# Thermal Management System Trade Study for SUSAN Electrofan Aircraft

Nic Heersema[1]
*NASA Armstrong Flight Research Center, Edwards, California, 93523, U.S.A.*

Ralph H. Jansen[2]
*NASA Glenn Research Center, Brook Park, Ohio, 44135, U.S.A.*

**Thermal management of power system components is one of the barriers identified towards the implementation of Electrified Aircraft Propulsion architectures. This paper documents the preliminary results of a trade space exploration of thermal management systems conducted for a new National Aeronautics and Space Administration regional transport aircraft concept called the SUbsonic Single Aft eNgine (SUSAN) Electrofan. Traditional methods of thermal management are evaluated alongside newer methods, which are still in development. Mass, power, and drag for traditional liquid / air heat exchangers were calculated, along with mass and area of oscillating heat pipes for outer mold line cooling. An initial assessment of the feasibility of using the fuel as part of the thermal management system was also conducted by evaluating the temperature over the full flight profile. Preliminary results and future work are discussed.**

## I. Introduction

This paper outlines a trade space exploration of a thermal management system for the SUbsonic Single Aft eNgine (SUSAN) Electrofan aircraft concept. The SUSAN Electrofan is a 180-passenger regional aircraft concept designed by National Aeronautics and Space Administration (NASA) with the intent of reducing emissions by 50 percent while retaining the speed, size, and range that is typical of large regional jets. Although the SUSAN Electrofan aircraft has the size of a large single-aisle aircraft, it has a range similar to the latest regional jets, which is why the aircraft is categorized as a regional jet. The emissions per energy unit are reduced by combining alternative fuels and Propulsion Airframe Integration (PAI) with a 10-MW class Electrified Aircraft Propulsion (EAP) system. A trade space exploration of certain key design characteristics of the SUSAN Electrofan aircraft concept is being conducted [1,2]. The current design features a traditional tube and wing design with a single aft turbofan providing thrust and power (via a generator) to drive the distributed electric propulsors on the wings. Supplemental power from rechargeable batteries allows for optimization of the performance and sizing of the turbofan (Fig. 1). Power from a single-use battery is available in the event of a power loss from the engine to power the propulsion system and would allow for safe landing of the aircraft. More details of the design are available in "Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept and Trade Space Exploration" by Jansen et al., and "Conceptual Exploration of Aircraft Configurations for the SUSAN Electrofan" by Chau et al. The intended flight profile for the SUSAN Electrofan aircraft concept is typical for regional jets, with a design range of 2500 nmi, an economic range of 750 nmi, at Mach 0.8, and an initial cruise altitude of 37,000 ft [2].

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[1]AST Structural Mechanics, Aerostructures Branch, AIAA Member.
[2]Technical Management, Aeronautics Mission Office, AIAA Member.

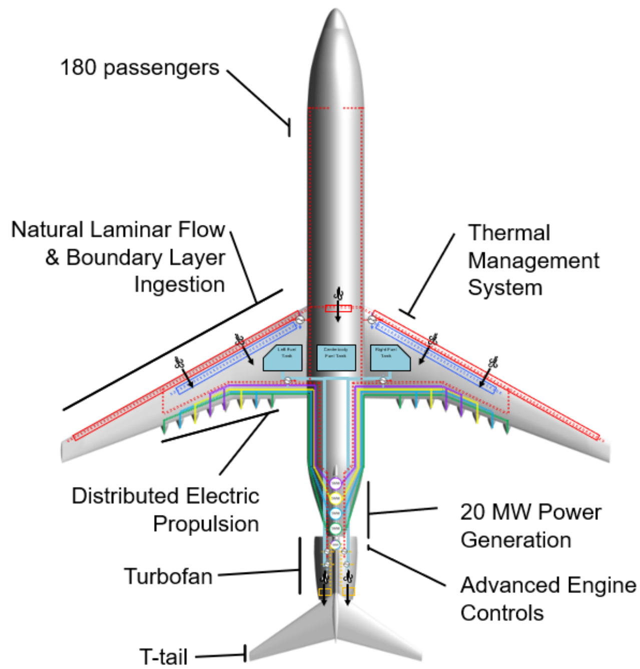


**Fig. 1 SUSAN Electrofan aircraft concept.**

One of the barriers to achieving the full benefits of EAP is the thermal management of the electric components. The thermal management challenge for the SUSAN Electrofan aircraft concept is particularly vexing because the amount of low-grade waste heat from electronics is, by order of magnitude, higher than any existing aircraft. The largest electrical power systems in operation on commercial transport aircraft utilize on the order of 1 MW of electrical power for secondary systems with on the order of 150 kW of waste heat, assuming 85% end-to-end power system efficiency [3]. The SUSAN Electrofan aircraft concept uses 20 MW of power with waste heat on the order of 1 MW. The temperature limits of most electric components require the waste heat to be rejected at relatively low temperatures between 30 and 200 °C. Traditional methods of heat rejection such as passively-cooled finned heat sinks and liquid-based pumped cooling loops with conventional heat-air exchangers incur significant weight, drag, and power penalties to reject such low-grade waste heat. One purpose of the SUSAN Electrofan aircraft concept study is to identify and evaluate any barriers related to the success of future aircraft utilizing multi-MW-class EAP and then determining potential solutions to these barriers.

Since traditional thermal management systems incur significant penalties that reduce the potential benefits of EAP architecture, different methods, that may have reduced weight, drag, and power penalties, are considered in this trade space exploration. Two primary aspects of the thermal management system are included in the evaluation: 1) moving heat from the components; and 2) removing the heat from the aircraft to the freestream air. At this stage, detailed design of the SUSAN Electrofan aircraft concept is not mature enough to design an optimized thermal management system. Overall heat loads to be managed have been estimated, but the specifics of the components to be cooled and their associated locations have yet to be finalized. Additionally, Computational Fluid Dynamics (CFD) analysis to calculate convective heat transfer to the freestream air has not yet been conducted. Analysis performed for the Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL) concept, under the Convergent Aeronautics Solutions (CAS) High-efficiency Electrified Aircraft Thermal Research (HEATheR) activity, can be used for initial estimates as the design and flight profile are similar, although there are significant differences which limit the use of the STARC-ABL results for low-fidelity analysis only [4]. This trade space exploration lays out the options and discusses considerations for the design of the thermal management system. Where possible, initial estimates of the weight, power, and drag of the different options are obtained using the information from the STARC-ABL analysis to fill in the information gaps.

## II. Trade Space Evaluation Methodology

### A. Defining the Trade Space

Aircraft systems are becoming increasingly energy-dense, driving the development of improved thermal management systems. Novel methods offer potential benefits over traditional methods in terms of weight, power, drag, and complexity. These novel methods are still in development and may not prove to be as beneficial as expected or mature enough for integration into the design in a timely manner. Traditional methods are included in the trade space, in part to provide known, reliable alternatives, and in part to provide a baseline for comparison against the novel methods used.

The options selected for evaluation were also evaluated under the CAS HEATheR activity for different aircraft concepts. The options included all proved viable for the STARC-ABL aircraft concept; it is expected that these options will prove to be viable for the SUSAN Electrofan aircraft concept as well. Additionally, the use of fuel for thermal management, which was not evaluated under the CAS HEATheR activity, is included in this trade space evaluation. Traditionally, the primary method of thermal management involved the use of a heat sink. For subsonic fuel-dependent aircraft, two heat sink options are readily available: fuel and freestream air.

Current aircraft use the thermal capacity of the fuel to manage heat loads from the hydraulic systems and sometimes other systems [5]. The fuel is also used for engine cooling, after which it is subsequently burned. To support the necessary cooling of the engine systems without exceeding the coking temperature limits of the fuel, the temperature of the fuel at the inlet to the engine system is generally limited to 200 °F [6]. Potential advances in engine technologies and fuel properties may permit an increase of the limit to 250 °F or higher in the near future. Limits on the temperature of the fuel in the tank also restrict the amount of heat that may be transferred into the fuel. Reduced reliance on hydraulic systems and lower heat rejection temperatures of electronic systems render fuel as a desirable option for thermal management. Furthermore, using the existing fuel system for thermal management reduces the necessary weight, power, and drag penalties from a dedicated thermal management system. One focus of this evaluation is the feasibility of using the fuel as a heat sink as a primary method of thermal management.

