# Tail-mounted engine Architecture and Design for the Subsonic Single Aft Engine Electrofan Aircraft

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**This paper describes the turbofan engine architecture for SUbsonic Single Aft eNgine (SUSAN) Electrofan is, a transformative concept hybrid electric aircraft. SUSAN has a single tail-mounted turbofan engine that produces a portion of the requires thrust and drives a 20 MW electric generator which in turn provides the power to the 16 electric propulsors located on the wing responsible for producing the remainder of the required thrust. The atypical operation of the turbofan due to the large levels of power extraction from the low pressure turbine (LPT) is described here. This paper investigates the most efficient engine architecture to enable this unique operation, as well as exploring natural gas as an alternative fuel for SUSAN.**

## I. Introduction

Aircraft emissions have to be reduced significantly with a goal of zero emissions. In the near future reductions must be achieved while continuing to utilize airport infrastructure through a cost effective path. The most viable solution to achieve this criteria is to use large hybrid electric aircraft. A hybrid system with a fuel burning power source and an electrical power source has the potential to provide a path to a single engine propulsion system for a regional jet, single aisle, or wide body aircraft at speeds around Mach 0.8.

The SUbsonic Single Aft eNgine (SUSAN) Electrofan considered in this work (Figure 1) is a subsonic regional jet transport aircraft concept which utilizes Electrified Aircraft Propulsion (EAP) to enable propulsive and aerodynamic benefits to reduce fuel usage, emissions, and cost (see [1]). Figure 2 represents a common sizing profile, which includes additional requirement for fuel allowance, missed approach, and additional cruise and descent segments. The aircraft is designed to fit within the existing regional transport market, with 180 passengers, a target range of 2500 nautical miles, and economic range of 750 nautical miles at cruise altitude of 37000 ft.

**Fig. 1 Rendering of the current version SUSAN concept aircraft.**

SUSAN's traditional tube and wing design is shown in Figure 3 and features a single tail-mounted turbofan providing thrust as well as electric power, via a generator, to drive the distributed electric propulsors on the wings. Eight electric engines per wing provide a substantial portion of the required total thrust (see [2]). Four main 5 MW generators are used to extract maximum of 65% of the available engine core power provided by the Low Pressure Turbine (LPT) at cruise. The 1 MW motor/generator connected to the high spool shaft of the engine provides means to implement advanced engine controls. The fuselage boundary layer ingestion system is implemented in the simplest possible configuration with a symmetric tail closeout. Lastly three main thermal management loops designed at different temperatures provide the advanced approach to control the temperature of engine, electrical systems, and the batteries (see [3]).

There are two fundamental challenges in designing the turbofan engine for this application. The first challenge is the engine's atypical operation where a large fraction of the total power is used to drive a generator. Approximately 35%

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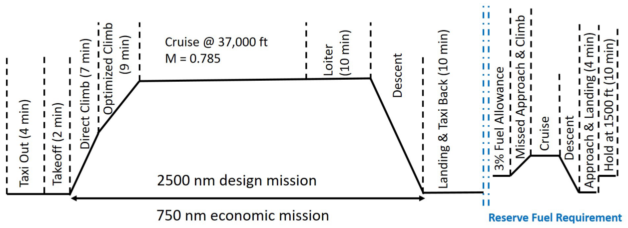

**Fig. 2 Nominal mission profile for the SUSAN Electrofan concept at the design cruise altitude of** 37000 ft**, design cruise speed of Mach** 0.785**,** 2500 nm **design mission, and** 750 nm **economic mission with included reserve fuel requirements.**

of the available core power (20MW) is converted to electrical energy in order to drive 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 impact 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. 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 the engine failure. Certain mechanical disconnects and design features need to be considered in order to implement the power switch for the electric machines and turbofan engine.

The design process and trade space study for the tail-mounted engine of SUSAN is presented in this paper. The rest of the paper is organized as follows Section II discusses the architectures considered for the engine including open rotor and ducted fan designs. The system level analysis of the core engine is described in section III for both traditional jet fuel and natural gas fuel.

