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

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Overview

- NASA is conducting an ongoing trade study analysis of the SUSAN Electrofan aircraft concept

- SUSAN 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.

Figure 1 – Artist Rendering of SUSAN Electrofan Concept

Concept

- 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.

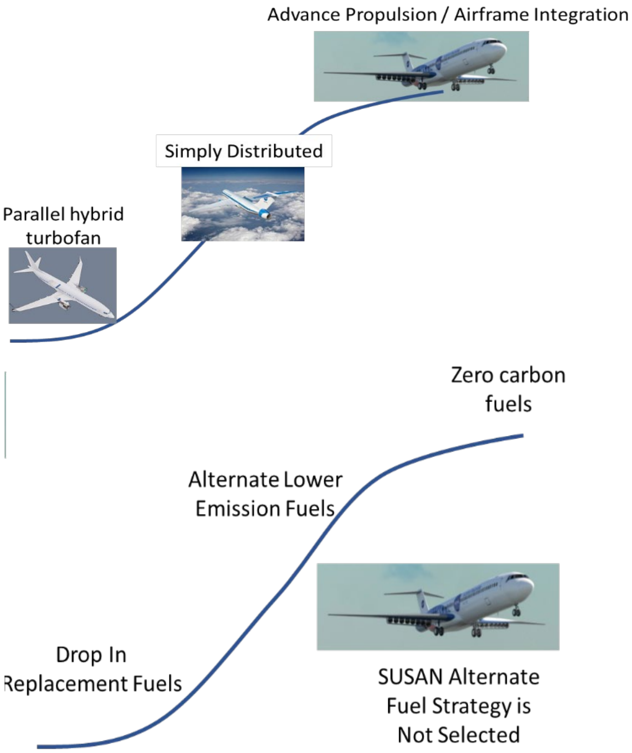
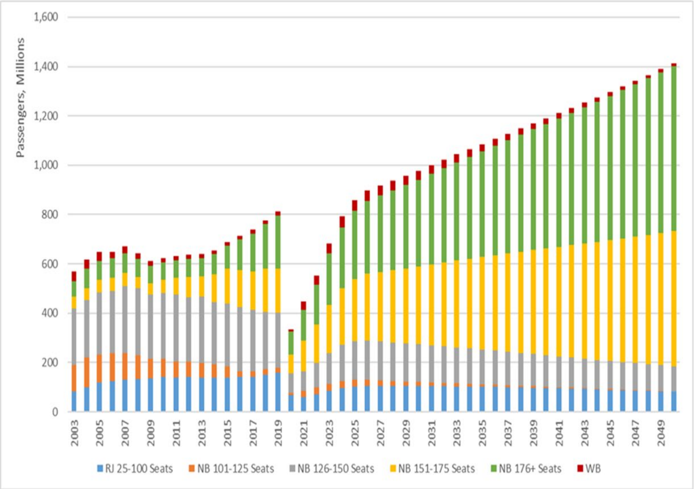


Figure 2 – SUSAN Electrofan is a concept to move up two technology S-curves.

Market

- 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
- 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.
- The 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.



Regional Jet 25-100 Seats
Narrow Body 101-125 Seats
Narrow Body 126-150 Seats
Narrow Body 151-175 Seats
Narrow Body 176+ Seats
Wide Body

Figure 3 – Fleet size category forecast output to 2050 from the MNL model.

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 4 reflects a common sizing mission profile, which includes additional reserve requirements for fuel allowance, missed approach, and additional cruise and descent segments.
- The mission profile with turbofan failure is shown in Figure 5, 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.

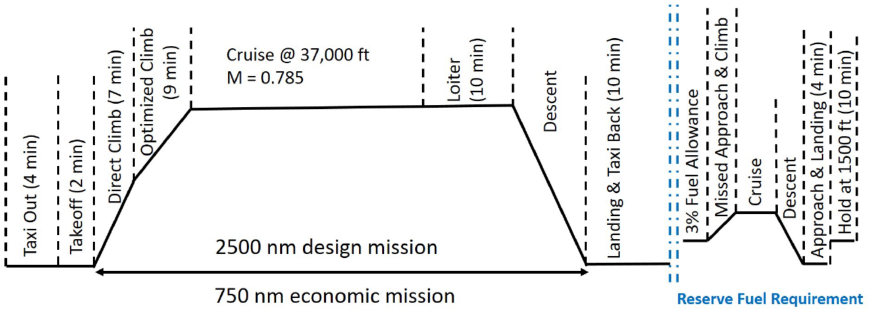


Figure 4 – Nominal mission profile for the SUSAN Electrofan concept with included reserve fuel requirements