The use of freestream air as a heat sink is subject to fewer restrictions than the fuel and is not a finite resource. Additionally, heat can theoretically be rejected from any area of the aircraft skin, which allows the heat rejection site location to be in an area of close proximity to the component from which the heat is rejected. From a practical perspective, however, rejecting heat from the skin will affect the air flow; therefore, a thermal management system that makes use of freestream air must be designed in close collaboration with the aerodynamics of the aircraft. The limited airflow and increased air temperatures while the aircraft is on the ground must also be considered in the thermal management system design. For skin-based heat exchangers, the thermal properties of the skin material are also important to the design.

### B. Evaluating the Trade Space

The options considered in this trade space evaluation encompass a range of potential solutions. The ultimate goal of the evaluation is to identify an optimal solution; however, as one aspect of a CAS activity is to address barriers to implementation, identification of viable options (other than the optimal solution) is another goal of this trade space evaluation. The viability of each option is assessed based on the ability to reject the heat loads from the components in a range of conditions, which will be discussed later in this paper. Evaluation of an optimal solution includes comparison of the power, weight, and drag impacts of each method. The heat load to be managed; the geometry of the thermal management system; and the interface with the freestream air all contribute to the calculations of the power, weight, and drag. These calculated values may be normalized by the amount of heat transferred, resulting in a more equivalent comparison between methods.

At this stage in the design process, not enough information is available to determine an optimal solution. The initial estimates of the total heat loads during takeoff and cruise have only recently been broken out by component [7]. Details about the design of the electrical power system, including physical locations of the components and the heat load during different phases of flight, are still in progress. A detailed flight profile, including fuel burn and heat loads from other components that require use of the heat capacity of the fuel for thermal management, has yet to be fully developed. The nominal temperature limit of the fuel at the engine inlet is selected based on current turbomachinery design; improvements to engine performance may require additional or less heat capacity from the fuel for cooling. For the purposes of determining the cooling potential of different areas of the outer mold line (OML), CFD analysis is not yet in the works; calculated values are available from the STARC-ABL CFD analysis and are for initial approximations only. Most importantly, an objective function that determines the relative impacts of weight, power, and drag on the aircraft performance has yet to be developed. An objective function is a primary method of evaluating different options towards selecting an optimized design for different subsystems, including the thermal management system. Nevertheless, some preliminary conclusions can still be drawn from this trade space evaluation.

Although power, weight, and drag penalties cannot be determined for all the options in this trade space evaluation, the relationships that were developed for the STARC-ABL concept provide some insight. Similarities in the overall design between the STARC-ABL and SUSAN aircraft concepts allow the using of these relationships to help narrow the options to be considered for further evaluation. A qualitative assessment of the complexity of each option is possible at this stage of the design and is used to support this trade space evaluation; considerations for aircraft integration of these options are also addressed. It is expected that different options may be more suitable for different components. The fuel system, for instance, is more suitable for non-arcing components located near existing fuel systems than for arcing components or components located far from existing fuel system architecture.

### C. Approach

For this trade space evaluation, power, weight, drag, and complexity were of primary interest to evaluate the desirability of different options. Other factors, such as complexity, reliability, affordability, and maintainability may also be considered if such information is available at this early evaluation stage. As many of the options are still in development, data on the reliability and maintainability were unavailable for those options, and available information on affordability is not expected to be representative of future production versions.

This trade space evaluation is a first step towards selecting an optimal thermal management system for the SUSAN Electrofan power system components. The trade space is defined by the options selected for evaluation, which encompass a range of technology development from well-established to novel solutions. The methods used to evaluate these options are discussed in this section as are the conditions used in the evaluation.

General design for thermal management systems depends on several factors, including heat loads to be managed and component temperature limits. Only electrical power system components from the generator through the wing motors are considered in this evaluation. The aft engine is not included as modern turbofan engines have integrated cooling systems separate from the aircraft thermal management system. Other sources of heat such as the environmental control system, hydraulics, and avionics systems are not considered in this evaluation as details of these systems are not available yet for the SUSAN Electrofan aircraft concept.

The thermal management system options considered in this evaluation are categorized by which aspect of thermal management they can be used for: movement of the heat internal to the aircraft, rejection of the heat to the freestream air, or both. Most of the methods can be used for both, including: the use of the fuel; a pumped fluid loop (fluid other than fuel); and oscillating heat pipe. Traditional heat pipes are an additional option for moving the heat internal to the aircraft; ram air heat-exchangers are an additional option for rejecting heat to the freestream air. It is unlikely that any of these methods would be used by themselves.

Evaluation of the different trade space options requires an understanding of the appropriate conditions. These conditions must be realistic and representative of the intended use of the system. For thermal management system design, two major influences are the heat loads on the system and the ambient conditions. The heat loads on the thermal management system are affected by the intended flight profile of the SUSAN Electrofan aircraft. The ambient conditions are determined both by the altitude, governed by the flight profile, and the atmospheric conditions present. As the SUSAN Electrofan aircraft would potentially be flown anywhere in the world, different atmospheric conditions must be considered. Other factors, such as temperature limits of the fuel system and other components of the thermal management system itself, are also relevant to this trade space evaluation and are discussed in the next section.

Thermal management systems rely on relatively cold air flowing over the heat exchanger to remove heat from the aircraft. The combination of warmer air temperatures at ground level and little-to-no airflow over the aircraft before takeoff pose a challenge to the design of the thermal management system. The heat loads during startup and taxi are generally lower than the heat loads during other phases of flight, still, both require management. From this perspective, a thermal management system that incorporates both a heat sink on the aircraft and a means of removing the heat from the heat sink later in the flight is desirable.

## III. Thermal Management System Approach and Architecture

The current approach for thermal management on the SUSAN Electrofan aircraft concept consists of five elements: 1) minimization of heat loads; 2) use of three different thermal management loops operating at temperatures appropriate for their thermal loads; 3) use of waste heat from the engine to warm electrical systems in Cold Day conditions; 4) management of transient heat loads through thermal capacitance of the fuel; and 5) transfer of excess heat to the surrounding airstream through a combination of traditional heat exchangers and outer mold line cooling. The basic layout of the thermal system as currently envisioned is shown in Fig. 2.

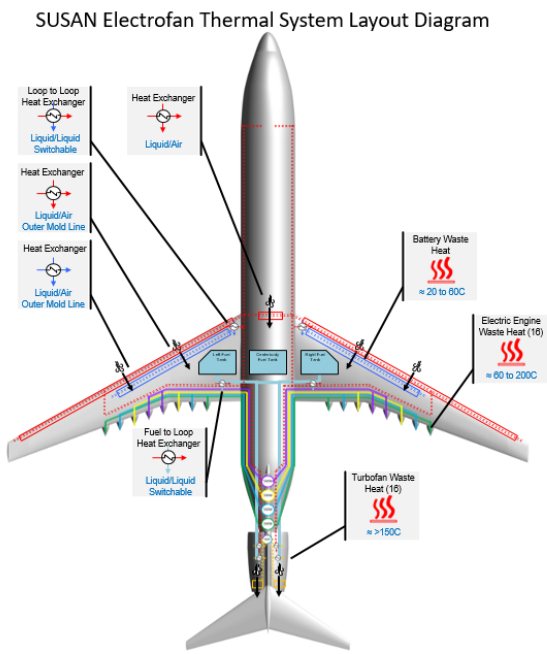


**Fig. 2 SUSAN Thermal System.**

### A. Minimization of Heat Loads

Heat loads for the SUSAN concept primarily consist of the waste heat from the 20 MW power system and the aft turbofan. The turbofan heat load is expected to be typical of a large modern turbofan engine. The minimization of the heat load will be a driving requirement for the power system. The SUSAN power system has a requirement for 95% source to load efficiency. The source of power is either the main generators (driven by the turbofan) or the single-use battery backup. The loads are the wing mounted propulsor units. This efficiency requirement reduces heat load from 4MW to 1 MW when compared to a typical power system of 80% source-to-load efficiency and is an enabling feature of the thermal management approach. To achieve this very-high efficiency and concurrently achieve very-low power system weight, new technology must be employed. The electrical machines (motors and generators) will use the partially superconducting NASA High Efficiency Megawatt Motor (HEMM) technology. Converters (AC to DC, DC to AC, AC to AC) will use a multilevel, interleaved, resonant architecture combined with advanced magnetic materials (created at NASA) for the filter components. An advanced cable system will be used for the distribution runs, which minimizes weight required for high currents, thus enabling operation at relatively low voltage (<2000) for a 20 MW system.