## II. Turbofan Engine Architecture

The tail-mounted turbofan engine is required to produce 4025 lbf maximum thrust at Top of the Climb (TOC). The engine also needs to provide enough power to drive the 20 MW electric generator. The electric power produced by the generator is transferred to the distributed electric propulsors on the wings. The main variations of the engine designs considered in this study were counter rotating open rotor and ducted fan. The possible architectures for each option were further evaluated to inform the most efficient and viable choice for this aircraft.

The open rotor design allows for a lower fan tip speed and significant improvements in fuel economy [4, 5]. However, it has a complex operation and design process as well as excessive noise. The ducted fan offers a more traditional design and mitigates the noise issues of open rotor fan but has to address the boundary layer ingestion (BLI) on the tail of the aircraft. A gearbox is utilized in both designs to connect the low spool shaft to the fan drive shaft. This would allow for the fan to rotate at a lower speed than the low spool thus, increasing the fan efficiency.

The open rotor structure studied in this work (engine architecture O-1) is shown in figure 4. Flow enters the Low Pressure Compressor (LPC) of the core engine directly and exhausts after the power turbine in the back. The 1 $MW$ high-spool motor/generator enables modern aircraft control concepts such as TEEM [6] in addition to power generation. The power turbine shaft is relatively short in this design. Mounting the engine is considerably simpler as the counter rotating fans are located in the rear part of the engine. However, the considerable weight of the power turbine in the back of the engine can cause possible structural issues. Additionally, the hot exhaust flow has to go through the counter rotating fan blades which increases the complexity of fan blade design. Further overall engine weight issues might rise due to the material choice for the fan blades as thee need to withstand the high exhaust flow temperatures. The lower exhaust gas density at the root of the fan blades impose another source of complexity in the blade design in order to avoid potential efficiency penalties.

The preliminary ducted fan design considered for SUSAN (engine architecture D-1) is shown in figure 5. This architecture uses a power turbine similar to the open rotor design discussed above. The main generator is moved inside of the aircraft's fuselage to accommodate its large length and weight. The ducted fan and its gearbox are positioned in front of the engine which help further reduce the over-hanging weight of the engine in the back compared to the open rotor design. The fan will be designed based on aerodynamics design principals for boundary layer ingestion [7]. The

