Thermal Requirements for Design and Analysis of Subsonic Single Aft Engine (SUSAN) Research Aircraft

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The purpose of this paper is to define a set of thermal requirements which can be used for conceptual design studies of the Subsonic Single Aft eNgine (SUSAN) aircraft and the early design phases of a 25% scale flight research aircraft. SUSAN presents an architecture for a subsonic regional jet transport aircraft coupling a single turbofan engine to an electrified aircraft propulsion system (EAP). NASA, military, FAA, and commercial standards and guidance on the design and analysis of thermal management systems for aircraft are reviewed and summarized. The approach toward using these sources to develop the SUSAN thermal requirements is described. These requirements address the definition of the thermal environment, the design requirements for certain components that interface with the thermal management system, and thermal analysis margins.

I. Introduction

This paper introduces the approach towards defining thermal design and analysis requirements for the Subsonic Single Aft eNgine (SUSAN) Electrofan aircraft concept. Because of the high amount of low-grade waste heat, the thermal management systems for electrified aircraft like the SUSAN Electrofan will have a significant impact on overall system performance and efficiency. Therefore, clear and well-defined thermal requirements are more critical for these aircraft than for previous generations. It is envisioned that the approach toward defining these requirements for the SUSAN Electrofan will be applicable for future electrified aircraft.

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 [1]. 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. 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. 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. 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.

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 difficult because the amount of low-grade waste heat from electronics is, by an order of magnitude, higher than any existing aircraft. The

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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. The SUSAN Electrofan aircraft concept uses 20 MW of power with waste heat on the order of 1 MW [2]. 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.

In order to define the design and analysis requirements for the SUSAN thermal management system, a comprehensive survey of relevant NASA, military, FAA, and non-government standards and regulations was completed. These standards and regulations primarily relate to:

1) the definition of the thermal environment, including outside air temperature, pressure, and solar heating
2) design requirements for subsystems and specific components that are part of, or interface with, the thermal management system, including batteries, fuel systems, and electronic components
3) analysis practices including thermal margin

Testing requirements are not the focus of this study; however, they are referenced as they relate to the thermal environment definition. Additionally, cabin thermal control and pressurization are considered out-of-scope for the SUSAN thermal management system.

II. Thermal Environment Requirements

A. Outside Air Environment

The definition of the thermal environment provides boundary conditions for the SUSAN thermal management system, particularly the temperature and pressure of the outside air which is the primary heat sink. FAA regulations for normal and transport category airplanes and rotorcraft, U.S. Code of Federal Regulations (CFR) Title 14 Parts 23, 25, 27, and 29, do not prescribe a thermal environment, other than for certain test conditions. However, some FAA Advisory Circulars (AC) reference military standards for informational purposes and guidance. AC 25-20 [3] provides guidance on methods of compliance for CFR Part 25 environmental systems. It references MIL-STD-210B [4] for guidelines on climatic extremes. AC 23-19A [5] provides guidance on solar and thermal effects for Part 23 composite airplane structures design. It includes a table of ambient air temperature and solar radiation derived from MIL-STD-210C [6] data.

Though the FAA regulations do not prescribe a thermal environment, 14 CFR 25.1527 requires that “The extremes of the ambient air temperature and operating altitude for which operation is allowed, as limited by flight, structural, powerplant, functional, or equipment characteristics, must be established.” CFR Parts 23, 27, and 29 have similar language regarding operating limitations of the aircraft and its components. Compliance with this regulation is often provided in the Airplane Flight Manual (AFM) as an environmental envelope [7], such as in Fig. 1.