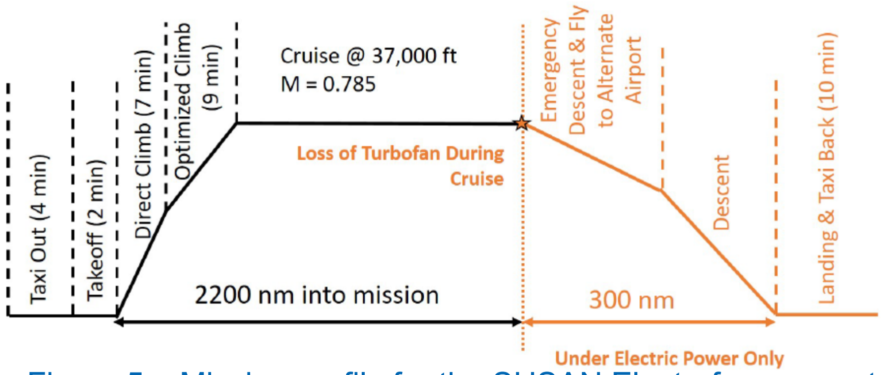


Figure 5 – Mission profile for the SUSAN Electrofan concept in the event of loss of the turbofan during cruise

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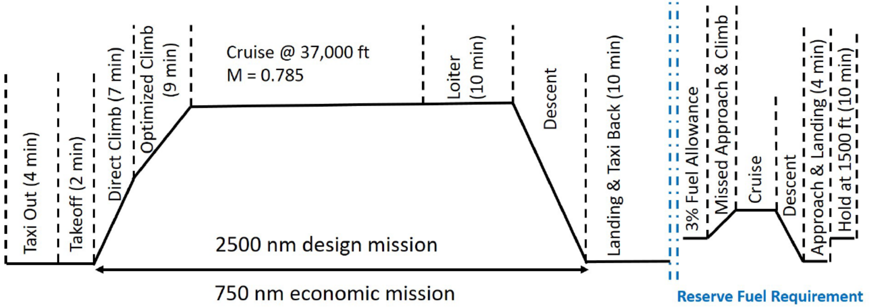

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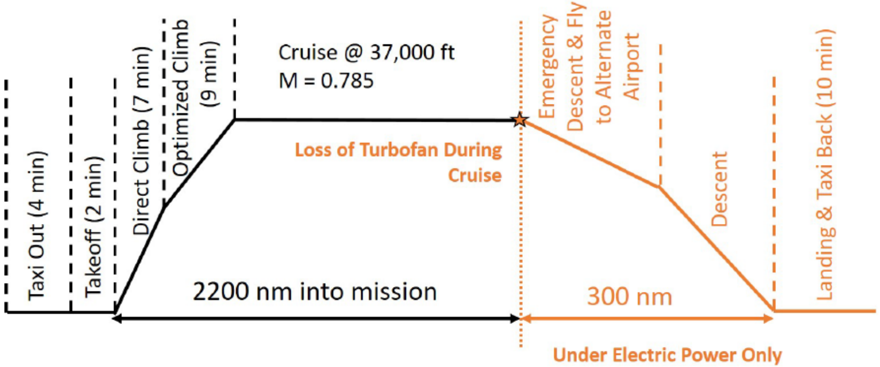

Figure 7 – Mission profile for the SUSAN Electrofan concept in the event of loss of the turbofan during cruise

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.

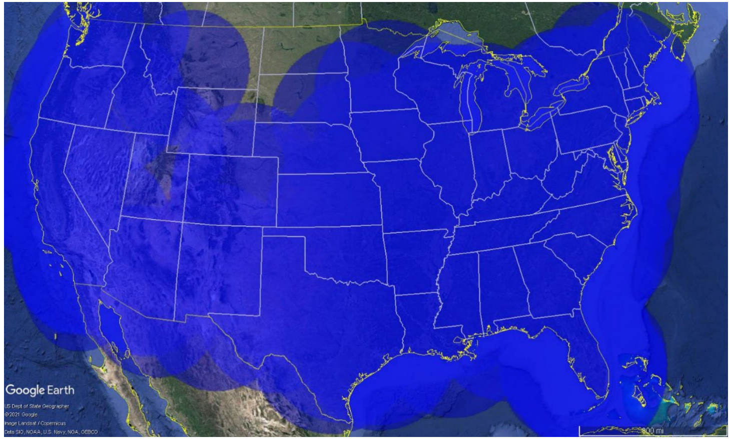

Figure 8 – Area covered by 300 nautical mile radius from U.S. primary airports, equivalent to 30 min flying time at Mach 0.785, shown in blue shading.

