspan, and length to existing narrow-body jet aircraft, the SUSAN aircraft can fit within existing gate dimensions. The aircraft is sized so that required minimum runway length, determined in part by CFR 25 Parts 109 and 125 [9], are in line with current airport runway lengths, allowing operation at existing regional airports. While the SUSAN Electrofan aircraft utilizes 20 MW of electrified aircraft propulsion, it does so by using a fuel-burning generator and rechargeable batteries, and therefore does not require ground-based charging or battery swaps. This enables operation at existing airport gates without requiring significant modification. The purpose of this trade exploration is to find a configuration that reduces fuel burn (total energy use) by at least 20%, which is typical between two generations of aircraft in a size class, and reduces emissions more.

The SUSAN Electrofan aircraft is designed to fit within existing airspace operations including terminal and en route operations. This includes communications with other aircraft, air traffic control, and operations, as well as safety systems such as the Traffic Alert and Collision Avoidance System (TCAS). However, due to its novel propulsion system, the SUSAN Electrofan concept has a slightly modified approach to the ETOPS (Extended Operations, formerly Extended Twin-Engine Operations), which determines the acceptable flight paths for multiengine passenger aircraft in the event of a loss of engine power [10]. Utilizing the backup battery system mentioned in the previous section, the SUSAN Electrofan aircraft is able to fly for approximately 30 min after loss of the turbofan engine in order to reach a suitable airport to land. Using U.S. primary airports, as designated by the FAA using passenger metrics, Figure *8* shows the approximate area, shaded in blue, where the SUSAN Electrofan concept would be able to safely operate given this requirement.

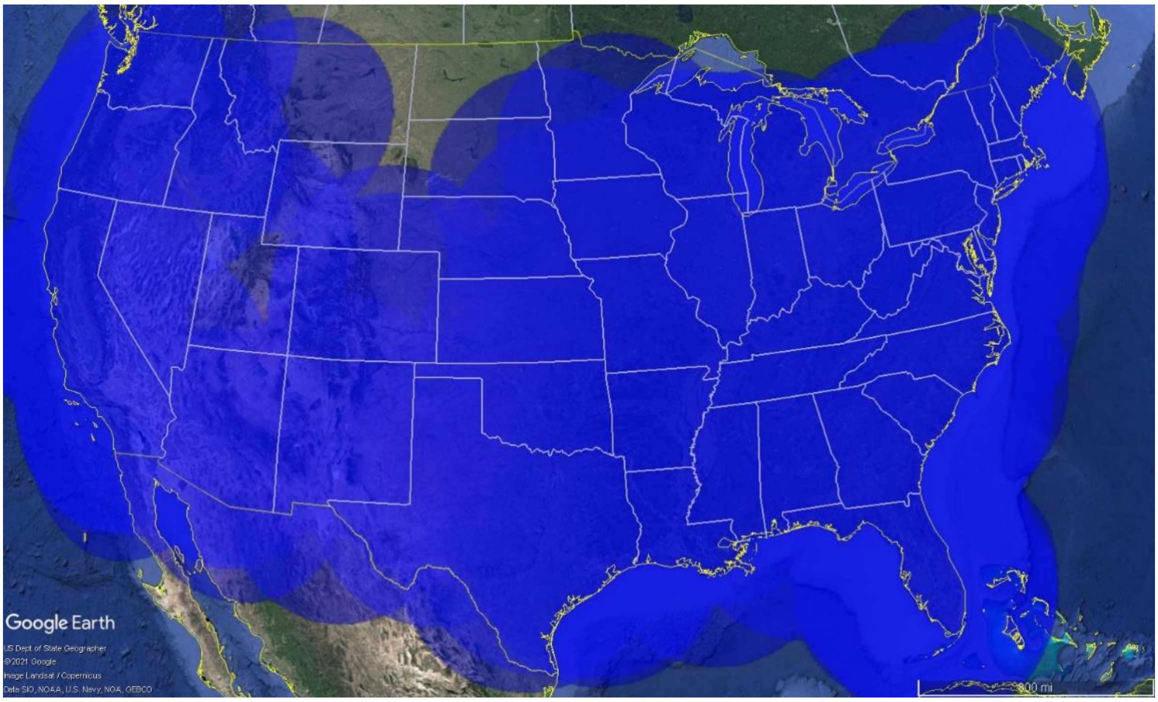

Figure 8 – Area covered by 300 nautical mile radius from U.S. primary airports, equivalent to 30 min flying time at Mach 0.785, shown in blue shading.

3. Key Features

3.1 Trade Study Approach

Several trade studies are being performed in a multiyear approach to continue the development of the SUSAN Electrofan concept, which involves the assessment of various aircraft and engine technologies, and the impact of each option on the concept's system-level performance. With such a highly integrated concept, the development of the SUSAN Electrofan follows a systematic and progressive approach, with the trade studies each year incorporating:

1. A wider range of design considerations as the design stage moves from conceptual to preliminary
2. Higher fidelity methods that can more accurately capture and resolve physical effects that govern the benefits of the configuration, especially those related to PAI
3. Higher levels of coupling and interaction between the development of the individual aircraft components and subsystems

In the first year, a preliminary set of top-level aircraft requirements was proposed for sizing the various aircraft components and subsystems. Examples include design and economy range mission definitions, thrust requirements, maximum electric power targets, and battery technology levels. These top-level aircraft requirements were then used by the disciplinary teams to develop preliminary models of the aircraft components and subsystems, which were harmonized through a conceptual multidisciplinary design and analysis framework to provide estimates of system-level performance metrics such as the design weights of the aircraft and its mission fuel burn. Although only a subset of technologies and benefits being considered were included in this study, several different aircraft concepts were assessed, with results indicating a 17.2–26.8% fuel burn reduction relative to a year 2005 baseline aircraft [11]. The current SUSAN Electrofan concept is shown in Figure *9*.

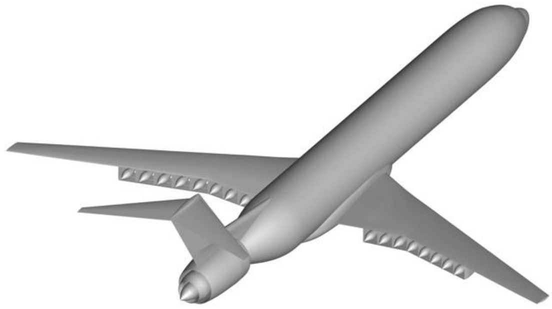

Figure 9 – SUSAN Electrofan with a fuel-consuming aft fuselage propulsor
and 16 electric ducted fans in a mail-slot nacelle configuration.

In the second and current year, efforts are focused on developing a preliminary design of the SUSAN Electrofan concept. One of the key areas of interest is the selection of the underwing distributed electric propulsion (DEP) system configuration. Three configurations are being investigated to quantify the relative benefits of distributed propulsion itself, as well as with boundary layer ingestion (BLI) technology. Once selected, the completed configuration will be reevaluated through the conceptual multidisciplinary design and analysis tool using an updated engine deck model from Numerical Propulsion System Simulation (NPSS), which will also account for BLI from the aft fuselage propulsor.

3.2 Propulsion Airframe Integration

3.2.1 Distributed Propulsion

Distributed propulsion for transport aircraft [12],[13] is a propulsion technology that is being investigated for the SUSAN Electrofan concept. As fan stages increase in diameter on typical turbofan engines, increases in capture area translate to higher bypass ratios and hence propulsive efficiency. However, as turbofan engines become larger, they become more difficult to integrate onto typical low-wing aircraft due to ground clearance limitations. Moreover, trades with weight and drag, including the weight of extended landing gear systems are now becoming less favorable as engine sizes continue to grow.