### B. Thermal Management Loops

The current plan is to have three different thermal management loops that operate at temperatures appropriate for their thermal loads. The trade study was begun with the initial assumption that three loops, which are optimized to the temperature of different load categories, will be a good architecture; however, as studies are conducted, it may be determined that a different number of loops is preferred. The first thermal management loop will service the battery system and operates nominally at 40 °C. Many battery chemistries have reduced capacity at temperatures below 20 °C and can be susceptible to thermal runaway at temperatures above 60 °C. The battery thermal management loop is planned to incorporate outer mold line cooling. The second thermal management loop will service the electrical systems and operates nominally at 60 °C. The primary loads on the electrical systems loop are the electrical machines (motors and generators), which have a hot spot temperature limit around 200 °C, and the converters (AC to DC, DC to AC, and AC to AC), which also have a limit of around 200 °C. The heat flux levels needed for both motor and converter are relatively high, requiring the cooling loop to have a significant temperature difference compared to the thermal limits of the electrical components. The electrical thermal management loop will be connected to an outer mold line surface heat exchanger as well as a liquid / air heat exchanger. The third thermal loop will service the turbofan and will be typical of a large geared-turbofan cooling loop, operating at a nominal temperature between approximately 80 and 150 °C. The turbofan thermal loop will include an in-engine liquid / air heat exchanger and a fuel / liquid heat exchanger. The discussion of the thermal management of the SUSAN turbofan will be the subject of a future paper as the engine is not sufficiently defined for a thermal design assessment. These three cooling loops are used to create relatively isothermal connections between similar heat sources and connect those heat sources to heat exchangers and the thermal capacitance of the fuel as needed.

### C. Waste Heat Utilization

The aircraft will use waste heat from the engine to warm critical components when operating in cold conditions, thereby eliminating the need for additional heaters. The aircraft may be designed for environmental temperature extremes at sea level between 48 and -61 °C. The three thermal management loops will be connected with heat exchangers with bypass paths for controlled heat transfer amounts between loops. The batteries are the most temperature sensitive and will be heated to a minimum of 20 °C. Electrical systems will be warmed to a minimum temperature of -40 °C, and if excess heat is available, to a nominal temperature of 20 °C.

### D. Transient Management with Thermal Capacitance

To reduce the impact of thermal transient conditions, the heat capacitance of the fuel will be used to level the load on the thermal systems. Fuel heat capacitance is largest at the beginning of the mission when the aircraft is at the maximum fuel load for the mission. Mission load transients where high electrical power is required include climb, go-around, and engine out conditions. By storing some of the heat load in the fuel during these transients and releasing the heat later in the mission, the sizing of the heat exchangers can be reduced. As previously mentioned, the fuel is also used to cool the turbofan before being burned.

### E. Outer Mold Line Cooling

Ultimately, all excess heat needs to be transferred off the aircraft to the airstream using heat exchangers through a combination of traditional heat exchangers and outer mold line cooling. Liquid / air heat exchangers will be used with one set nominally located in an underbelly location of the fuselage and another in the turbofan bypass air stream. Outer mold line cooling will be used on the wing and possibly areas of the fuselage. Outer mold line cooling is a method of transferring heat through the skin of the aircraft, which was previously shown to be conceptually feasible on the NASA HEATheR activity [4]. The wing fuel tanks, being integrated directly into the structure of the wing, are also considered as a method of outer mold line cooling.

## IV. Thermal Conditions

### A. Environmental Temperatures

Atmospheric conditions are a significant factor in the ability to transfer heat from the aircraft to the surrounding air. The wide variation of atmospheric conditions present around the world and throughout the year poses a particular challenge to the design and evaluation of a thermal management system. As a result of the global nature of air transportation, an aircraft must be designed to handle the widest range possible of atmospheric conditions. Depicted in Fig. 3 are different atmosphere models, codified in Atmospheric Ambient Temperature Characteristics Versus Pressure Altitude (AS210) and used in this evaluation, particularly, the Standard Day and 1% Hot Day models [8]. This evaluation briefly considers the 1% Cold Day model because those temperatures are found in polar regions that have reduced air traffic and aircraft modifications are required to enable flight in those regions. Selection of appropriate Cold Day conditions is ongoing. More detail on these models and their use for the SUSAN Electrofan evaluation can be found in Ref. [1].

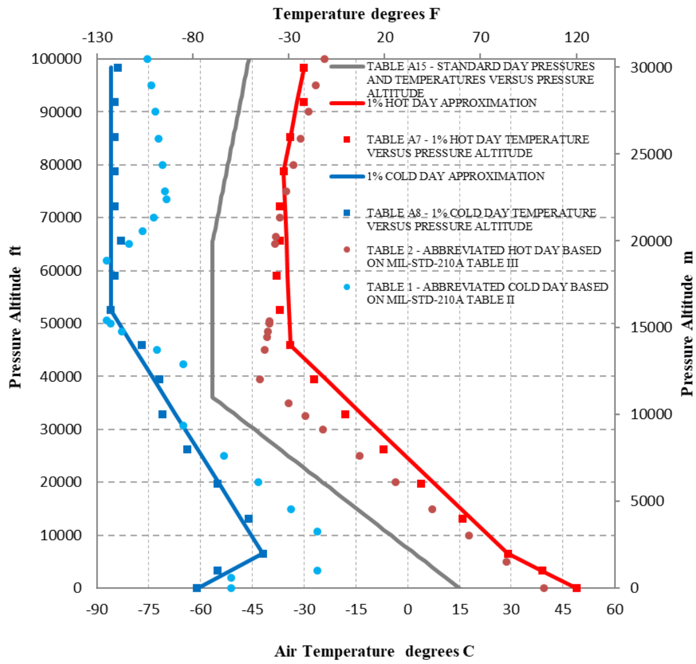


**Fig. 3 Atmospheric Ambient Temperature Characteristics Versus Pressure Altitude (AS210) reference air temperatures [8].**

Designing a thermal management system capable of accommodating wide variations in atmospheric conditions is a challenge. Removal of heat from the aircraft is highly dependent on the difference between the ambient temperature and the hotter temperature of the thermal management system. Hot Day conditions reduce this difference in temperatures, either limiting the amount of heat that can be moved off of the aircraft or requiring an increase in either the heat transfer coefficient or the heat exchanger area to compensate. Cold days present the opposite challenge; increased difference in temperatures can result in too much heat being removed from the thermal management system. The corresponding component temperature drops could result in temperatures falling below the lower limits of those components. The severity of such an occurrence depends on the component; batteries, for instance, lose effectiveness at temperatures colder than their limit, which could limit flight duration. Proper thermal management system design must account for these possible temperature extremes. In many cases, it is possible to design the system to alter the amount of heat extraction based on temperature, although doing so adds complexity. Expanding the temperature limits of the thermally-managed components is another potential solution to this challenge. The 1% Hot Day condition is used as the worst-case hot conditions for this evaluation. The appropriate worst-case cold conditions will be identified for use in future evaluations.

### B. Mission Profile

The fight profile of the aircraft is another significant factor that needs consideration when determining how to transfer heat from the aircraft to the surrounding air. The flight speed of the aircraft and the altitude directly affect the convective heat transfer coefficient and outside air temperature. Design or evaluation of the thermal management system requires a flight profile that contains - at a minimum - the altitude, airspeed, heat loads, and duration for each phase of the flight. Heat loads can be estimated from required engine/motor power. A detailed flight profile is still in progress for the SUSAN Electrofan aircraft; a nominal flight profile is depicted in Fig. 4 [9]. Designed for a maximum range of 2500 nmi, the 750-nmi economic mission is more typical of actual usage for regional jets.