Distributed Propulsion

- Distributed propulsion, where the thrust generated can be spread across a larger number of propulsors with smaller diameters, is being investigated for the SUSAN Electrofan concept.
- Increased capture area of the propulsion system lowers the design fan pressure ratios and hence the shaft power required to achieve a certain level of thrust.
- Trades include
    - The aerodynamic drag, when considering the greater wetted area and cross-sectional area of the system.
    - The weight 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.

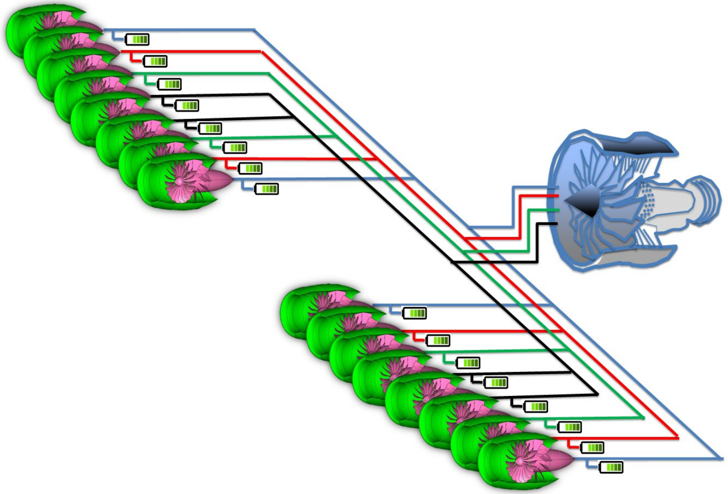

Figure 9 – Simplified SUSAN powertrain diagram showing the turbofan and connections from its four main generators to the wing-mounted electric engines.

Boundary Layer Ingestion and Natural Laminar Flow

- Boundary Layer Ingestion (BLI) 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 is being investigated
- Currently SUSAN features tail cone thruster and an underwing DEP system to capture fuselage and a portion of the wing boundary layer flow.
- The main wing and empennage surfaces are being considered for NASA's Crossflow Attenuated Natural Laminar Flow (CATNLF) technology.
- 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

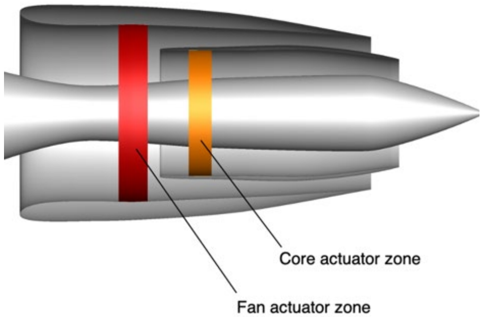

Figure 10 – A representative model of the Tail Cone Thruster (TCT) cross section .

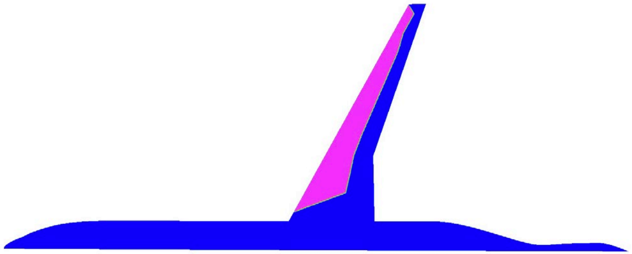

Figure 11 – Planform view of the NLF design showing the predicted transition front (pink is laminar, blue is turbulent) at the cruise-point design condition.