One alternative is to explore the concept of distributed propulsion where the thrust generated can be spread across a larger number of propulsors with smaller diameters. This increases the capture area of the propulsion system, thereby lowering the design fan pressure ratios and hence the shaft power required to achieve a certain level of thrust. Trades with aerodynamic drag must be accounted for, however, when considering the greater wetted area and cross-sectional area of the system. Trades with increased weight must also be considered, which stems from the increased number of propulsors and cores. This can be offset by adopting an electric architecture that simplifies each propulsor to a motorized ducted fan. Weight trades are also counterbalanced by the addition of the electric systems (e.g., from the motors, batteries, and cables). These factors are being considered in the development of the wing-mounted DEP system on the SUSAN Electrofan, with the benefits of BLI also being investigated, as described in Section 3.3.2. With a BLI configuration, some of the weight and drag penalties can be mitigated by merging part of the nacelle with the outer mold line (OML) of the wing.

3.2.2 Boundary Layer Ingestion

Another propulsion technology currently being considered for the SUSAN Electrofan concept is BLI. This technology leverages the boundary layer flow that develops on the vehicle's surfaces to increase the propulsive efficiency of airframe embedded propulsors that ingest this lower momentum flow, thus decreasing the shaft power required to achieve a specific thrust level. In parallel, integration with the airframe allows a reduction in nacelle and pylon wetted areas and weight.

However, the inherent inlet flow distortion characteristic of such an integration poses important challenges to an effective implementation of this technology, introducing complexities in fan design and engine performance penalties.

The current SUSAN Electrofan concept features a tail cone thruster developed for type-II BLI, as well as an underwing DEP system intended to capture the boundary layer from the lower surface of the wing in a type-I BLI arrangement. Type I BLI I is an arrangement where 180° flow, like on top of a blend wing body or wing, is captured. Type II BLI is an arrangement where 360° flow around a tube, like a fuselage, is captured [14].

3.2.3 Natural Laminar Flow

Application of Natural Laminar Flow (NLF) technology to the SUSAN Electrofan is being investigated. NLF is known to improve vehicle performance by reducing both skin friction and profile drag. Several components are being considered for NLF for the SUSAN Electrofan configuration, including the main wing and empennage surfaces. The largest potential for performance improvement comes from NLF on the main wing of the vehicle, so that has been the team's first focus. The computational study investigated NLF benefits on the main wing by utilizing a NASA design method referred to as Crossflow Attenuated Natural Laminar Flow (CATNLF). The CATNLF design method enables large extents of laminar flow on highly-swept components by reshaping the airfoils to obtain pressure distributions that limit crossflow growth at the leading edge [15].

The primary goal of the NLF study was to quantify any performance improvement resulting from adding NLF to the main wing of the SUSAN Electrofan vehicle. To accomplish this, the wing component of a wing-body configuration was designed for the primary cruise-point condition. Two wing designs were completed, one fully-turbulent wing to serve as a baseline for performance comparisons, and one wing with NLF on a significant portion of the suction side of the wing. The NLF design supported laminar flow on 53% of the surface area of the wing upper surface, as shown in the planform view of the transition front in Figure 10. The flow solver results indicate that NLF on the wing provided a 19-count (8.8%) reduction in drag of the wing-body configuration compared to the fully turbulent design. Off-design analyses of both the fully turbulent and NLF designs were performed and showed sustained extents of laminar flow on the NLF design at all Mach and angle of attack conditions analyzed. The 8.8% reduction in drag with the addition of NLF to the wing provided confirmation that the technology was worth pursuing further for the SUSAN Electrofan configuration [16]. The integration of the DEP system on the back of the wing can impact the amount of NLF area on wing. Trades between above, below, and behind wing at different cord locations are ongoing to determine best tradeoff between NLF and DEP.

The secondary goal of the NLF study was to begin identifying any impact that adding NLF to the main wing would have on other technology being considered for the configuration. The primary technology that an NLF wing would interfere with is the wing-mounted distributed BLI engines. If the BLI engines are mounted such that they ingest the wing suction surface boundary layer, the technologies may reduce the efficacy of each other. BLI engines rely on thicker boundary layers to maximize performance benefit, but laminar flow inherently thins the boundary layer. Additionally, the presence of the engine has been found to push the shock forward on the wing, thereby limiting the extent of laminar flow possible. If the BLI engines are mounted on the pressure side of the wing where no laminar flow is expected, there is little anticipated interaction between the two technologies. The interaction of the NLF airfoils and wing-mounted BLI engines, and any resulting performance losses, must be properly understood for the team to identify the layout of the final SUSAN Electrofan vehicle.

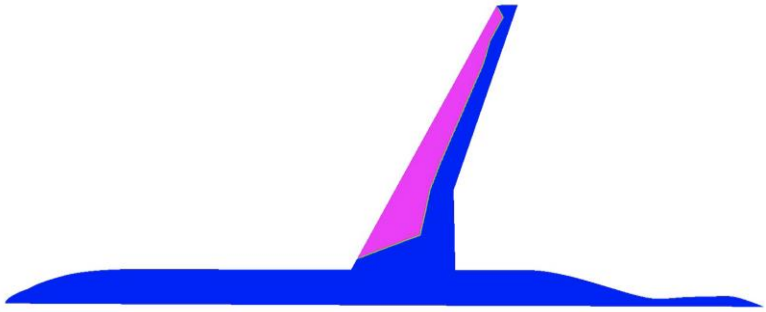

Figure 10 – Planform view of the NLF design showing the predicted transition front (pink is laminar, blue is turbulent) at the cruise-point design condition.

3.3 Propulsion, Power, and Thermal Systems to Enable Propulsion Airframe Integration

3.3.1 Turbofan Engine

Given the highly integrated BLI design of the aft engine turbofan, both low- and high-fidelity investigations were conducted.

At low fidelity, a detailed system analysis was performed and iterated on to obtain a power split for the aft-mounted tail cone thruster (TCT) [17]. This analysis optimizes the configuration for a mission and uses a variable area fan nozzle to ensure good operability of the fan. Figure 11 shows a schematic of the engine design including electric power extraction at the top of climb (TOC) condition, as well as the rolling take off (RTO) condition. The schematic is based on a traditional architecture, which does not have a low-spool motor/generator. The fan size and power would be much smaller. As can be seen in the figure, the low-spool shaft provides much more electric power than the high-spool shaft. In this configuration, the generators on both shafts produce 18.5 MW of electric power at RTO and 10 MW at TOC.

At high fidelity, investigations were made to benchmark engine performance and inform design sizing in order to develop a tail cone thruster model that could meet system-level metrics such as thrust requirements and fan pressure ratio targets [18]. A representative model of the TCT is presented in Figure 12. Given the early stage of the design process, the engine model used in this analysis is highly simplified, which features a fan, a bypass duct, and a core duct that neglects the actual flow path. Propulsion is modeled through two actuator zones, a primary one intended to model the fan propulsive effects, and a secondary one used to accelerate the core flow to approximately mimic the influence of turbomachinery.