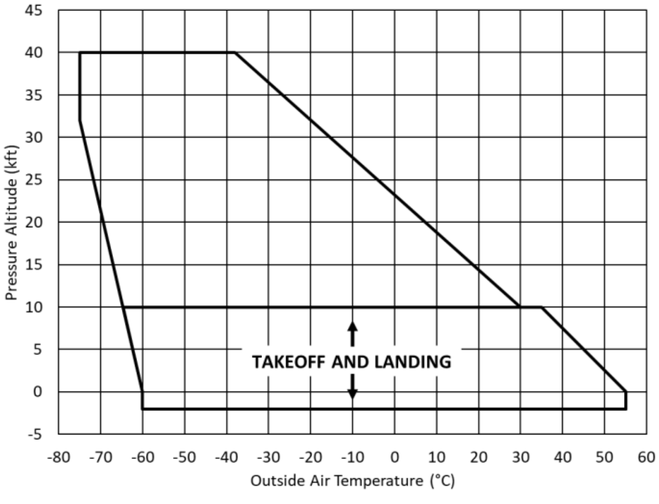
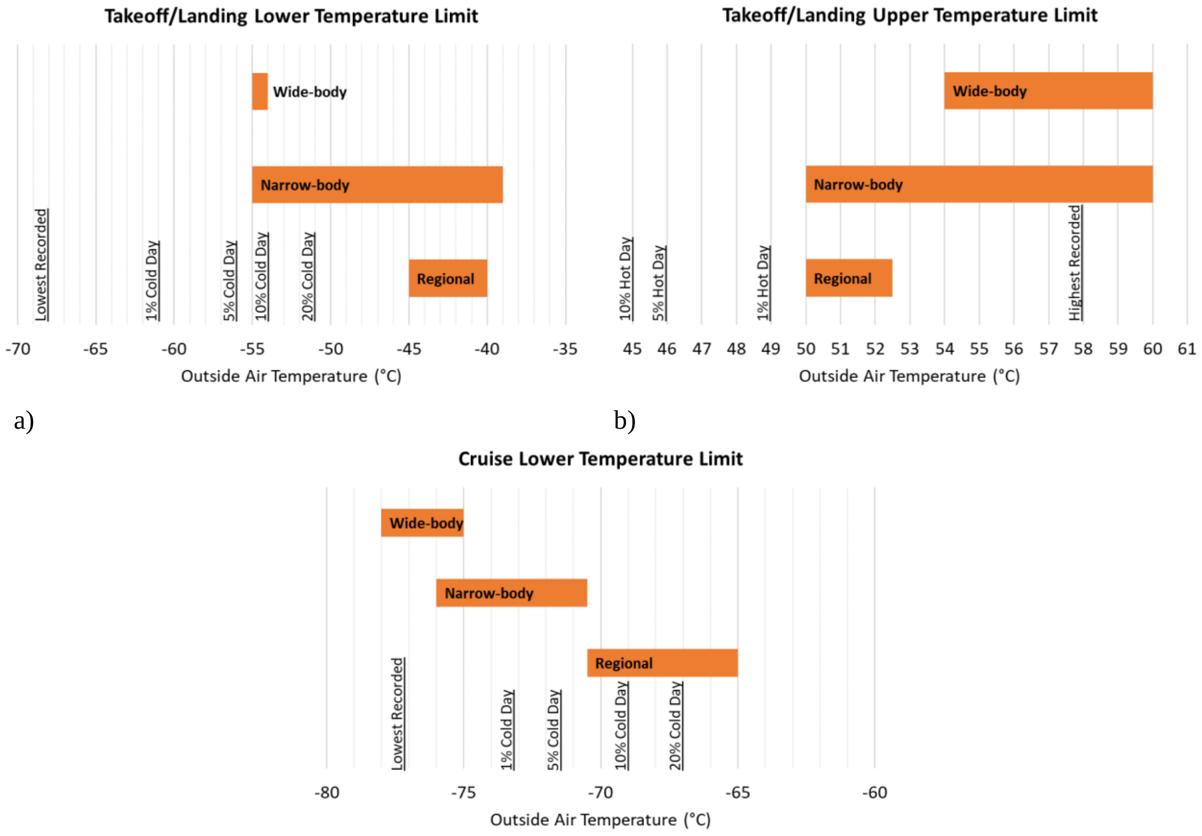


Fig. 1 Typical environmental envelope.

The most constraining part of the envelope are the takeoff/landing upper limit, the takeoff/landing lower limit, and the cruise lower limit, i.e., the lower right, lower left, and upper left corners of the envelope, respectively. An investigation of the environmental envelopes for existing aircraft is useful for developing requirements for new electrified aircraft. A survey of the ranges of these temperatures was completed for transport category airplanes and is summarized in Fig. 2.



a)

b)

c)

Fig. 2 Temperature limit ranges for 3 classes of aircraft; a) Takeoff/landing lower limit, b) takeoff/landing upper limit, and c) cruise lower limit.

Of the aircraft surveyed, all have a takeoff/landing upper limit greater than 50 °C, with larger aircraft tending to have higher limits up to 60 °C. A similar trend is seen at the lower limits, with larger aircraft tending to be compatible with colder temperatures. For the takeoff/landing lower limit, temperatures range from -39 °C down to -55 °C. At the cruise lower limit, temperatures range from -65 °C to -78 °C. It is worth noting that though an aircraft is certified to operate at all points within an environmental envelope, other limitations such as weather may prevent operation on a given day.

Also shown in Fig. 2 are record temperatures and temperatures for several frequency-of-occurrence day types, based on data in MIL-STD-210 and MIL-HDBK-310, which supersedes MIL-STD-210 [8]. This data is also compiled in a consistent format in SAE AS120 [9]. The frequency-of-occurrence day types, e.g., “1% Hot Day”, “20% Cold Day”, refer to the frequency of occurrence of a temperature during the most severe month in the hottest or coldest part of the world (excluding the Antarctic). For example, if a temperature at a given pressure altitude occurs or is exceeded for an average of 74 hours in a 31-day month, then it has a frequency of occurrence of 10%. Each temperature/pressure altitude pair for these day types is given regardless of the location or month in which they occur. Therefore, they represent extremes that can be experienced at a specific altitude, but do not necessarily represent realistic atmospheric profiles. Additionally, the data represent static air temperature, not total air temperature. The 1%, 5%, 10%, 20%, and record temperatures for hot and cold days are plotted in Fig. 3.