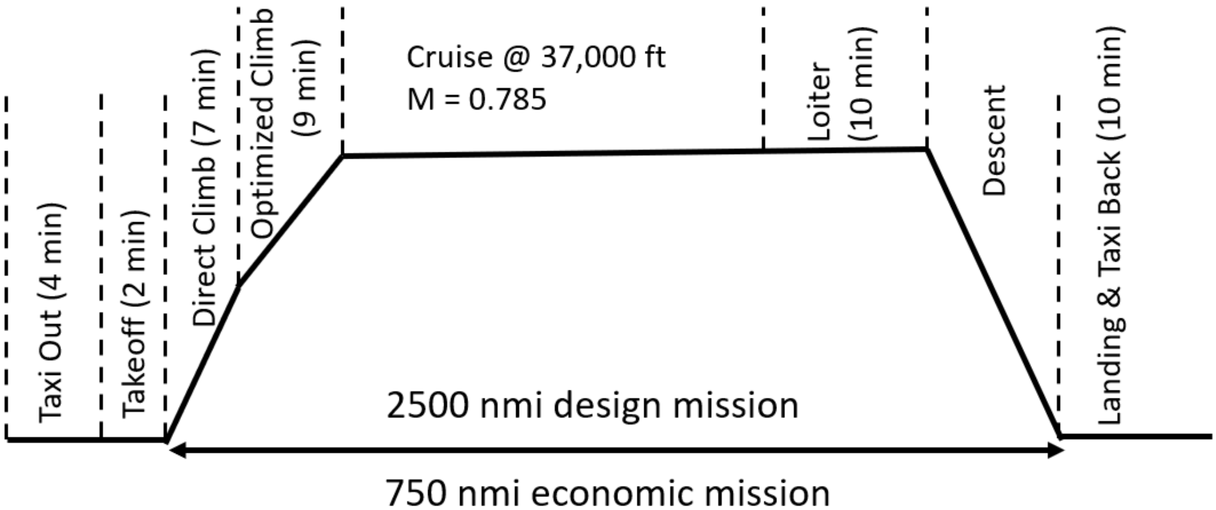


**Fig. 4 Nominal flight profile for the SUSAN Electrofan aircraft.**

For the flight profile to be useful for thermal management system design, an estimate of the heat loads at each of the flight phases, other than takeoff/climb and cruise was required, along with flight phase durations. Cruise duration is calculated from range and speed. Durations of climb and descent are estimated based on current single-aisle regional flights of similar cruise duration. Heat loads from the EAP components at takeoff and cruise are specified; heat loads at other phases of flight have been estimated as percentages relative to the cruise value. Heat loads from the single rear Boundary Layer Ingestion (BLI) engine are not included in this analysis as most modern engines have their own dedicated cooling system and do not rely on an external thermal management system. Figure 5 shows the nominal flight profile altitude and estimated heat loads that were used in this evaluation.

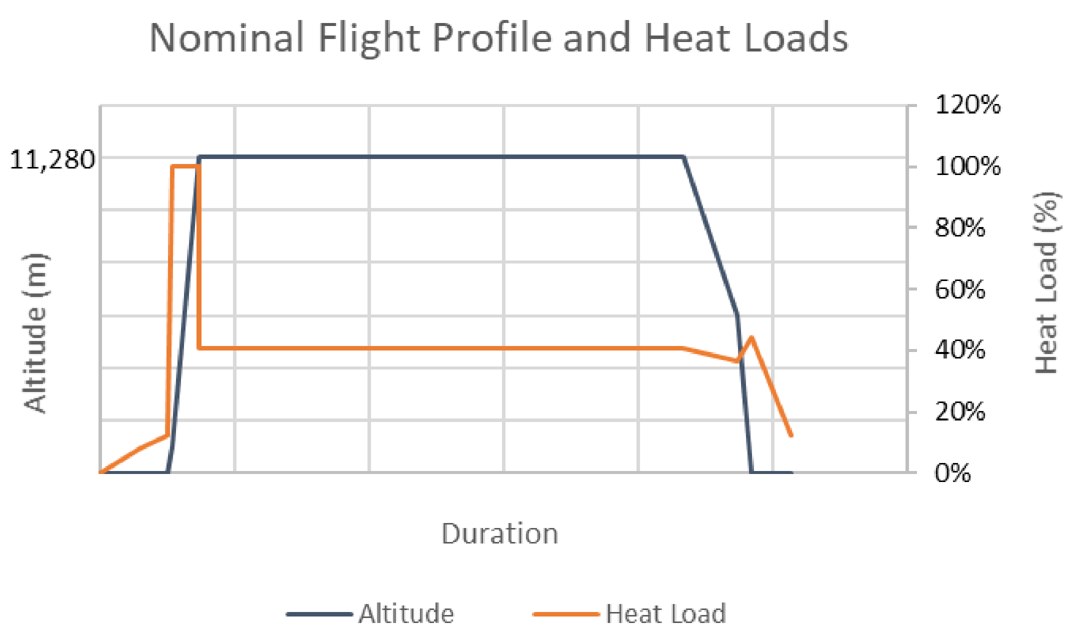


**Fig. 5 Flight profile and heat loads.**

### C. Power System Heat Loads

The overall SUSAN power system heat loads are calculated based on the SUSAN power system architecture, the electrical component sizing, and the efficiency of each component. Table 1 lists each component type, efficiency, and heat load. The power levels are based on nominal, full-power continuous-operation mode. The component efficiencies are the nominal values used in the trade space evaluations, along with variations of efficiency above and below the nominal values. The rechargeable battery power level is an approximate average level needed to implement the turbine energy management control. The single-use battery is listed at zero power because it is not used during normal operation. The single-use battery is employed when the main generator or the turbofan has failed; thermal loads from either of the failed primary sources are replaced with the thermal load of the single-use battery and will be explored in planned future work. Initial estimates of overall heat loads during takeoff and cruise were provided by the design team as 1310 and 530 kW, respectively. Details of the power system architecture, including refined estimates of the heat loads to be managed, are currently undergoing a separate trade space evaluation. Specifics of the power system architecture are available in "Electrical System Trade Study for SUSAN Electrofan Concept Vehicle" [7]. A summary of details most pertinent to the thermal analysis is provided in Table 1.

**Table 1 SUSAN power system sizing and heat loads.**

| | | | Component Efficiency | | | Heat Load | | |
|---|---|---|---|---|---|---|---|---|
| Electrical Component | Quantity | Component Power (kW) | Nominal % | Minimum % | Maximum % | Nominal | Minimum | Maximum |
| **Main Generators** | | | | | | | | |
| Main Generator | 4 | 5000 | 99.0 | 98.0 | 99.5 | 200 | 400 | 100 |
| Main Generator Converter (MGC) AC to DC | 16 | 1250 | 99.0 | 97.0 | 99.5 | 200 | 600 | 100 |
| AC Circuit Interrupters | 16 | 1250 | 99.5 | 99.7 | 99.9 | 100 | 60 | 20 |
| Turbine Control Motor/Generator (TCMG) | 1 | 1000 | 99.0 | 98.0 | 99.5 | 10 | 20 | 5 |
| Turbine Control M/G Converter (TCC) AC to AC | 4 | 250 | 98 | 94.0 | 99.0 | 20 | 60 | 10 |
| AC Circuit Interrupter | 4 | 250 | 99.5 | 99.7 | 99.9 | 5 | 3 | 1 |
| **Electric Engines** | | | | | | | | |
| Electric Engine Motor (EEM) | 32 | 600 | 98.5 | 97.0 | 99.0 | 288 | 576 | 192 |
| Electric Engine Motor Converter (EEMC) DC to AC | 32 | 600 | 99.0 | 97.0 | 99.5 | 192 | 576 | 96 |
| AC Circuit Interrupter | 32 | 600 | 99.5 | 99.7 | 99.9 | 96 | 57.6 | 19.2 |
| Rechargeable Battery | 16 | 63 | 97.0 | 90.0 | 98.0 | 30 | 100 | 20 |
| Total Heat Load | | | | | | 1141 | 2453 | 563 |

Component locations are also relevant to the design of a thermal management system. While not all component locations have been determined yet, certain locations are more likely to be used than others. From a power perspective, the motor/generator should be located in the rear of the plane, as close to the tail-cone thruster as possible. The AC/AC converters should likewise be located as close to the motor/generator as possible. The propulsors are distributed along the wings. The number and location of the wing propulsors has changed over the course of the evaluation; currently, distributed electric propulsion is undergoing evaluation. The planned locations for reusable batteries are in the wings for proximity to the propulsors; additionally, this location will provide benefits for cooling these batteries. The single-use battery is used only in the event of an engine failure to power the propulsors; the size of this battery restricts placement to a location somewhere in the fuselage. The AC/DC converters will be located between the batteries and the propulsors. Cables transmitting power between the various components are not included in this evaluation. If the cables are later determined to require thermal management, they will be added to the evaluation. Figure 6 shows a notional layout of the major electric power system components.