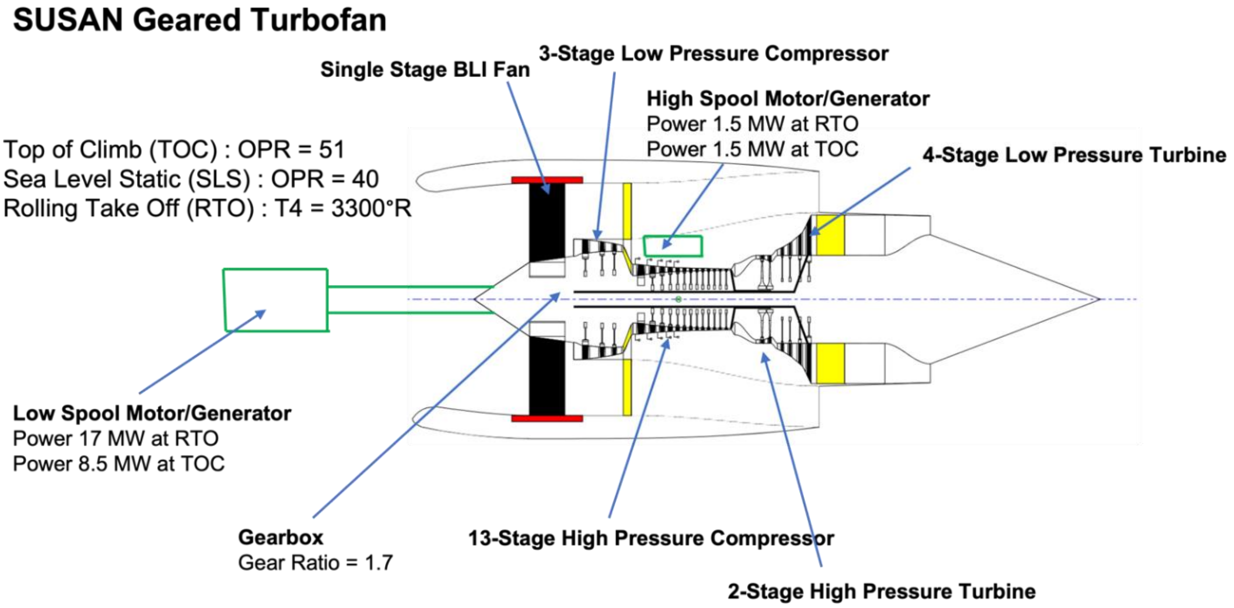

Figure 11 – Schematic of the SUSAN Tail Cone Thruster Geared Turbofan.[17]

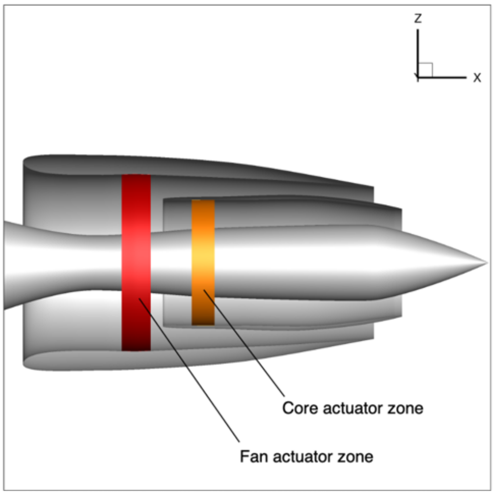

Figure 12 – A representative model of the TCT cross section [20].

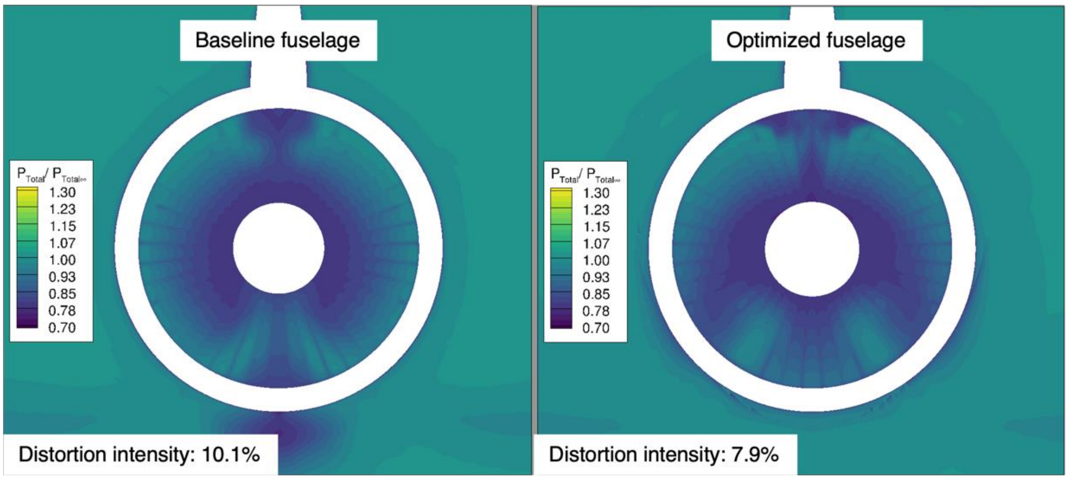

Figure 13 – TCT distortion profiles at the fan face [20].

Subsequently, aerodynamic shape optimization tools were utilized to reshape the aft fuselage diffuser with the objective of minimizing engine inlet distortion, a key aspect that can hinder the performance of the aft fuselage BLI engine. A comparison between the distortion profiles at the TCT fan face is presented in Figure *13*, with indication of the ARP1420 distortion metric utilized in this study.

Future studies will address the design of the inlet guide vanes, installed to further reduce distortion penalties.

3.3.2 Electric Wing Engine/Propulsor

Based on a system analysis of a preliminary SUSAN Electrofan concept with 16 identical electric wing-mounted fans, a ducted fan model was developed that could meet system-level requirements such as thrust targets for a given fan pressure ratio, and geometric constraints.

Given the BLI concept currently being considered for the integration of the electric engines, a dual counterrotating fan design was adopted for this application, with a design fan pressure ratio of 1.25 distributed equally between each stage. This feature is currently being considered to improve the robustness of the very low rotational speeds and fan pressure ratios to inlet distortion when considering off-design conditions and BLI. The low pressure ratio on each fan stage enables high efficiency on each blade row, and the low rotational speed permits good operability over a wide range of conditions along the engine speed line [19].

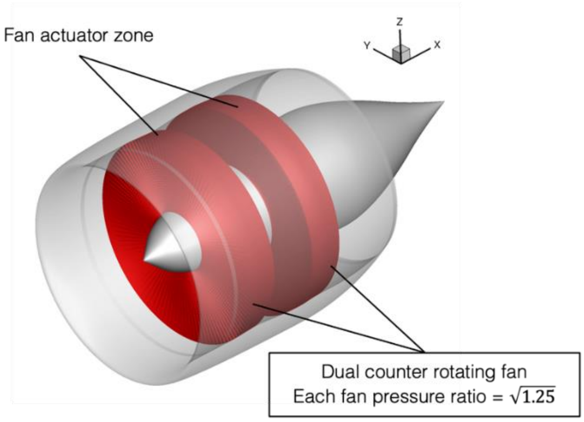

Figure 14 — Electric propulsor computational fluid dynamics (CFD) model [20].

A thorough external aerodynamics propulsor design followed, where adverse flow features such as shocks and flow separation, were minimized. In this process, key propulsor parameters were identified related to the overall nacelle and hub design, an example of which includes the nacelle leading edge droop angle. The propulsor model utilized in the high-fidelity analysis is presented in Figure *14*, where the fan propulsion is modeled through actuator zones.

The power produced by the tail cone engine is split between the 16 wing-mounted propulsors. At RTO, that would be roughly 1 MW each. For a counter rotating fan with two motors, that would be 500 kW for each motor. If the propulsor is a single fan, it would be 1 MW. NASA has been working on improving the power density of motor, power electronics, and cables under the Advanced Air Transport Technology (AATT), Electrified Powertrain Flight Demonstration, Transformational Tools and Technologies, and Convergent Aeronautics Solutions Projects. NASA is partnering with Advanced Research Projects Agency – Energy (ARPA-E) (part of the Department of Energy) who has two programs to move the technology rapidly. The first is the Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives (ASCEND) Program, which has set a benchmark of the fully integrated all-electric powertrain system (includes motor, power electronics, and cooling) at a power density of greater than12 kW/kg with an efficiency greater than 93%. The other program is called Connecting Aviation By Lighter Electrical Systems (CABLES) for decreasing the weight of electric cables. Both programs show great progress and demonstrate that the technology for the propulsors will be in hand in the near future.

3.3.3 Power System

The SUSAN electrical power system (EPS) architecture concept is designed to meet the target efficiency and emission requirements, while providing the necessary redundancy for a single turbofan aircraft. An overview of the EPS architecture is shown in Figure *15* [20].