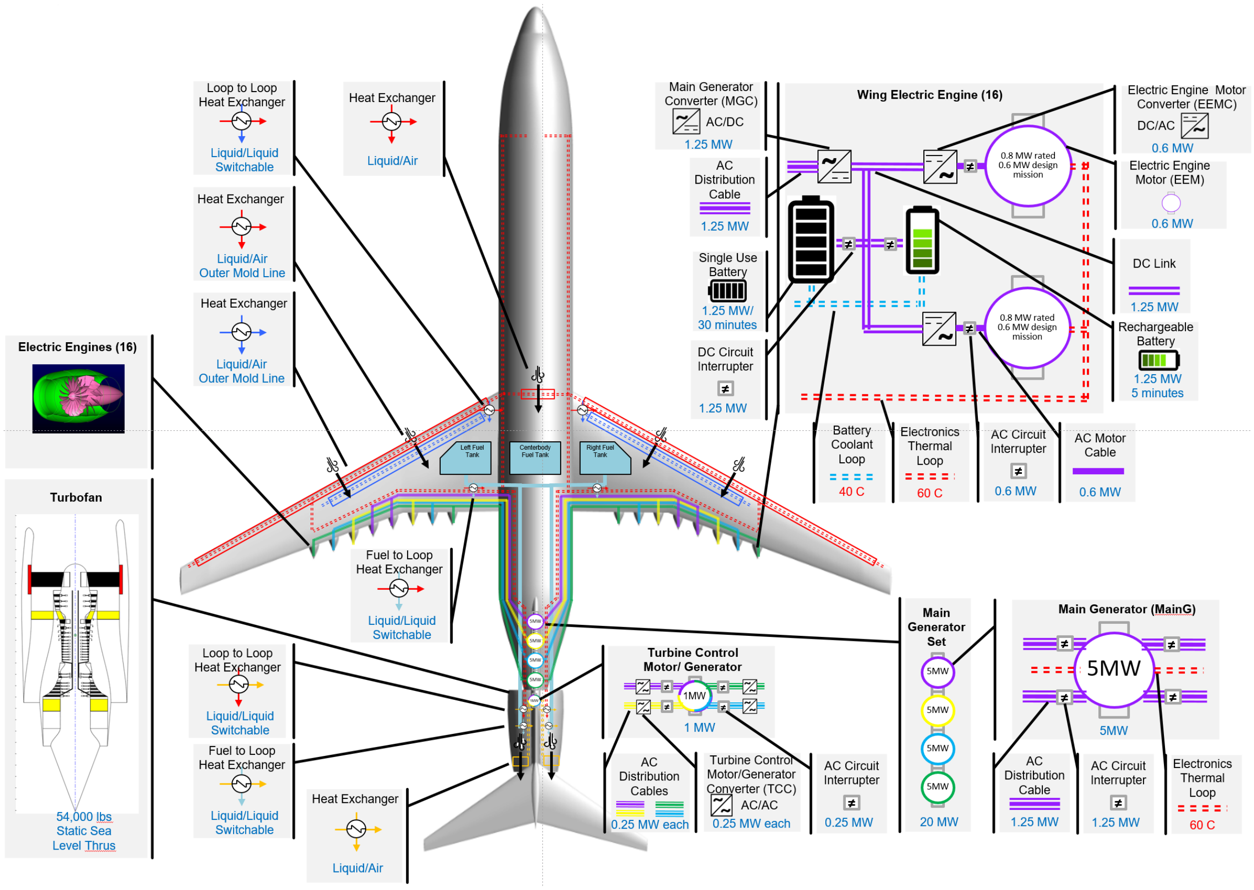

**Fig. 3 System diagram representing SUSAN Electrofan.**

engine intake in this architecture is downstream of the fan which reduces the BLI distortion effects on the performance of the engine core. This architecture does not require complex flow path design to redirect flow from LPT exit to the power turbine inlet which is a result of moving the generator to the front of the engine.

The above architecture is further developed in D-2 architecture to remove the need for a power turbine as shown in Figure 6. The electric power to drive the electric propulsors on the wings is extracted from the LPT in this geared turbofan design. The 1 MW motor/generator connected to the High Spool shaft will enable advanced engine control similar to the previous designs. The D-2 architecture is considered as the current main choice for SUSAN. The conceptual architecture of the engine core is used to develop numerical models to perform system level analysis of the engine which will be discussed in the next section.

## III. System Analysis

SUSAN's engine was designed as a dual spool geared turbofan. In this configuration 1/3 of the thrust comes from the engine and 2/3 of the thrust comes from four electric propulsors. The ratio of the split is chosen based on the analysis provided in the STARC-ABL design [8] and will be further optimized in the course of this work. The design point was selected as 0.79 Mach number at 37000 ft, with a total system thrust of 11500 lbf (4025 lbf generated by the fan and 7475 lbf generated by the electrically driven fans).

Power for the electric propulsors is drawn from generators connected to both the low and high pressure spools with 73% of the power draw taken from the low pressure spool at maximum power. The electric propulsors have counter rotating rotors with a disk loading of 60hp/ft$^2$ and a 7.36ft diameter. The advanced electrical system is assumed to provide power to the propulsors with an end-to-end efficiency of 95%. The schematic of the engine derived from the analysis performed in WATE code (see [9]) is shown in Figure 7. The number of stages, pressure ratios, and efficiency