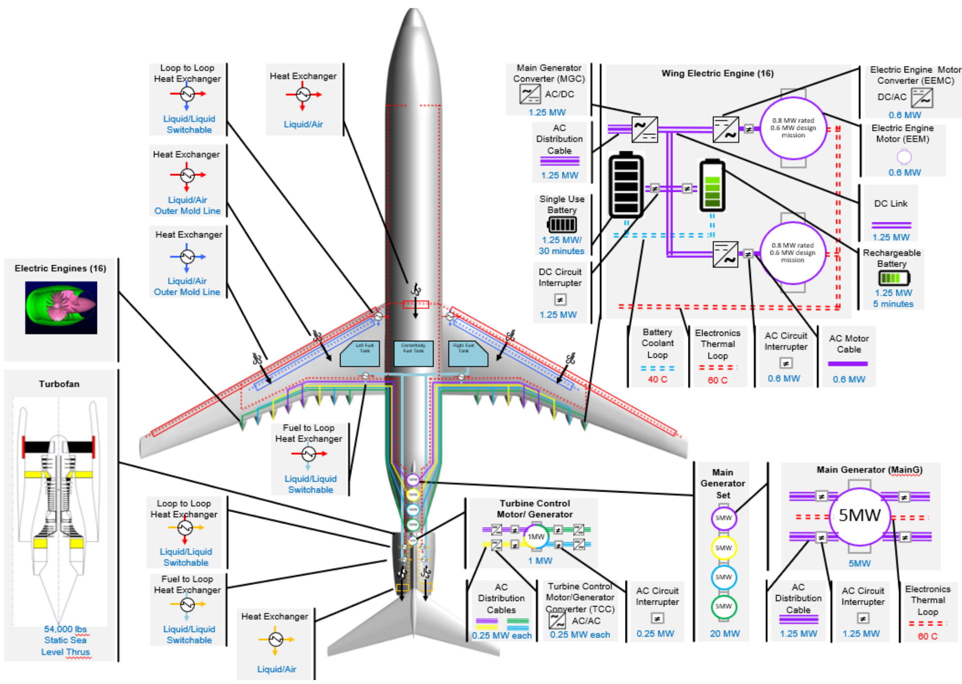


**Fig. 6 The SUSAN Electrofan power, propulsion, and thermal layout.**

## V. Heat Transfer Analysis

### A. Fuel as a Heat Sink

Aircraft have two readily available heat sinks: fuel carried onboard and the freestream air. Transferring heat to the freestream air will be discussed in the following section. This section discusses the initial phase of the trade space evaluation - evaluating the capability of the fuel to serve as a heat sink for the electric power system components of the SUSAN Electrofan aircraft. Current single-aisle aircraft use the thermal capacity of the fuel primarily for highly-variable heat loads, such as those generated by the hydraulic system; using fuel to cool electric components has primarily been limited to military aircraft [5]. With the reduction of reliance on hydraulic systems in More Electric Architecture (MEA) aircraft, the thermal capacitance of the fuel should be evaluated for use as a heat sink for the electric power system components. Temperature limitations of the fuel are relatively well matched to the temperature limits of the electric power system components, making the fuel particularly well-suited to this method of thermal management. Caution should, of course, be exercised when there is proximity between flammable substances and potential ignition sources, but proper design of both the electric components and the thermal management system should be possible to mitigate potential risks.

From a thermal management perspective, one of the primary concerns of using the fuel as a heat sink is that the thermal capacitance is limited by the finite volume of the fuel. This volume decreases over the course of the flight as the fuel is consumed by the engine. The reduction from two engines to one subsequently reduces the amount of fuel that must be carried for an equivalent flight duration. When these factors are considered, the fuel may not seem like a particularly desirable option for thermal management; however, while heat is added to the fuel over the course of the flight, heat is also removed. Current single-aisle aircraft have the fuel tanks integrated into the wings. This design results in direct thermal contact between the fuel in the tank and - at a minimum - the bottom surface of the wing, which acts as a heat exchanger with the freestream air. In colder regions or at higher altitudes, this removal of heat from the fuel may require the addition of a fuel heater to prevent the fuel from freezing in the tanks. Using the fuel as a heat sink may enable the removal of a fuel heater system, resulting in a slight weight and power benefit to the aircraft.

The other aspect of using the fuel for thermal management is transferring the heat from the component into the fuel. Components located in close proximity to the fuel system can be thermally managed by the fuel with a minimum of added weight compared to dedicated thermal management systems. For the SUSAN Electrofan aircraft, the fuel system will need to run from the wing tanks to the engine at the rear of the aircraft. The location of the wing propulsors is still being evaluated; however, some of the propulsors will still be in close proximity to the fuel tanks, regardless of their final location [10]. The generator, located very near to the rear engine, will be in proximity to the fuel being transported to the engine. A determination of the fuel flow rate necessary to provide thermal management versus the flow rate required by the engine will require more accurate estimates of the heat load from the generator and the fuel burn of the engine than are currently available. The location of other power system components has not yet been determined; it may be possible to locate these components near the fuel system. Any components that are not located near the fuel system would require some means of transporting the heat from the component to the fuel system, adding weight. Alternatively, such components might be better suited for one of the other thermal management system options. This analysis of the feasibility of the fuel for thermal management assumes the full heat load from all electric power system components is managed by the fuel.

Some assumptions are required to perform the analysis at this stage of the SUSAN Electrofan design process, in addition to the flight profile already discussed. Typical Jet-A fuel is used for the initial analysis, although future efforts are planned to evaluate alternative fuels that are under consideration by the airline industry. The temperature limits for the fuel and fuel system are drawn from current single-aisle aircraft and are listed in Table 2 [6,11]. Fuel burn is also estimated based on values for existing single-aisle aircraft and adjusted for the single fuel-burning engine on the SUSAN Electrofan aircraft [11]. Takeoff fuel mass is an initial estimate calculated during early mission planning and may require updating as the design matures.

**Table 2 Fuel parameters from current single-aisle aircraft.**

| Parameter | Value |
|---|---|
| Minimum fuel temperature | -37 °C |
| Maximum fuel temperature in tank | 49 °C |
| Maximum fuel temperature at engine inlet | 93 °C |
| Fuel burn rate | 0.315 kg/s |
| Takeoff fuel mass (design mission) | 14606 kg |

The wing planform area of 119 $m^2$ and the convective heat transfer coefficients for takeoff and cruise of 150 $W/(m^2 \cdot K)$ and 70 $W/(m^2 \cdot K)$, respectively, are drawn from the STARC-ABL analysis [4]. As discussed in the section on atmospheric conditions, both Standard Day and 1% Hot Day conditions are used in the analysis.

The effect of the waste heat on the temperature of the fuel in the tank is evaluated for each phase of flight, and the temperature is compared to the temperature limits of the fuel tank. As the design of the power system progresses, it will be possible to refine the analysis to account for components located between the fuel tanks and the engine and the reduced effects of the waste heat of these components on the temperature of the fuel in the tank. The change in fuel temperature, $T$, is calculated in the standard manner from rearranging Eq. (1):

$$q = mc_p \Delta T \tag{1}$$

The mass, $m$, decreases from the takeoff fuel mass; the specific heat, $c_p$, varies slightly with temperature. The total heat transfer, $q$, includes the waste heat from the EAP components, solar radiation on the top surface of the wing, reflected solar radiation on the bottom surface of the wing, and convection of the airflow over the wing surface. Radiative heat transfer from the wing to the atmosphere is also included, although the radiative heat transfer does not have a significant effect on the fuel temperature. The absorption value used is 0.25 (the approximate value for white paint); the same value as was used previously for the CAS HEATheR activity. For this initial analysis, a simplified approach is used for short flight phases at constant altitude; the temperature at the end of the phase is calculated from the total heat load during that phase. For the more critical flight phases of climb and cruise, a more refined approach was used. These phases were subdivided into intervals of equal duration to account for time variations of key parameters. During the climb phase, outside air temperature was the key parameter that varied. The outside air temperature was calculated for each interval using a simple linear variation between the temperature on the ground and the temperature at cruising altitude. The convective heat transfer coefficient was held fixed at the takeoff value.

During cruise, the key parameters that varied were the fuel mass and the temperature difference between the fuel and the outside air.

In addition to comparing the calculated fuel temperature to the limits specified for Jet-A fuel, the thermal limits of the batteries were also considered. As a significant contributor to the waste heat, the batteries will require cooling throughout the duration of the flight. At cruise altitudes, the heat transfer capability of the fuel to the airstream exceeds the waste heat generated by the EAP components. As a result, the temperature of the fuel may drop below the temperature limit for optimal battery operation, which would have implications for the design of the thermal management system.