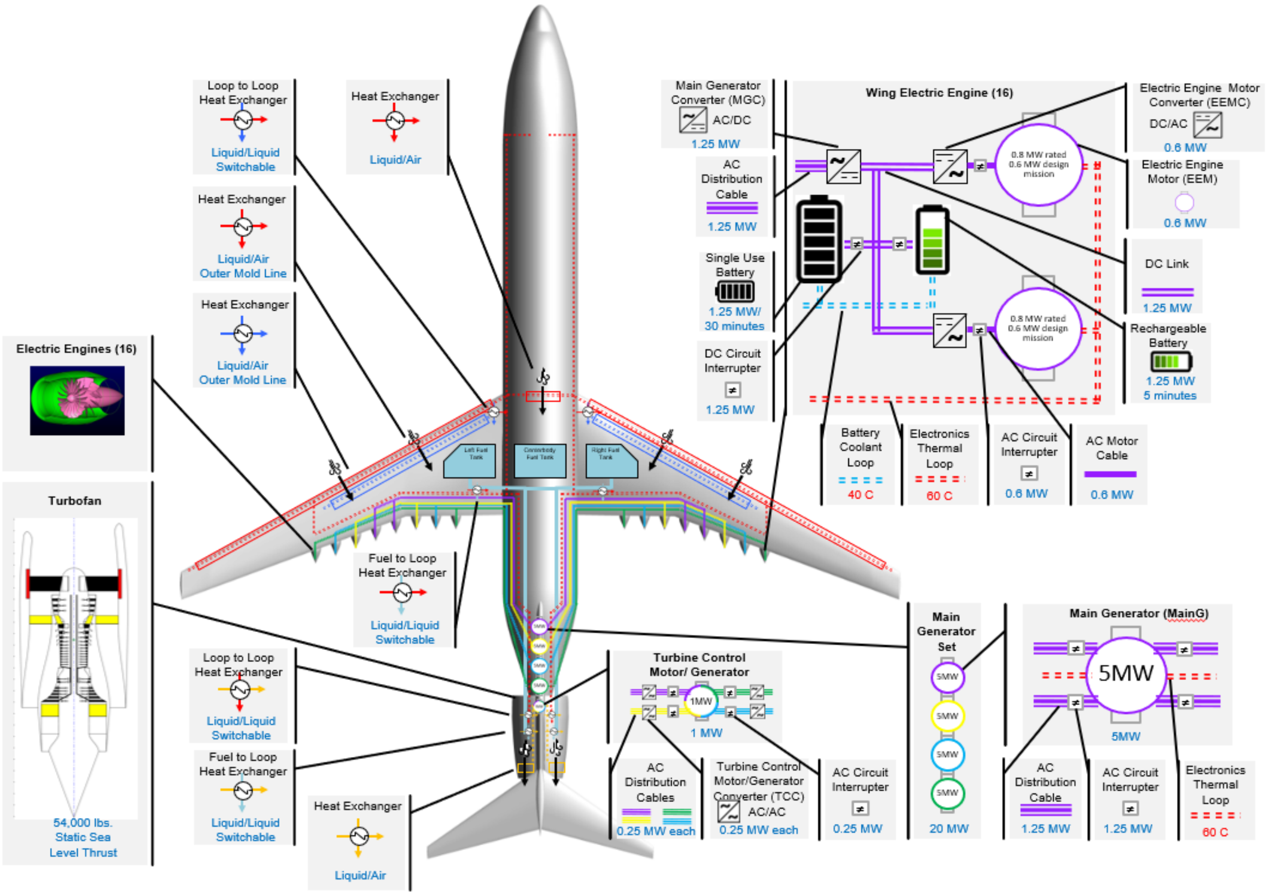

Figure 15 – SUSAN electrical power system (EPS).

The main source of electrical power in the EPS is the Main Generator (MG), driven by the low-pressure spool (LPS) of the turbofan engine, generating 20 MW of electrical power using four 5-MW machines. Also, a single 1-MW generator, the Turbine Control Motor-Generator (TCMG), is driven by the high-pressure spool (HPS). The output of the HPS is connected to four alternating current (AC)/AC converters that enable the outputs of the MG and TCMG to be electrically connected. The purpose of this generator on the HPS is to implement the Turbine Electrified Energy Management (TEEM) concept, discussed in Section 3.4.2.

The battery and wing propulsor portion of the electrical system includes two types of batteries that serve two different purposes. Single-use batteries are non-rechargeable batteries to be used in the event of a turbofan engine failure and will provide electric power to the wing propulsors allowing the aircraft to continue flight for 30 min. The rechargeable batteries will be used during normal flight to provide electrical power to the wing propulsors, and as the energy storage mechanism to enable TEEM implementation.

The Main Generator Converter (MGC) converts AC from the generators to direct current (DC) for the rechargeable batteries and feeds each of the 16 propulsors, 8 on each wing. Each propulsor consists of two counterrotating electric engine motors (EEM), each driven by an EEM controller (EEMC).

The power system ***enables the aerodynamic and propulsive benefits of the SUSAN approach*** [21]. The SUSAN EPS electric engines can be placed strategically to optimize propulsion aircraft integration benefits. The flexibility of connecting the primary power source on the aircraft, either the generators or the battery, to the electrical engine enables placement in optimal locations to maximize aerodynamic and propulsive efficiency.

Efficiency improvements from increased bypass ratio (BPR), higher propulsive efficiency due to BLI, and lift-to-drag ratio improvements have been frequently cited as enabled by turboelectric propulsion. Adding an electric drive system between turbine and fan enables decoupling of speeds and inlet-to-outlet area ratios. Using this approach, high BPR can be achieved by driving many configurations (number and size of fans) from a single turbine. The speed ratio between turbine and fan can be arbitrarily set and varied during operation, adding optimization opportunities, which allows the fan pressure ratio and the turbine-to-compressor speed ratios to be optimized independently.

BLI increases propulsive efficiency by ingesting lower velocity flow near the airframe into the propulsors, reenergizing the wake and thereby reducing drag. In the SUSAN implementation, the propulsor is mounted such that the slow-moving flow near the aircraft is ingested, reenergized, and exhausted, reducing drag.

The key performance parameters of specific power and efficiency can be implemented using several NASA technologies. The NASA High Efficiency Megawatt Motor (HEMM) is a partially superconducting, synchronous, wound field machine with a superconducting rotor and normal operating temperature stator that can operate as a motor or generator, promising very high efficiencies. And the NASA High-Efficiency Electrified Aircraft Thermal Research (HEATheR) converter technology development uses multilevel, interleaving, and other technologies to simultaneously achieve high specific power and high efficiency. This can be implemented using new NASA magnetics materials for lower weight filter components. Additionally, NASA is currently developing megawatt-class, high-speed circuit interrupters under industry and university efforts. Additional efforts are being undertaken in development of cabling and batteries.

3.3.4 Thermal System

One of the barriers to successful implementation of all-electric or hybrid-electric aircraft is managing the waste heat rejected by the batteries and other electronic components. A thermal management system (TMS) is required to reject the waste heat and maintain the electronic components and batteries in the temperature range for optimal performance and prevent failure due to temperature exceedances (high or low) or thermal cycling. Rejecting the amount of heat generated while maintaining this narrow temperature range using conventional technologies adds significant weight, power, and/or drag to the aircraft. Designing the TMS into the system early allows for optimization of the design and evaluation of options for multifunctionality. Weight reductions in secondary subsystems are possible through integration with the TMS. Electrically driven cabin and cargo environmental systems can be coupled with the electronics cooling loops, thereby reducing the number of TMS-specific components such as ram-air heat exchangers. Additionally, anti-icing systems can be augmented by utilizing the waste heat transported by the cooling loops prior to rejection, reducing the weight or power required by an independent system. Other possible options for multifunctional use of the TMS being considered include incorporation into the structure or skin, EMI shielding, and fuel heating in cold environmental conditions. Initial trade space exploration of the feasibility of different TMS options included an evaluation of using the fuel as part of the TMS [22].