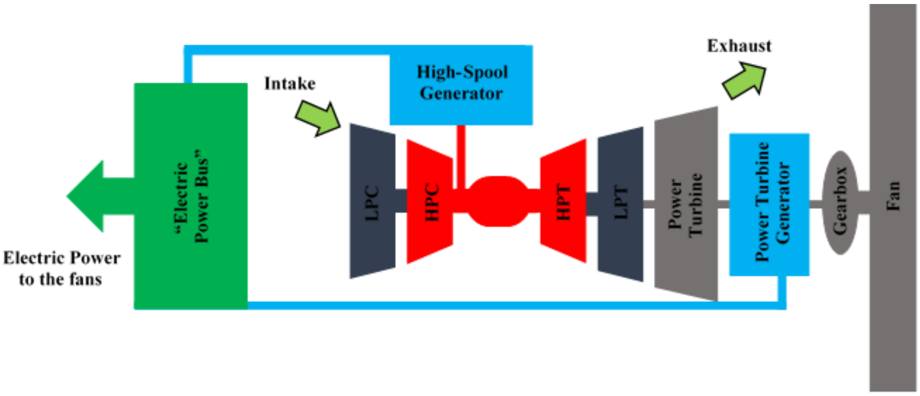

**Fig. 4 Schematic of the open rotor architecture.**

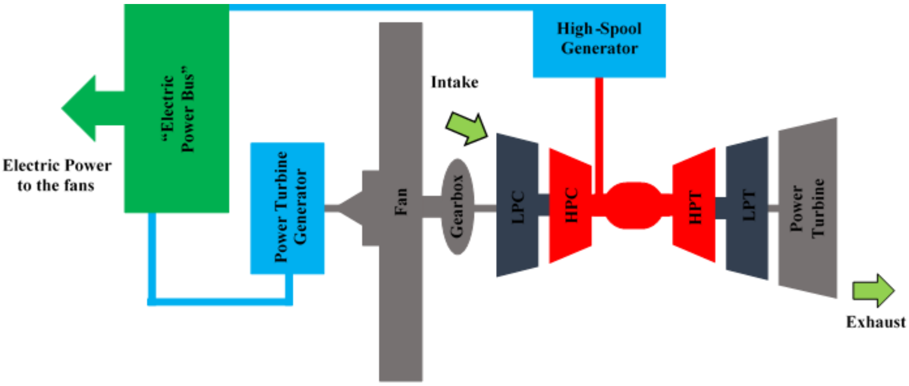

**Fig. 5 Schematic of the ducted fan architecture D-1 with power turbine.**

values for the engine components are detailed in table 1. Inlet mass flow rate, fuel flow, and bypass ratio, are then adjusted to meet design TIT (turbine inlet temperature) at 3300 R, thrust at 11500 lbf, and engine core to bypass velocity ratio at 1.4 during the design process.

The engine has an overall Operating Pressure Ratio (OPR) of 76 and Bypass Ratio of 5.38 at the top of the climb. The low speed shaft rotates at a speed of 5417 rpmand 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, which is considered as a design criteria for choosing the best engine architecture. D-2 architecture offers 9.5% and 37% reduction in the total engine weight compared to the D-1 and O-1 architectures respectively. This weight reduction can be mostly attributed to removing the power turbine and the two counter rotating fans. The smaller D-2 architecture also offers slight improvements in the Thrust Specific Fuel Consumption (TSFC) rates at both take off and top of the climb. D-2 has a TSFC of 0.16 at take off which is a significant improvement compared to 0.2268 and 0.25 TSFC values for O-1 and D-1 architectures respectively. D-2 has a TSFC of 0.44 at TOC which is similar to that of the O-1 architecture but

| Component | No. of Stages | Pressure Ratio | Efficiency(%) |
|---|---|---|---|
| Fan | 1 | 1.37 | 92.0 |
| LPC | 3 | 1.99 | 91.0 |
| HPC | 12 | 28.0 | 91.0 |
| HPT | 2 | 6.47 | 91.0 |
| LPT | 5 | 11.0 | 91.0 |

**Table 1 Number of stages, pressure ratio and efficiency of the engine components for D-2 architecture.**

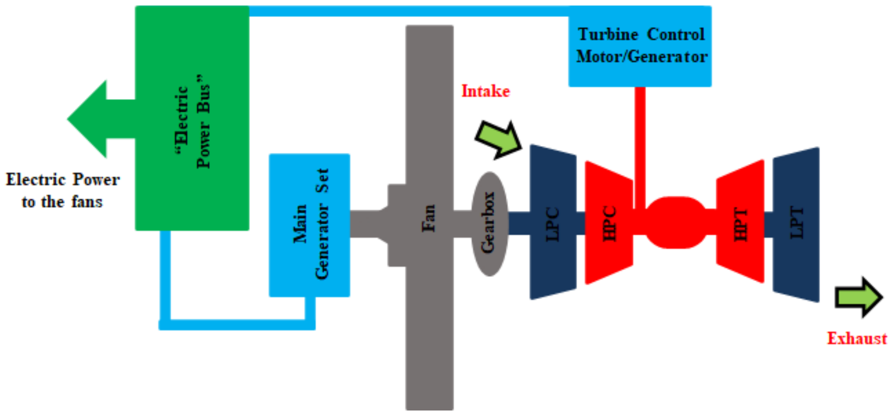

**Fig. 6 Schematic of the current geared ducted fan architecture D-2.**

offers a 12% improvement in comparison with the D-1 design.