Turbofan Engine

- SUSAN uses a single low bypass ratio, rear mounted turbofan which acts as a turbogenerator to power the wing electric engines and provide thrust at the rear of the aircraft.
- 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.
- Low fidelity, detailed system analysis was used to obtain a power split between the wing electric engines and the aft-mounted tail cone thruster (TCT).
- 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

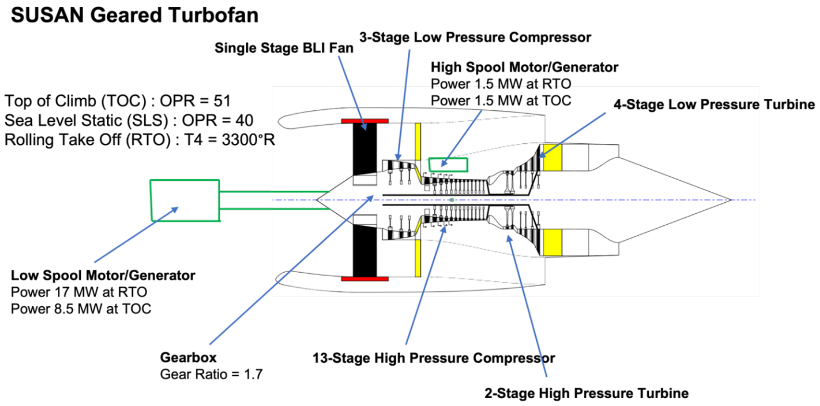

Figure 12 – Schematic of the SUSAN Tail Cone Thruster (TCT) Geared Turbofan.

Electric Engines

- Based on 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.
- A dual counterrotating fan design was adopted for this application, with a design fan pressure ratio of 1.25 distributed equally between each stage.
- Counter rotating fans are 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

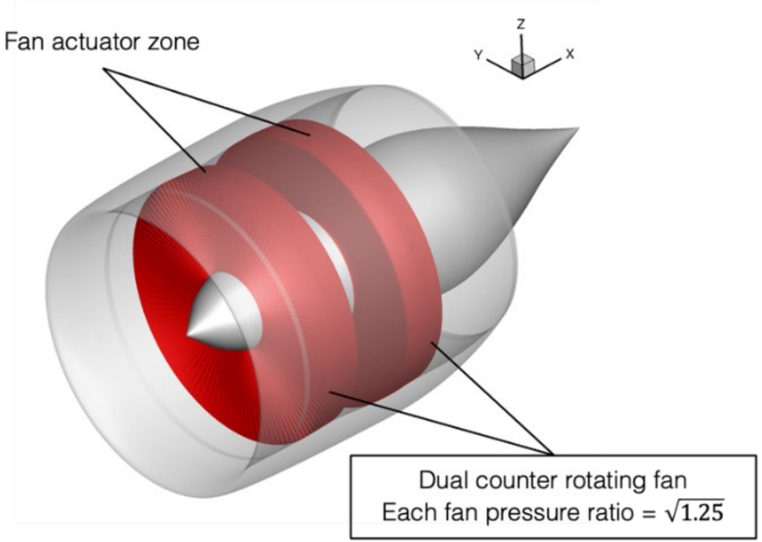

Figure 13 – Electric propulsor computational fluid dynamics (CFD) model [20].

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.
- 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.
- A single use battery allows the aircraft to fly for 30 minutes if the turbofan fails
- Relatively small rechargable batteries provide a temporary power boost during climb, enable TEEM control, and support rapid response of the electric engines during acceleration.
- **The power system enables the aerodynamic and propulsive benefits of the SUSAN approach.**

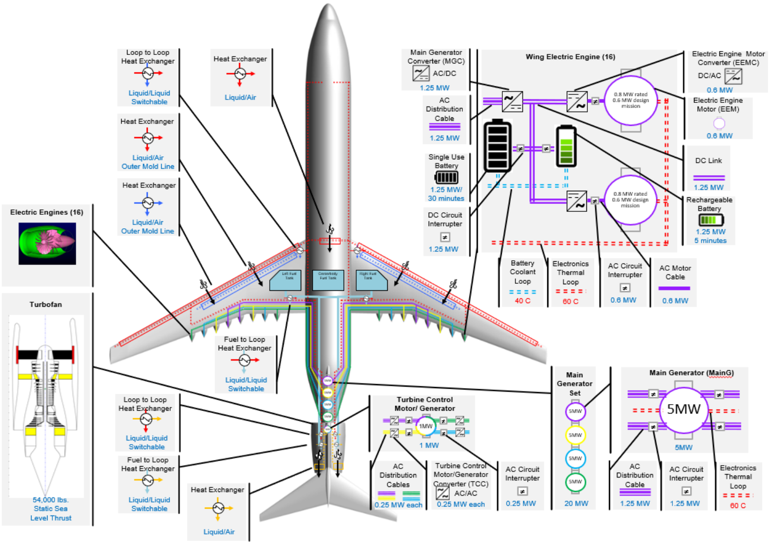

Figure 14 – SUSAN electrical power system (EPS)

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.
- 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
- Anti-icing systems can be augmented by utilizing the waste heat transported by the cooling loops prior to rejection
- 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
- Different options thermal system configuration and multifunctionality will be evaluated.