The nominal layout of the TMS is included in Figure 9. Current efforts towards refining this design are focused on determining requirements and evaluating options for multifunctionality, including heat sharing between components in cold environmental conditions. Current regulations, standards, and guidelines are being researched to identify relevant requirements and best practices to use when designing the system. The design of other subsystems also drives the requirements of the TMS. Additionally, areas available for heat rejection that are favorable or neutral in the overall aircraft design are being explored. Rejecting heat near the component location reduces overall TMS weight but may impact the implementation of other technologies such as BLI or NLF. Future work includes evaluating different options for multifunctionality, determining requirements related to thermal runaway of batteries, and applying any lessons learned from the 25%-scale flight research vehicle that are relevant to the design of the full-scale TMS.

3.3.5 Electric Taxi

As the daily number of commercial air travelers continues to grow within the existing infrastructure, airports are encountering an increased level of congestion. This has resulted in an upward trend of aircraft taxi times over the last 20 years [23]. Additionally, this taxi operation constitutes a significant portion of the fleet fuel consumption for operators constituting up to 6% of total fuel expenditure for short-haul fleets [24]. The current state-of-the-art electric taxi relies on use of the electric motors on the landing gear to reduce fuel burn during ground operation.

The SUSAN architecture allows the use of the existing onboard battery power to perform all or a portion of taxi maneuvers using the engines under electric power. This allows the pilots to perform a more traditional and familiar taxi operation while reducing or eliminating fuel burn for the taxi phase without the need for additional component weight.

3.3.6 Reduction of Bleed Air Systems

Historically, air requirements for aircraft pneumatic system were provided by the engine via compressor bleeds or off-takes. These aircraft systems include aircraft needs such as, air-conditioning, cargo compartment heating, wing and engine anti-icing, engine start, thrust reverser, hydraulic reservoir pressurization, rain-repellent nozzles, water tank pressurization, and air driven hydraulic pumps. These air requirements for the engine represent a significant load because it makes use of high-pressure compressor (HPC) air removed from the engine system, which reduces engine efficiency. This high-cost air must also be ducted and routed to use points and in some cases cooled for use, which infers additional cost on the aircraft. The SUSAN aircraft does away with this system and replaces it with an electrically driven concept. Here, the power is taken from the engine more efficiently via an electric generator and used on more efficient subsystems for an estimated 35% reduction in power requirement. This power can then be provided to the subsystems using electric wiring rather than air ducting, which can reduce weight. It is estimated that these changes reduce engine fuel consumption in the range of 1 to 2% with an overall aircraft system benefit of 3% off fuel burn [23],[26].

3.4 Integrated Flight/Engine/Power Control to Enable Additional Benefits

3.4.1 Thrust-Based Flight Control to Reduce Flight Control Surfaces

DEP has the potential to enable the practical use of thrust for flight control on transport-category aircraft. High electric engine bandwidth is expected to overcome the limitations imposed by turbofan response times on stability and control augmentation. Placing some engines far from the center of gravity produces significant control moments, which would be hazardous on two- and four-engine configurations. Distribution mitigates the upset following the failure of any one engine while providing redundancy for both propulsion and flight control. DEP is being used to increase the effectiveness of the SUSAN flight control system, and in doing so, increase the efficiency of the aircraft configuration.

Differential thrust provides yaw control authority, but on SUSAN, control effectiveness is not limited to the directional axis. PAI makes it possible for thrust to induce aeropropulsive forces and moments. Thrust increases local lift, and so differential thrust produces rolling moment in addition to yaw. Symmetric thrust enhances total lift. In addition to providing control authority directly, aeropropulsive interaction might similarly enhance the effectiveness of conventional control surfaces. These effects will be leveraged to reduce control surface usage and drag, and if possible, surface and actuator size and weight.

Preliminary flight dynamics models and flight control laws have been implemented in simulation. Initial aerodynamic predictions are based on DATCOM and XFLR5 and have been augmented to include first-order aeropropulsive interactions. DATCOM is a collection, correlation, codification, and recording of best knowledge, opinion, and judgment in the area of aerodynamic stability and control prediction methods [27]. XFLR5 is an analysis tool for airfoils, wings and planes operating at low Reynolds Numbers [28]. The flight control system is based on a control allocation scheme that determines the fan, elevator, aileron, and rudder inputs needed to achieve forward, roll, pitch, and yaw acceleration commands. As part of the trade space exploration, the allocation scheme can be configured to employ differential thrust for aileron and rudder functions, separately or in combination.

Aerodynamic model fidelity will be improved iteratively, with emphasis on aeropropulsive effects. Stability and control coefficients will be updated to include predictions from VSPAero [29], and eventually refined using CFD. CFD will also inform design trades by providing estimates of control surface drag. As the aerodynamic model develops, the flight control system design will evolve with it. The study will explore surface sizing and gain tuning to minimize surface usage, drag, and weight, while also satisfying performance and robustness requirements.

3.4.2 Turbine Electrified Energy Management (TEEM) Control

TEEM [30] is one of the technologies leveraged by SUSAN to achieve a system-level benefit. TEEM is a controls approach that leverages an EPS, notably comprising electric machines and energy storage, interfaced with turbomachinery. The goal is to selectively modify operation of the engine via application or extraction of power from the engine spools to the benefit of the overall system. Development of this concept has focused primarily on improving transient operability with the goal of alleviating design constraints on the engine such that performance improvements related to efficiency and weight can be achieved. The operability benefits are achieved by applying torques to the engine shafts with electric machines such that the engine, and the compressors in particular, operate closer to steady-state conditions through a change in speed and power. Several applications have been covered in the literature [31],[32],[33].

The direct benefit of TEEM is improved operability. The indirect benefit is what improved operability enables. Transient operability, which is associated with rapid changes in thrust/power demand, places constraints on the engine design. Most notably, compressor stall/surge is of concern during transients. The engine design must account for the worst-case transients, which constrain the engine design. There are trades between engine responsiveness, performance, and operability. Furthermore, requirements for engine responsiveness and operability lead to compromises in engine performance. These constraints on the engine design can be alleviated with TEEM leading to potentially more efficient and lighter weight engines. While the benefit has not been formally quantified, as it is a topic of on-going research, it is believed that the benefits could include a few percent in thrust specific fuel consumption and a several percent reduction in engine weight. Potential penalties of integration could be applicable if TEEM were to buy its way onto an engine by itself. This would include the weight, cost, maintenance, and added complexity of the EPS components necessary for TEEM. However, with a concept such as SUSAN that inherently has some of these components already present, the penalty of integration is diminished.

To date, TEEM has been applied to an iteration of the SUSAN propulsion system model. It utilizes the generator inherent on the LPS of the engine. In addition, it utilizes an electric machine on the HPS and a modest amount of reusable energy storage. These components could have other synergistic uses such as applications for engine starting, power off-take, etc. A steady-state NPSS model was converted to a dynamic MATLAB®/Simulink® (The MathWorks, Inc.) model using the Toolbox for Modelling and Analysis of Thermodynamic Systems (T-MATS) [34]. A full-flight envelope controller has been developed, and the TEEM control approach for improving transient operability was applied. Figure 16 shows a plot of the movement of the operating point on the HPC and low-pressure compressor (LPC) maps during a burst and chop transient scenario. Such a transient scenario is characterized by a rapid acceleration followed by a rapid deceleration. In the plot, PR refers to the pressure ratio, and Wc is the corrected mass flow rate at the inlet of the compressor. The stall lines are the top cyan line on the maps. As is evident, the use of TEEM shifts the transient running line away from the stall line and reduces the deviation from the steady-state operating line. Similar results can be shown throughout the flight envelope.