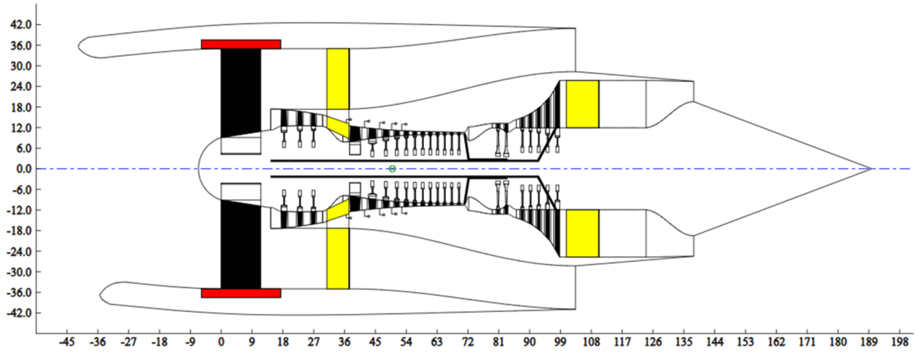

**Fig. 7 Schematic of the D-2 ducted fan architecture derived from the WATE code.**

Natural gas was considered as an alternate fuel which will improve the engine emissions. A comparison of runs utilizing jet fuel and Natural Gas were performed for the D-1 architecture noting that the qualitative results from this comparison would be valid for the D-2 design. Similar comparative analysis will be performed on the optimized engine architecture rather than the current D-2 version. In performing this change only the Lower Heating Value (LHV) of the fuel type was updated. Both fuels are carbon based, therefore the thermodynamic properties of the spent fuel chemical compounds would be similar, however small changes cause shifts in the cycle performance. Fuel temperature was not taken into account in this analysis. The comparison for the two types of jet fuel are detailed in table 2.

| Item | Traditional Jet Fuel | Natural Gas Fuel |
|---|---|---|
| LHV | 18400 btu/lbm | 21500 btu/lbm |
| Inlet mass flow | 323.65 lbm/hr | 326.65 lbm/hr |
| BPR | 3.53 | 3.719 |
| Fuel flow | 5718.25 lbm/hr | 4871.11 lbm/hr |
| Engine Weight | 9594.2 lbm | 9334.8 lbm |

**Table 2 Comparison between the traditional jet fuel and natural gas fuel for D-1 architecture.**

It can be seen that the higher energy fuel along with the changes in chemical thermodynamic properties of natural gas lowers the fuel flow and engine mass by 14% and 2% respectively. The drop in engine mass occurs because the core does not need to be as large to provide the same amount of power.

Engine air flow and bypass ratio are increased by 1% and 5% respectively. This is due to the energy content of the fuel has increased allowing the core to be slightly smaller. This decrease in core size then requires the bypass to be slightly bigger, resulting in a larger bypass ratio (BPR). Bypass flow is more efficient at providing thrust than core flow, but requires slightly more flow to provide the same amount of thrust, which is the reason for the increase in the total mass flow rate.

## IV. Conclusions and Scope of Work/Ongoing Work

The architecture of a tail-mounted turbofan engine for a hybrid electric single aisle aircraft was described. Three architectures considered: The O-1 architecture was an open rotor counter rotating design with a power turbine, the D-1 design was a ducted fan turbofan design where the fan ingest boundary layer flow. The D-1 design has a power turbine in the back of the engine but the main electric generators are 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 D-1 architecture. The power turbine is removed in this design iteration.

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.

In the current power analysis there is 1/3 split of the engine power dedicated to the electric propulsors on the wings. This split is subject to an optimization study which will consider the changes in the weight and efficiency of both turbofan and electric engines with change in the split ratio. If the optimization study results in a new split, that would change the current D-2 design of the engine consequently. In order to properly size the engine it is important to consider the engine out during the different parts of the mission profile as well. Regulatory studies for SUSAN will inform on how much thrust will be required from the turbofan engine and a single electric propulsor (see [10]).

The effects of BLI are not considered in the current analysis of the engine. An important point of focus for the future work is to add a distortion tolerant fan to the current analysis and 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.

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