Electric Taxi / Reduction of Bleed Air Systems

- Airport 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
- 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.
- Historically, air requirements for aircraft pneumatic system were provided by the engine via compressor bleeds or off-takes.
- Systems include: 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.
- The SUSAN aircraft replaces the pneumatic system with an electrically driven concept.
- 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.

Thrust Based Flight Control

- 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.
- Preliminary flight dynamics models and flight control laws have been implemented in simulation.

Turbine Electrified Energy Management (TEEM)

- 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.
- The direct benefit of TEEM is improved operability.
- 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.

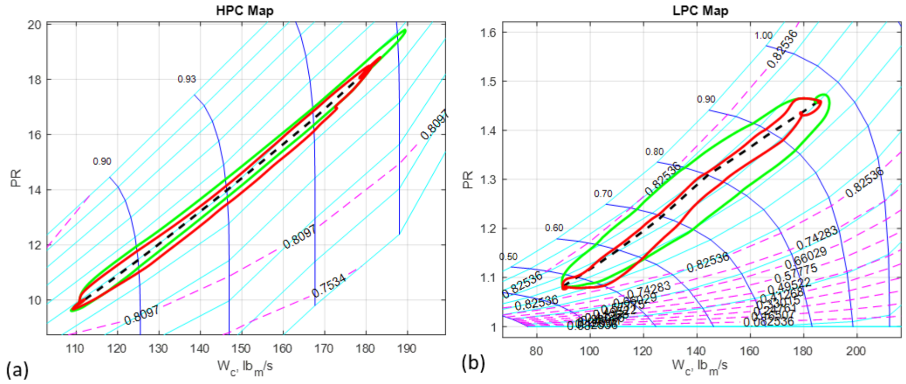

Figure 15 – HPC and LPC map for a burst and chop transient. Shown is the steady-state operating line (dashed black line) and the running lines without TEEM (green) and with TEEM (red).

Other Control-Enabled Benefits

- Because of the design of the SUSAN flight control system, engine, and powertrain, the interaction of the components is highly coordinated and automated.
- With power extraction approximately proportional the speed of the turbofan, 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.
- The connection and coordinated control of the four low-spool generators to four electric engines symmetrically means that differential thrust can be applied with the most impact
- 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.

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.
- The SUSAN flight deck is being designed for two flightcrew members (14 CFR §121.385c)
- 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.

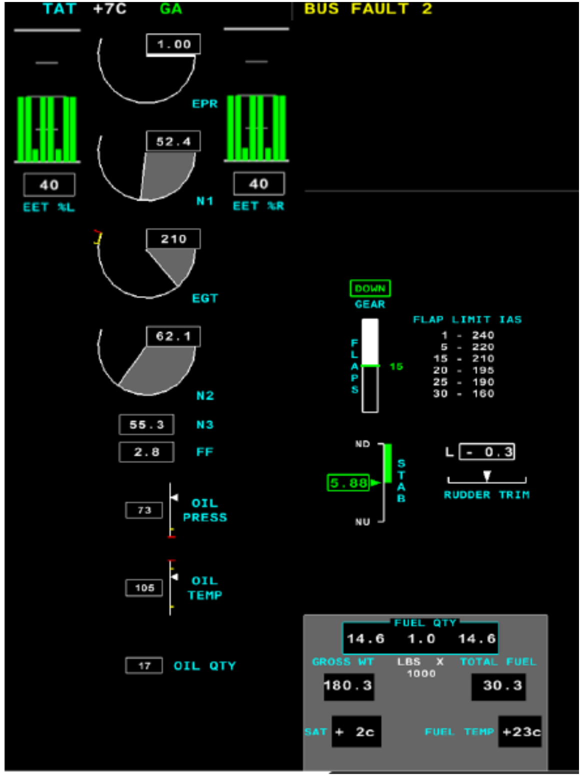

Figure 16 – Display based on typical EICAS display (left) with the addition of electric engine states.

Conclusion and Next Steps

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- 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.

Additional Information can be found at:
https://www1.grc.nasa.gov/aeronautics/eap/airplane-concepts/susan/