### B. Heat Transfer to Atmosphere

As discussed previously, the thermal capacitance of the fuel is not anticipated to be sufficient for thermal management of the electric power system components. Other methods of rejecting heat to the atmosphere were evaluated as part of the CAS HEATheR activity for use in a range of hybrid-electric aircraft architectures [4,12]. The methods found to be potentially feasible for the STARC-ABL concept are being considered in this trade space evaluation.

#### *1. Liquid / Air*

Liquid / air heat exchangers are commonly used on aircraft for thermal management. Heat is extracted from a component and carried to the heat exchanger by a coolant loop. The heat exchanger rejects the thermal energy to the air flowing past it. The air is fed into the system from the freestream using a puller fan or ram air intake and exhausts back into the freestream further aft. The choice to use a ram air scoop or a puller fan is partially dictated by the needs of the heat exchanger and is partially a tradeoff between power and drag. A puller fan requires more power but may contribute to an increased amount of thrust, generally an insignificant amount, whereas ram air requires less power but increases drag. The relative impact of power, weight, and drag on the overall aircraft performance will vary between aircraft and affects the optimized system design. An assessment of these factors has yet to be made for the SUSAN Electrofan aircraft; thus, an optimized design of a liquid / air heat exchanger is not yet possible. The design of the heat exchanger is also dependent on several other factors including: the heat load to be rejected; temperature limits of the component; and design point (in terms of altitude and Mach number). The sensitivity of the heat exchanger design to these inputs was evaluated for the STARC-ABL aircraft under the CAS HEATheR activity and can be used to help inform initial designs for the SUSAN Electrofan aircraft concept [12]. Detailed design of the heat exchanger, including the liquid used and the geometry of the heat exchanger could not be evaluated as part of the trade space exploration since the system design is not yet mature enough to provide the necessary inputs. Relationships developed for the STARC-ABL concept under the CAS HEATheR activity (shown in Table 3) are used for initial, low-fidelity estimates for the SUSAN Electrofan aircraft concept [10].

**Table 3 Liquid / air heat exchanger sizing relationships developed for the STARC-ABL aircraft concept.**

| Aircraft | Technology Level | Coolant | TMS Sizing Relations, weight(kg), power(kW), and drag (lbf) |
|---|---|---|---|
| STARC-ABL | Baseline | PGW30 | $\text{weight} = 0.346 * power_{rejected} + 1.480$<br>$power_{required} = 3.65\text{e}-4 * power_{rejected} - 1.19\text{e}-4$<br>$\text{drag} = 4.06\text{e}-2 * power_{rejected} + 4.41\text{e}-5$ |
| STARC-ABL | Advanced | PSF-5 | $\text{weight} = 0.442 * power_{rejected} + 2.195$<br>$power_{required} = 3.13\text{e}-3 * power_{rejected} + 4.01\text{e}-3$<br>$\text{drag} = 4.55\text{e}-2 * power_{rejected} - 1.05\text{e}-2$ |

### 2. Outer Mold Line

The use of outer mold line cooling for MW-class aircraft was explored under the previous CAS activity, HEATheR [3]. The research conducted under the CAS HEATheR activity determined the feasibility of this method and the potential benefits of reduced weight and power compared to more traditional liquid / air heat exchangers. This method is expected to have the greatest benefit to the electronics cooling loop, where the temperature differential with the outside air is minimal. Two different methods of outer mold line cooling were explored under CAS HEATheR activity: oscillating heat pipes and a pumped fluid loop. Oscillating heat pipes are a passive method used to transport heat from a component and exchange that heat with the freestream air. Liquid slugs alternate with vapor bubbles in serpentine capillary tubes. Within the evaporator section of the tubes, the working fluid evaporates which increases the vapor pressure and pushes the liquid slugs towards the condenser section. Lower temperatures in the condenser section causes condensation and increases the pressure differential, driving continued motion of the working fluid, resulting in oscillating motion of the vapor bubbles and liquid slugs; hence, the "oscillating heat pipe" method name. The pumped fluid loop is a liquid / air heat exchanger, similar to the type discussed in the previous section. The primary difference and reason for discussion in this section, is that the cold section of the loop is embedded into the external skin of the aircraft and directly exposed to the freestream air; therefore, no ram air or puller fan is required to supply the airflow necessary for heat exchange. Additionally, the tubes for the pumped fluid loop are spread out over a region of the OML rather than densely clustered in a compact heat exchanger - the favored method for aircraft use.

Although these methods are still being developed for use in aircraft, one of the primary advantages over traditional liquid / air heat exchangers is the lack of a drag penalty due to ram air or a puller fan. A downside to these methods is that they are of minimal use on the ground when there is little airflow. A liquid / air heat exchanger with a puller fan can be operated by using ground support equipment if necessary; such an option does not exist for these OML-based cooling methods. The oscillating heat pipes have an additional advantage in that they are purely passive and don't require power. The trade-off is that there may be an increase in weight compared to an equivalent liquid / air heat exchanger, as was the case for the STARC-ABL concept [4]. The relative importance of the increased weight from an overall performance perspective must be considered when selecting the optimal thermal management method. For the STARC-ABL concept, the pumped fluid loop did not trade well compared to the oscillating heat pipes and the traditional liquid / air heat exchanger. It is possible that optimization of the design may make this method more desirable.

For the STARC-ABL concept, the wings and lower fuselage were identified as suitable regions for OML cooling [4]. The use of distributed electric propulsion and natural laminar flow over the wings for the SUSAN Electrofan aircraft limit the ability to use the wings for OML-based cooling methods. Additionally, a dedicated thermal management system must not interfere with the natural cooling of the wing tanks if the fuel will also be used for thermal management. The CFD analysis for the STARC-ABL concept also identified the forward part of the fuselage as a region with relatively high heat flux [4]. Although this region was not considered for OML-based cooling for the STARC-ABL concept, it may be worth considering for localized cooling for the SUSAN Electrofan aircraft concept should there be any electrical power system components forward of the wings. The horizontal stabilizer is another region worth considering. The STARC-ABL analysis also identified this region as having a relatively high heat flux, although the drastic differences in the design of the tail section between the STARC-ABL and the SUSAN Electrofan designs render the data unreliable for the SUSAN Electrofan aircraft concept. Once the design is sufficiently mature, a CFD analysis will be required to calculate the heat flux for the SUSAN Electrofan aircraft concept.

The same methods used for the STARC-ABL analysis can be used to calculate the power, weight, and drag penalties as appropriate for each of the OML-based cooling methods. As with the liquid / air heat exchanger, further refinement of the power system architecture is necessary before this evaluation is possible. The heat fluxes to be obtained from CFD analysis are also required. In addition to power, weight, and drag penalties, other integration considerations such as complexity and durability may influence the selection of the optimal thermal management method.

## VI. Results

Initial results were obtained to allow for preliminary evaluation of the feasibility of some of the different thermal management methods. These results assume that each method is used individually to manage the entire load - an unlikely situation in reality, but useful in preliminary evaluation for its simplicity. The use of the thermal capacitance of the fuel was evaluated by calculating the temperature of the fuel over the entire mission profile and comparing results to known temperature limits. The mass of the liquid / air heat exchanger and the associated power draw and added drag were calculated for different anticipated heat loads. The mass of the oscillating heat pipes and the required OML area were also calculated for the same heat loads.

### A. Fuel Temperatures

Initial results show the use of fuel for thermal management to be promising for the design mission in Standard Day conditions with nominal component efficiencies, as shown in Fig. 7. For the nominal flight profile analyzed, the fuel temperature approaches the upper tank limit during climb and descent and is just barely above the tank limits during landing and taxi back to gate. As expected, thermal management of the components cannot solely rely on the fuel system but use of the fuel as a heat sink does show promise, particularly during the early phases of the flight when other thermal management system options are less effective.