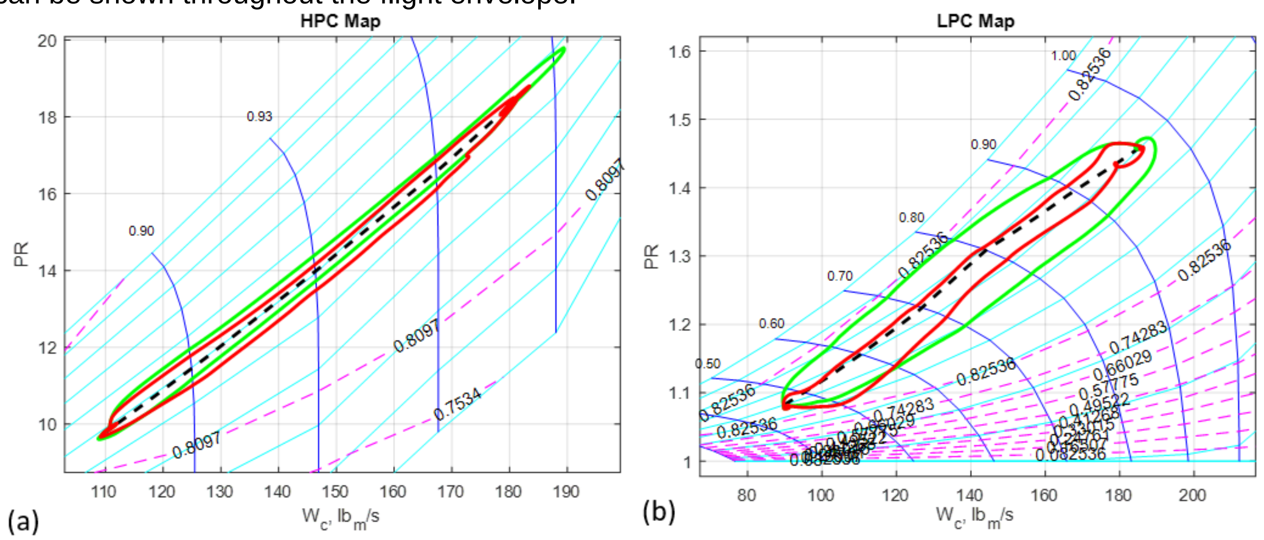

Figure 16 – HPC and LPC map for a burst and chop transient. Shown is the steady-state operating line (dashed black line) and the running lines without TEEM (green) and with TEEM (red).

The next steps are to update the dynamic engine model to remain consistent with updates to the SUSAN concept. The propulsion system controller, including the TEEM controller, will be updated as well. A more thorough analysis will be conducted to determine requirements for implementing TEEM and estimating benefits for the most recent iteration of SUSAN. Time and resource permitting, the use of TEEM in conjunction with take-off/climb boost could be investigated.

3.4.3 Other Control-Enabled Benefits

The SUSAN powertrain under nominal conditions consists of a single turbofan engine, a power system, 16 electric engines, and rechargeable batteries. The power system converts mechanical power extracted from the engine to electricity used to drive the 16 electric engines. Because of the design of the powertrain, the interaction of the components is highly coordinated and automated. The power split between the gas turbine engine and the electric engines is defined throughout the flight envelope. Thus, the power extracted from the turbofan is set as a function of its power level and is just enough to drive the electric engines at their specified speed in steady state.

The rechargeable batteries provide a temporary power boost during climb, enable TEEM control, and support rapid response of the electric engines during acceleration. Because the batteries can temporarily provide additional power beyond that extracted from the gas turbine engine, the turbofan can be sized for cruise operation with the extra power required for climb coming from the batteries. The use of the batteries for TEEM control was described previously. The small incremental power demand TEEM requires has the potential to reduce the size of the engine even further. Battery power also fills the temporary power extraction gap during transients. While TEEM control reduces the turbofan’s off-design operation during acceleration, the engine still takes several seconds to achieve a large power-level change. With power extraction approximately proportional to fan speed, the electric engine acceleration would be tied to that of the turbofan, resulting in a relatively sluggish response considering the capability of the electric motors. Temporary augmentation with battery power enables a much faster response from the electric engines while still respecting the gas turbine engine’s power extraction design limits. Small deviations in power extraction from the design point once in steady state allow the batteries to recharge to their desired level after use.

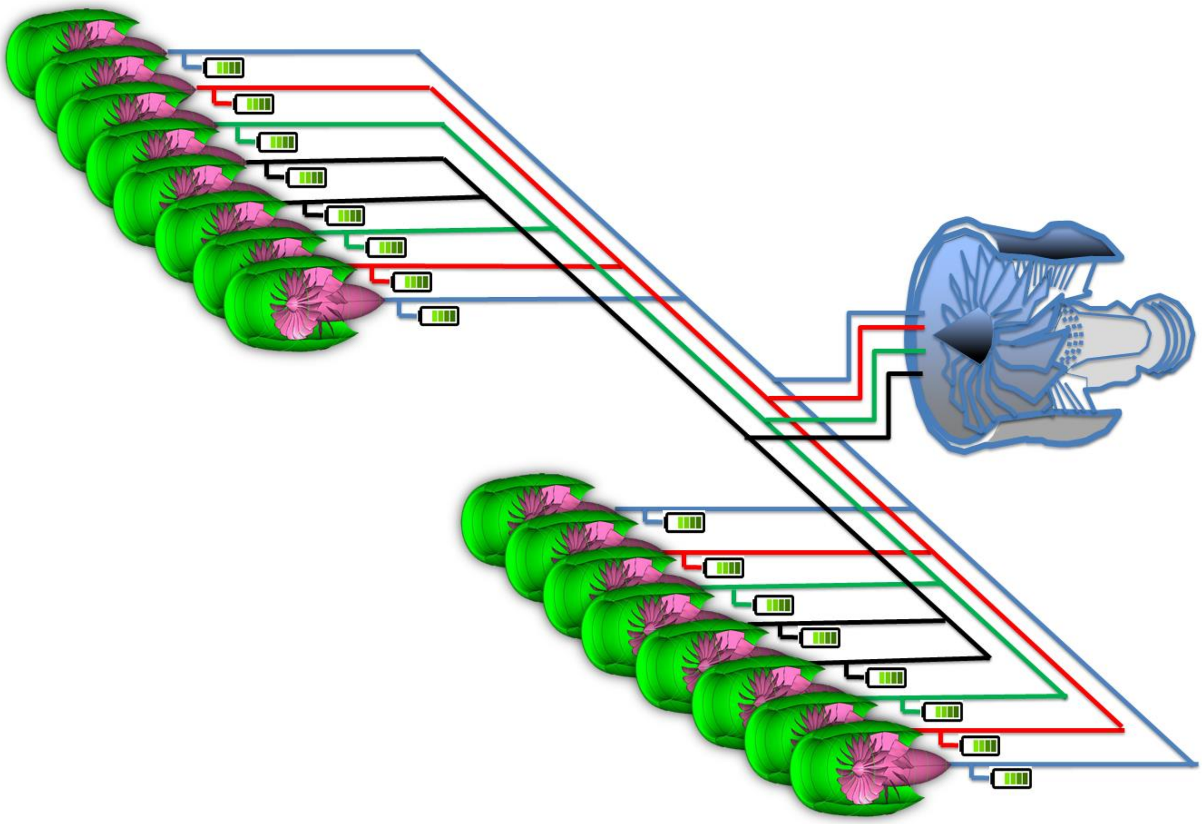

Figure 17 – Simplified SUSAN powertrain diagram showing the turbofan and connections from its four main generators to the wing-mounted electric engines. The symmetric layout of each bus ensues a failure will not cause a thrust asymmetry. Each electric engine has an associated rechargeable battery to provide additional benefits.