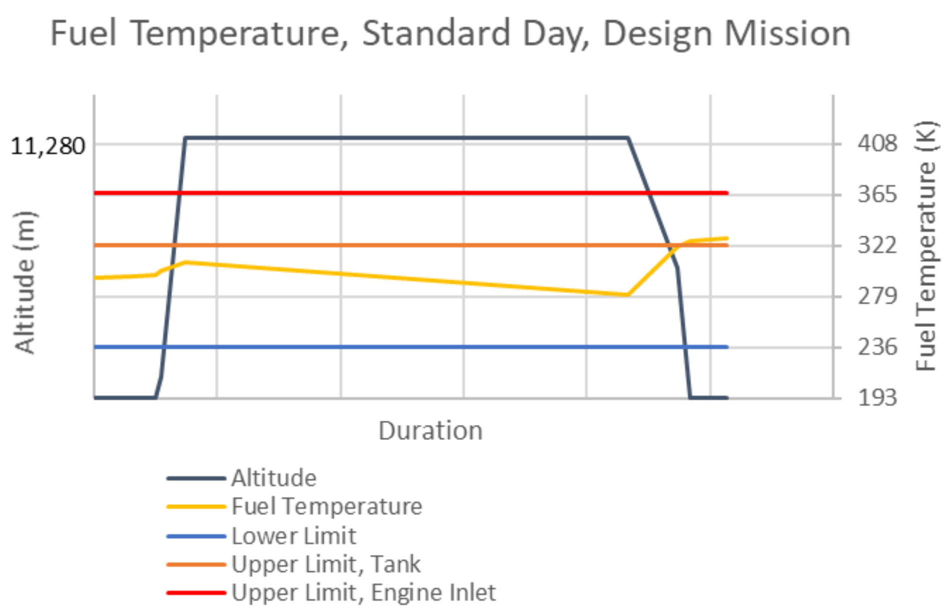


**Fig. 7 Fuel temperatures over flight duration for design mission in Standard Day conditions.**

For the shorter economic mission, shown in Fig. 8, the fuel temperature exceeds the tank limit during climb as a result of the lower initial fuel quantity. The cruise portion of the flight is too short for adequate cooling of the fuel before descent and landing, resulting in fuel temperatures exceeding the engine inlet limits during descent and landing.

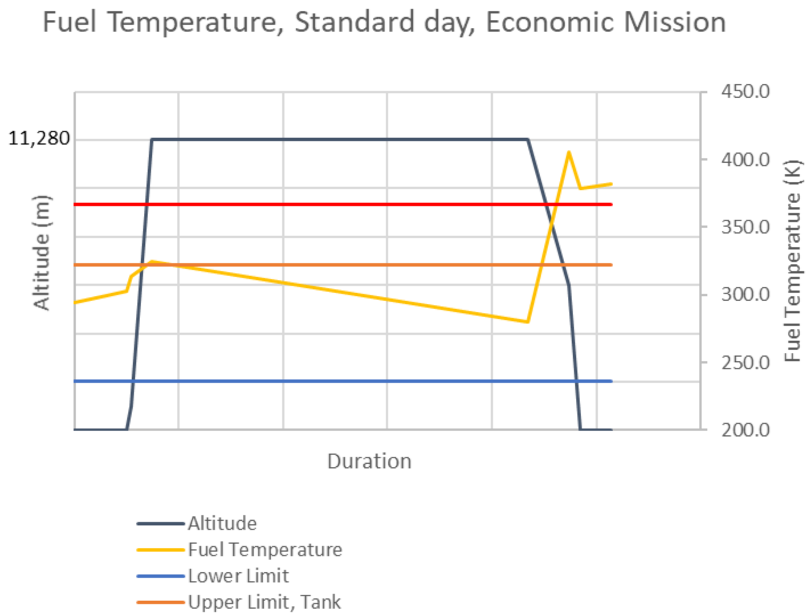


**Fig. 8 Fuel temperatures over flight duration for economic mission in Standard Day conditions.**

Hot Day conditions, of course, only exacerbate these limit exceedances. Higher temperatures on the ground result in higher fuel temperatures during the early flight stages. Higher temperatures at cruise altitude reduce the temperature differential between the fuel and the outside air, limiting the amount of heat that can be rejected to the freestream. Fuel temperatures for the design mission in Hot Day conditions are shown in Fig. 9.

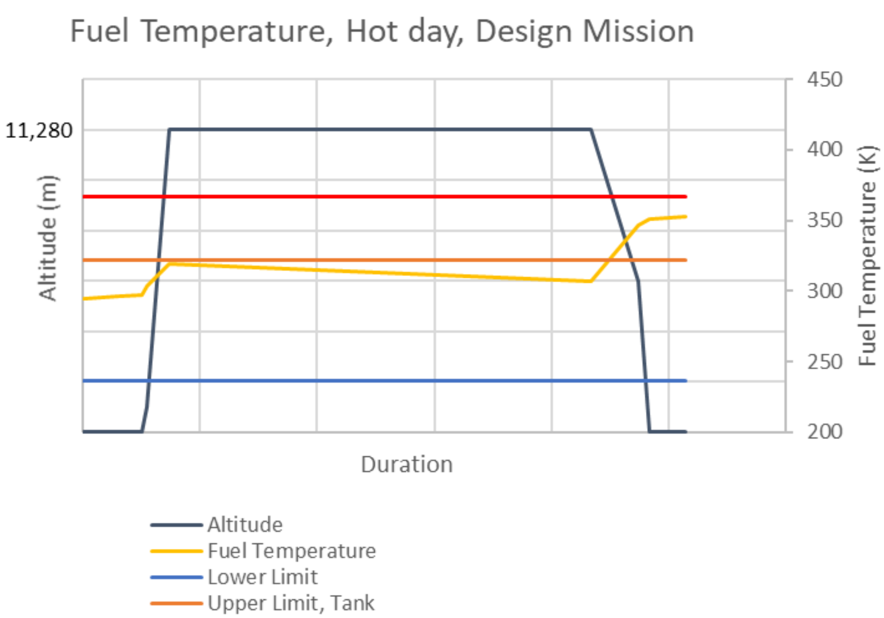


**Fig. 9 Fuel temperatures over flight duration for design mission in Hot Day conditions.**

The shorter cruise duration of the economic mission, coupled with the reduced fuel quantity at takeoff, results in the fuel temperature exceeding the tank limit during takeoff and remaining above the limit for the rest of the flight. These results are shown in Fig. 10.

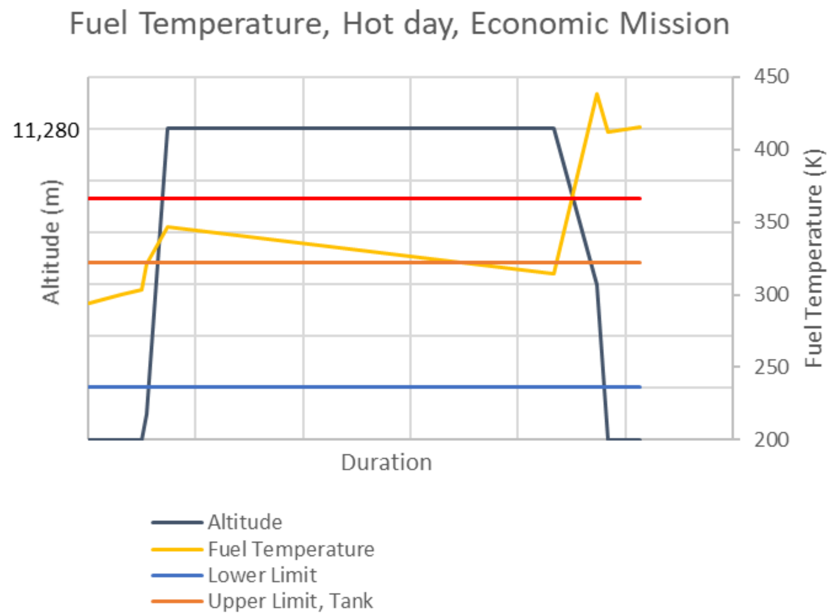


**Fig. 10 Fuel temperatures over flight duration for economic mission in Hot Day conditions.**

One benefit of utilizing the fuel system for thermal management is that even in 1% Cold Day conditions, the fuel temperature remains well above the tank lower limit without requiring a dedicated fuel heating system. The cruise flight phase holds some concern for the batteries; however, as the temperature of the fuel drops below the temperature limit for optimum operation. At these temperatures, the batteries will still operate but with a reduced capacity. Two options exist to address this concern: 1) include additional batteries to account for the degraded performance; or 2) provide some thermal isolation between the fuel and the batteries. Both options potentially add weight to the aircraft which must be considered when evaluating the weight penalties associated with this approach to thermal management.