The distributed nature of the propulsion components and design of the power system enables further benefit. As described previously, the flight control system takes advantage of the positioning of the electric engines across the wing for enhanced maneuverability. Differential application of power influences the aircraft's attitude, particularly in the roll and yaw axes, which can potentially be leveraged for reducing the size of the flight control surfaces, thereby saving weight. The connection of each of the four low-spool generators to four electric engines symmetrically means that differential thrust can be applied with the most impact (Figure 17). The thrust on one side, and especially that of the outermost engines, can be increased while that on the opposite side can be decreased, all while maintaining total power. This allows for the largest overall thrust differential while essentially maintaining total thrust, without impacting power extraction.

An integrated control scheme that coordinates the turbofan engine speed, battery state of charge, and electric engine speed is being developed and optimized. It takes throttle commands from the pilot, as well as differential thrust commands from the flight control system. Overall results of testing will help determine the component and control surface sizing requirements.

3.4.4 Flight Deck

Initial research has begun on the SUSAN flight deck to address the flightcrew's ability to safely operate a hybrid-electric commercial aircraft. In 2022, most U.S. commercial transport aircraft propulsion systems consist of two wing-mounted engines and two throttle handles. The engine performance of modern commercial aircraft is completely managed by a Full Authority Digital Engine Control (FADEC) system [35]. The flightcrew modulates the aircraft's thrust either by engaging the autothrottle system or manually moving the throttles. Asymmetric thrust in a multiengine airplane is caused from either a failure or degraded/reduced thrust of an off-body axis engine. The autothrottle system can handle small thrust asymmetry; but the autothrottle system will disengage if the asymmetric thrust becomes too large. For a SUSAN airplane with 17 engines (1 turbofan and 16 wing-mounted electric engines), manually controlling 17 thrust levers will be too high of a workload for the flightcrew even under nominal flight conditions; thus, flight critical thrust automation will be required.

The SUSAN flight deck is being designed for two flightcrew members (14 CFR §121.385c) [36], leveraging from current state-of-the-art commercial transport aircraft [37][38]. The rationale for this evolutionary approach to the SUSAN flight deck design is to baseline from a proven concept and modify the flight deck to accommodate the unique hybrid-electric propulsion system. The Primary Flight Display (PFD) and the Navigational Display (ND) will remain mostly unchanged. The thrust of a SUSAN airplane will be highly optimized by the engine control system; therefore, the flightcrew will not need differential throttle control. However, the flightcrew may need to manually shutdown any of the 17 engines. A human-in-the-loop study will be conducted to explore the need for multiple throttle handles in nominal and off-nominal conditions. Several candidate information display approaches are being developed including a SUSAN Engine Indicating and Crew Alerting System (EICAS) shown in Figure 18.

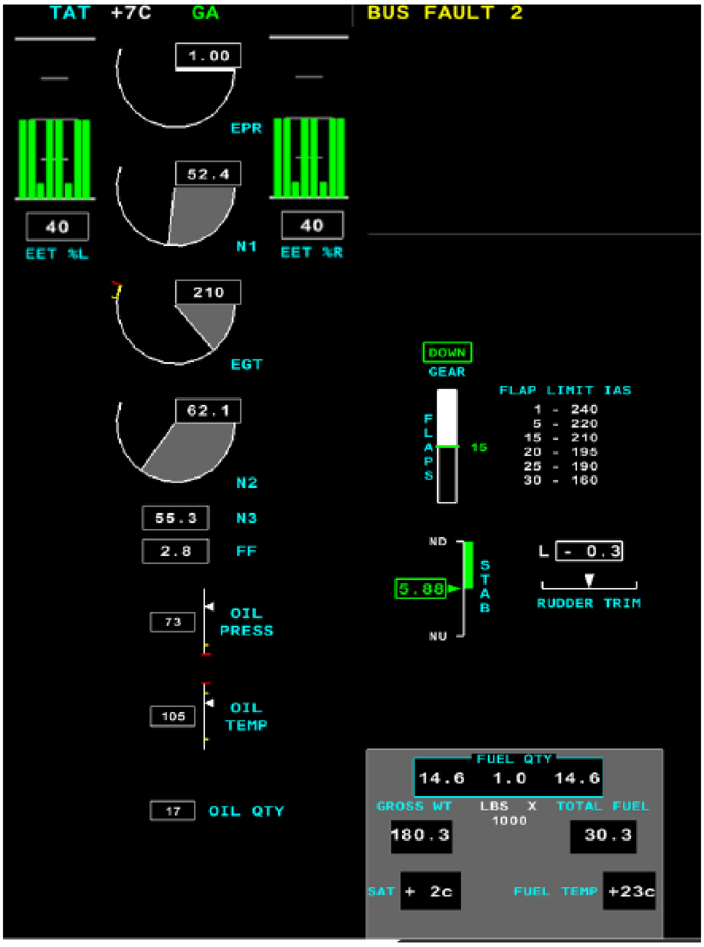

Figure 18 – Display based on typical EICAS display (left) with the addition of electric engine states.

Pilot studies will be conducted to evaluate a range of throttle and display configurations during nominal and off-nominal conditions. An analysis of Situational Awareness Rating Technique (SART) [39], NASA Task Load Index (TLX) [40], and posttest comparisons via Subjective Workload Dominance (SWORD) [41] will be used to compare the throttle and display concepts.

4. Conclusion and Next Steps

NASA is conducting an ongoing trade study analysis of the SUSAN Electrofan aircraft concept, which utilizes 20-MW-class electrified aircraft propulsion to enable propulsive, aerodynamic, and control benefits while retaining the range, speed, and size of typical narrow-body regional aircraft. The study is constrained by the ground rules of operating within the current airport and airspace infrastructure. This ongoing study seeks to find a configuration and combination of technologies that yield significant fuel burn and emissions benefits. Another key goal is to reduce cost per passenger mile. Currently, the study is focused on a configuration that utilizes jet A or sustainable aviation fuels, however, we plan to consider other fuel alternatives in the future. The work is sponsored by the Transformative Aeronautics Concepts Program (TACP), Convergent Aeronautics Solutions (CAS) Project.

References

[1] Jansen, R. H., et al. Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept and Trade Space Exploration. *AIAA SciTech 2022 Forum*, San Diego, CA, January 2022. https://ntrs.nasa.gov/citations/20210025324

[2] International Civil Aviation Organization (ICAO), "2022 Environmental Report", https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022.pdf

[3] Bureau of Transportation Statistics, "Data Bank 28DM - T-100 Domestic Market Data - U.S. Air Carriers Traffic and Capacity Data", U.S. Department of Transportation, https://www.bts.gov/browse-statistical-products-and-data/bts-publications/%E2%80%A2-data-bank-28dm-t-100-domestic-market-data-us

[4] United States Federal Aviation Administration. "Terminal Area Forecast (TAF)." FAA, Washington, DC. Available: https://www.faa.gov/data_research/aviation/taf

[5] McFadden, D. and Train, K. Mixed MNL Models for Discrete Response. *Journal of Applied Economics*, Vol 15, Issue 5, pp 447-470, 2000.

[6] Berry, S., Levinsohn, J. and Pakes, A. Automobile Prices in Market Equilibrium. *Econometrica*, Vol. 63, No. 4, pp. 841-890, 1995.

[7] Bhadra, D. Choice of Aircraft Fleets in the U.S. Domestic Scheduled Air Transportation System: Findings from a Multinomial Logit Analysis. *Journal of the Transportation Research Forum*, Vol. 44, No. 3 (Fall 2005), pp. 143-162, 2005.

[8] Denham, C. L. and Jansen, R. Initial Regulatory and Certification Approach for the SUSAN Electrofan Concept. *AIAA SciTech 2022 Forum*, AIAA 2022-2180, San Diego, CA, Jan 2022. doi:10.2514/6.2022-2180, URL https://arc.aiaa.org/doi/10.2514/6.2022-2180, https://ntrs.nasa.gov/citations/20210024770

[9] Federal Aviation Administration. Standard Airworthiness Certification Regulations, 2022. URL https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-25

[10] Federal Aviation Administration. Standard Airworthiness Certification Regulations, 2022, URL https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-25/subpart-G/subject-group-ECFR4acc68774858806/section-25.1535

[11] Chau, T., Kenway, G. K. W. and Kiris, C. Conceptual Exploration of Aircraft Configurations for the SUSAN Electrofan. *AIAA SciTech 2022 Forum*, AIAA 2022-2181, San Diego, CA, January 2022, https://doi.org/10.2514/6.2022-2181, https://ntrs.nasa.gov/citations/20210025477

[12] Wick, A. T., Hooker, J. R., Hardin, C. J. and Zeune, C. H. Integrated Aerodynamic Benefits of Distributed Propulsion. *53rd AIAA Aerospace Sciences Meeting: SciTech Forum*, Kissimmee, FL, AIAA 2015-1500, 2015.

[13] Schmollgruber, P., Donjat, D., Ridel, M., Cafarelli, I., Atinault, O., Francois, C. and Paluch, B. Multidisciplinary Design and Performance of the ONERA Hybrid Electric Distributed Propulsion Concept (DRAGON). *AIAA SciTech 2020 Forum*, Orlando, FL, AIAA 2020-0501, 2020.

[14] Celestina,M. and Long-Davis, M. Large-scale Boundary Layer Ingesting Propulsor Research, ISABE-2019-24264, 2019. https://ntrs.nasa.gov/citations/20190031845.

[15] Lynde, M. N. and Campbell, R. L. Computational Design and Analysis of a Transonic Natural Laminar Flow Wing for a Wind Tunnel Model. *35th AIAA Applied Aerodynamics Conference*, Denver, CO, AIAA-2017-3058, June 2017. https://ntrs.nasa.gov/citations/20170005688

[16] Lynde, M. N. Campbell, R. L. and Hiller, B. H. A Design Exploration of Natural Laminar Flow Applications for the SUSAN Electrofan Concept. *AIAA SciTech 2022 Forum*, San Diego, CA, AIAA-2022-2303, January 2022. https://ntrs.nasa.gov/citations/20210024470

[17] Mirhashemi, A., Chapman, J. W., Miller, C. J., Stephens, J. E., Jansen, R. H., Tail-mounted engine Architecture and Design for the Subsonic Single Aft Engine Electrofan Aircraft. *AIAA SciTech 2022 Forum*, San Diego, CA, AIAA 2022-2182, January 2022. https://ntrs.nasa.gov/citations/20210024573

[18] Machado, L., Chau, T., Kenway, G., Duensing, J. and Kiris, C. High-Fidelity Aerodynamic Analysis and Optimization of the SUSAN Electrofan Concept", *AIAA SciTech 2022 Forum*, San Diego, CA, AIAA 2022-2304, January 2022. https://doi.org/10.2514/6.2022-2304 , https://ntrs.nasa.gov/citations/20210025462

[19] Lee,B.J. and Liou, M.F. Conceptual Design of Propulsors for the SUSAN Electrofan Aircraft. *AIAA SciTech 2022 Forum*, San Diego, CA, AIAA 2022-2305, January 2022. https://doi.org/10.2514/6.2022-2305

[20] Haglage, Joseph, et al. Electrical System Trade Study for SUSAN Electrofan Concept Vehicle. *AIAA SciTech 2022 Forum*, San Diego, CA, January 2022, https://ntrs.nasa.gov/citations/20210024949.

[21] Jansen, Ralph, et al. Turboelectric aircraft drive key performance parameters and functional requirements. *51st AIAA/SAE/ASEE Joint Propulsion Conference*, Orlando, FL, 2015. https://ntrs.nasa.gov/citations/20160006295

[22] Heersema, N. and Jansen, R. Thermal Management System Trade Study for SUSAN Electrofan Aircraft. *AIAA SciTech 2022 Forum*, San Diego, CA, January 2022. https://ntrs.nasa.gov/citations/20210024094

[23] Goldberg. B, Chesser, D., "Sitting on the Runway: Current Aircraft Taxi Times Now Exceed Pre-9/11 Experience" BTS Special Reports and Issue Briefs SR-008. 2008

[24] Johnson. T, "Electric Green Taxiing System (EGTS) for Aircraft" IEEE Transportation Electrification Newsletter, 2014.

[25] Sinnett, Mike. 787 no-bleed systems: saving fuel and enhancing operational efficiencies. *Aero Quarterly*, Vol. 18,pp. 6-11, 2007.

[26] Moir, I. and Seabridge, A. *Aircraft Systems: Mechanical, Electrical, and Avionics Subsystems Integration*. 3rd Edition, AIAA Education Series, John Wiley & Sons, 2008.

[27] Hoak, D. E., et al., The USAF Stability and Control DATCOM, Air Force Wright Aeronautical Laboratories, TR-83-3048, Oct. 1960 (Revised 1978).

[28] XFLR5 organizational home page: URL: http://www.xflr5.tech/xflr5.htm

[29] Open VSPAero home page: URL: http://openvsp.org/wiki/doku.php?id=start

[30] Culley, D., Kratz, J. and Thomas, G. Turbine Electrified Energy Management (TEEM) For Enabling More Efficient Engine Designs. *AIAA Propulsion & Energy Forum*, Cincinnati, OH, 2018. https://ntrs.nasa.gov/citations/20190002775

[31] Kratz, J., Culley, D. and Thomas, G. A Control Strategy for Turbine Electrified Energy Management. *AIAA Propulsion & Energy Forum*, Indianapolis, IN, 2019.

[32] Kratz, J. and Culley, D. Enhancement of a Conceptual Hybrid Electric Tilt-Wing Propulsion System through Application of the Turbine Electrified Energy Management Concept. *AIAA SciTech 2021 Forum,* Virtual Conference, AIAA 2021-0875, 2021. https://ntrs.nasa.gov/citations/20205010591

[33] Kratz, J. and Simon, D. Failure Modes and Mitigation Strategies for a Turboelectric Aircraft Concept with Turbine Electrified Energy Management. *AIAA SciTech 2022 Forum*, San Diego, CA. 2022. https://ntrs.nasa.gov/citations/20210024961

[34] Chapman, J., Lavelle, T., May, R., Litt, J. and Guo, T.-H. Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) User's Guide. NASA TM-2014-216638, 2014. https://ntrs.nasa.gov/citations/20150000137

[35] Scoles, R. FADEC - Every Jet Engine Should Have One. SAE Technical Paper 861802, *SAE Aerospace Technology Conference and Exposition*, Dayton, OH, October 1986. URL https://doi.org/10.4271/861802.

[36] Federal Aviation Administration. Standard Airworthiness Certification Regulations, 2022, URL https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-121/subpart-M/section-121.385

[37] Wong, D., Wang, Y., Li, X. and Dong, D. Commonality Considerations in the Design of Flight Deck of Civil Aircraft. Conf. Ser. 1678 012037, *Journal of Physics*, 2020. doi:10.1088/1742-6596/1678/1/012037

[38] Neville, R. and Dey, M. Innovative 787 Flight Deck Designed for Efficiency, Comfort, and Commonality. *Boeing Commercial Aero Magazine*, QTR 01.12, Seattle, WA, 2012.

[39] Taylor, R. M. Situational awareness rating technique (SART): The development of a tool for aircrew systems design. *Situational Awareness*, 1st Edition, Routledge, 2011.

[40] Hart, S. G. and Staveland, L. E. Development of a NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in Psychology*, Vol. 52, pp. 139-183, 1988.

[41] Vidulich, M. A., "The use of judgment matrices in subjective workload assessment - The Subjective WORkload Dominance (SWORD) technique," Human Factors and Ergonomics Society, 33rd annual meeting, Denver, CO, 1989, pp. 1406–1410.

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