Careful design of the thermal management system, including fuel and other methods of heat removal, will be required to ensure that fuel temperatures remain within limits. The shorter duration of the economic flight profile is of particular concern as the aircraft is not at cruise altitude long enough to sufficiently cool the fuel before descent and landing, especially in Hot Day conditions. This analysis will need to be reevaluated as the power system design matures. The location of the components is a factor in determining if fuel cooling is an appropriate method of thermal management; components located far from the fuel system may be better suited for other types of thermal management. Fuel temperature limits are higher at the engine inlet than in the wing tanks; it is possible that components located between the fuel tanks and the engine could be fuel-cooled without affecting the temperature of the fuel in the wing tanks. Estimated power requirements and heat loads over the full flight profile will be refined as the flight profile matures and power system components efficiencies are more accurately determined. It is possible that the challenges associated with utilizing the fuel as a heat sink could also be solved through modification of the flight profile and/or use of ground support equipment to provide additional cooling while on the ground on hot days. The thermal management system for the SUSAN Electrofan aircraft concept will be designed to make best use of the thermal capacitance of the fuel, combined with other methods for heat rejection to the freestream air.

### B. Liquid / Air Heat Exchangers

Relationships developed for the previous CAS HEATheR activity were used to estimate power, weight, and drag impacts from the heat exchanger, which are listed in Table 4. Liquid / air heat exchangers operate most efficiently when there is a high temperature differential between the outside air and the heat source. For the SUSAN Electrofan aircraft concept, this method of heat removal from the aircraft is of most interest with regards to the mechanical systems cooling loop, given the wider allowable temperature range for those components.

**Table 4 Power, weight, and drag for liquid / air heat exchangers.**

| Relationship | Coolant | Component Efficiency | Heat Load | Weight | Power | Drag |
|---|---|---|---|---|---|---|
| STARC-ABL Baseline | PGW30 | Minimum | 2453 kW | 864 kg | 894 W | 100 lbf |
| | | Nominal | 1141 kW | 410 kg | 415 W | 46 lbf |
| | | Maximum | 563 kW | 210 kg | 204 W | 23 lbf |
| STARC-ABL Advanced | PSF-5 | Minimum | 2453 kW | 1106 kg | 7719 W | 112 lbf |
| | | Nominal | 1141 kW | 526 kg | 3612 W | 52 lbf |
| | | Maximum | 563 kW | 271 kg | 1803 W | 26 lbf |

The relationships developed for the STARC-ABL aircraft considered two power system architectures: a state-of-the-art baseline and an advanced power system with higher-efficiency components [12]. Pure silicone fluid (PSF-5) was used as a coolant for the advanced power system because the High Efficiency Megawatt Motor required a dielectric cooling fluid. The higher viscosity of PSF-5 results in significantly higher power required for pumping the fluid through the cooling loop as well as slightly higher weight and drag. These higher penalties make PSF-5 a less desirable choice for thermal management, except for components that require the dielectric properties. Other coolant fluids, including the propylene glycol 30% (PGW30) used for the STARC-ABL baseline relationship, are more commonly used. Further evaluation of liquid / air heat exchangers, including different coolant fluid options, will require a customized design for the SUSAN Electrofan architecture. Further refinement of the power system components will be required, along with analysis to determine the relative impacts of power, weight, and drag on the overall aircraft performance.

### C. Outer Mold Line Cooling (Oscillating Heat Pipes)

Mass requirements for OML cooling via oscillating heat pipes were calculated using the same proprietary software code as was used for the CAS HEATheR activity [4]. Area requirements were also calculated to ensure that sufficient OML area is available in the selected regions. Different heat load conditions were analyzed based on the range of component efficiencies provided in Table 1. Values for heat flux rejection from the OML surface were required for the calculations and were drawn from the cruise values for STARC-ABL aircraft for this initial analysis [13]. Table 5 provides the results of the analysis.

**Table 5 Oscillating heat pipe area and mass requirements.**

| | Maximum efficiency | | | Nominal efficiency | | | Minimum efficiency | | |
|---|---|---|---|---|---|---|---|---|---|
| **Component** | **Heat Load (kW)** | **Mass (kg)** | **Area ($m^2$)** | **Heat Load (kW)** | **Mass (kg)** | **Area ($m^2$)** | **Heat Load (kW)** | **Mass (kg)** | **Area ($m^2$)** |
| Main Generator | 100 | 67.5 | 11.7 | 200 | 135.0 | 23.4 | 400 | 269.9 | 46.8 |
| MGC AC to DC | 100 | 67.5 | 11.7 | 200 | 135.0 | 23.4 | 600 | 404.9 | 70.2 |
| AC Circuit Interrupters | 20 | 13.5 | 2.3 | 100 | 67.5 | 11.7 | 60 | 40.5 | 7.0 |
| TCMG | 5 | 3.9 | 0.9 | 10 | 7.8 | 1.9 | 20 | 15.6 | 3.7 |
| TCC AC to AC | 10 | 7.8 | 1.9 | 20 | 15.6 | 3.7 | 60 | 46.9 | 11.2 |
| AC Circuit Interrupter | 1 | 0.8 | 0.2 | 5 | 3.9 | 0.9 | 3 | 2.3 | 0.6 |
| EEM | 192 | 126.7 | 20.6 | 288 | 190.0 | 30.9 | 576 | 380.0 | 61.9 |
| EEMC DC to AC | 96 | 63.3 | 10.3 | 192 | 126.7 | 20.6 | 576 | 380.0 | 61.9 |
| AC Circuit Interrupter | 19.2 | 12.7 | 2.1 | 96 | 63.3 | 10.3 | 57.6 | 38.0 | 6.2 |
| Rechargeable Battery | 20 | 13.8 | 2.5 | 30 | 20.7 | 3.7 | 100 | 68.9 | 12.4 |
| TOTAL | 563 | 377.4 | 64.2 | 1141 | 765.5 | 130.6 | 2453 | 1647.2 | 281.8 |

For the maximum- and nominal-efficiency cases, the area required is less than the total area available in the wings (119 $m^2$) and rear fuselage (53 $m^2$), indicating that this approach is potentially viable as the sole means of thermal management. However, the area required has potential impacts on the fuel temperature and flow into the engine and motors, which must be assessed. The total area required for the minimum efficiency case exceeds the area available, limiting the use of this method of thermal management to either components with sufficient efficiencies or a subset of components - likely those located nearest the skin. In all cases, the oscillating heat pipes will be evaluated for use in combination with other thermal management system types.

### D. Summary Table

A comparison of the oscillating heat pipes and the liquid / air heat exchanger for the nominal efficiency case in Standard Day conditions is shown in Table 6. The mass required for the oscillating heat pipes is higher than for the traditional liquid / air heat exchanger; however, the liquid / air heat exchanger has power requirements and added drag hthat the oscillating heat pipes do not have. An evaluation of which method is better for each loop requires an understanding of the relative impacts of mass, power, and drag on the performance of the aircraft. The required relationships have not yet been developed for the SUSAN Electrofan aircraft concept.

**Table 6 Summary of results.**

| | | **Oscillating Heat Pipes** | | **Liquid / Air Heat Exchanger** | | |
|---|---|---|---|---|---|---|
| Loop | Heat Load (kW) | Mass (kg) | Area ($m^2$) | Mass (kg) | Power (W) | Drag (lbf) |
| Battery | 222 | 147 | 24 | 80 | 81 | 13 |
| Electronics | 919 | 618 | 106 | 330 | 334 | 37 |

## VII. Conclusions and Future work

Design of the SUSAN Electrofan aircraft concept is continuing under the CAS activity to identify and evaluate barriers to implementation of MW-class More Electric Aircraft and determine potential solutions. Thermally managing the electric power system components is the barrier addressed by this trade space exploration. Work done under CAS HEATheR activity for the STARC-ABL concept was used to inform initial evaluation of the thermal management options included in the trade space. Preliminary values for mass, power, and drag of traditional liquid / air heat exchangers were calculated, along with mass and area for oscillating heat pipes to inform future optimized designs. The thermal capacitance of the fuel and the ability to use the fuel as part of the thermal management system were examined by calculating the fuel temperature over the full mission duration. The preliminary conclusion drawn from this trade space evaluation is that none of the methods evaluated can realistically be used as the sole method of thermal management; some combination of methods will be required. Further evaluation is ongoing as the SUSAN Electrofan aircraft concept design matures and the relevant inputs are available. Future planned work for this effort includes designs for the liquid / air heat exchanger and OML-based cooling methods customized for the SUSAN Electrofan power system components. Evaluation of the feasibility of using the fuel system for thermal management is also ongoing and is updated as the relevant portions of the SUSAN Electrofan design mature.

## VIII. Acknowledgments

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