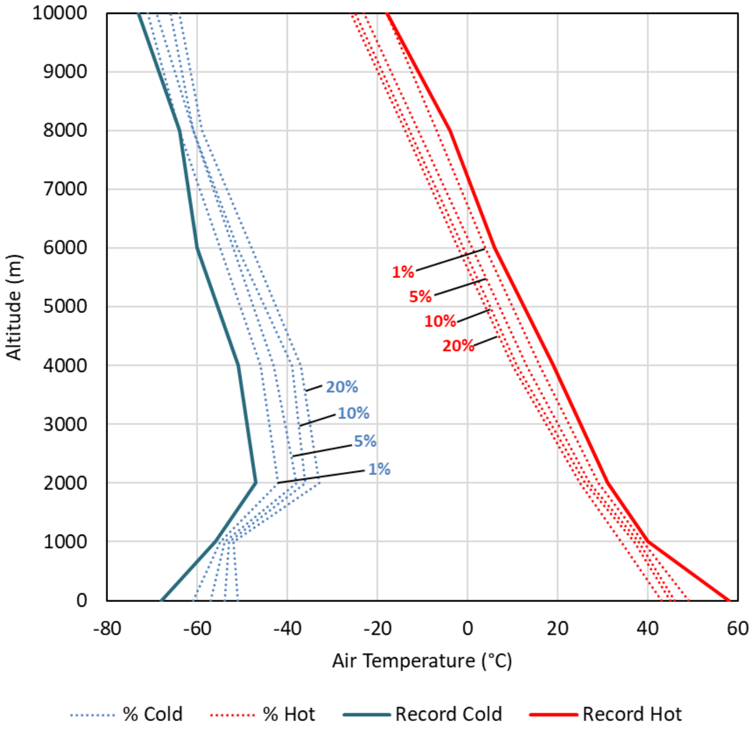


Fig. 3 Frequency of occurrence 1%, 5%, 10%, 20% and record temperatures for hot and cold days.

The original dataset used to generate these day types was collected from radiosonde stations across the world. Details on the data analysis, limitations, and the locations associated with a given extreme are covered in Ref. [10]. These data are intended for use in designing airborne equipment on a worldwide basis. MIL-STD-310 states that "The agency or department responsible for the development of materiel shall determine the operational requirements of the item or system. These requirements should then be used to determine the acceptable frequency of occurrence of a climatic element." It recommends a 1% Hot Day and 1% Cold Day be initially considered as the worldwide air environment for military equipment but recommends the 1% Hot Day and 20% Cold Day values for the worldwide surface environment. These frequencies of occurrence are also suggested in JSSG-2001B, which serves as a tailorable template for US military air vehicle specifications [11]. JSSG-2001B points to MIL-HDBK-310 and similarly notes that "Each environmental condition should be evaluated to determine if the air vehicle must withstand the condition and/or be subjected to that condition throughout its service life."

For operation on a regional as opposed to worldwide basis, surface environments are defined in MIL-HDBK-310, AR 70-38, NATO STANAG 4370, and AECTP-230 [12-14]. (A useful comparison of MIL-HDBK-310 and AR 70-38 is provided in Part Three, Annex C of MIL-STD-810H [15].) Regional data for air environments is not currently compiled in any published standards, however a similar frequency-of-occurrence analysis could be performed if regional radiosonde or other atmospheric data is available.

NASA standards that include thermal environment definitions, such as SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE), primarily focus on space applications [16-18]. These do not cover worldwide extremes, but some define local atmospheric temperatures and pressures near launch facilities. More detailed information on local environmental extremes is documented in NASA Technical Memoranda [19-20] that have been maintained and updated for many decades [21]. NASA TM-2008-215633 includes air temperature data at various geometric altitudes for launch sites at Kennedy Space Center (KSC), Vandenberg Air Force Base (VAFB), Edwards Air Force Base (EAFB), White Sands Missile Range (WSMR) [19]. For worldwide air temperature extremes, this TM references MIL-HDBK-310. The launch site datasets are compiled from radiosonde and rocketsonde measurements and list minimum, median, and maximum values. Also included are "extreme atmospheres" for summer (hot) and winter (cold). In contrast to the MIL-HDBK-310 temperature profiles, these profiles obey the hydrostatic equation and the ideal gas law. They represent realistic extremes that a space vehicle may encounter during ascent or reentry and are not necessarily intended for use in aircraft design and analysis.

NASA/TM-2016-218229 Natural Environments Definition for Design (NEDD) includes air temperature data at various geometric altitudes for KSC (Eastern Range) and EAFB. It lists annual mean temperature and ±2σ deviations, calculated at each altitude level. The use of standard deviation is an important distinction between the NEDD and MIL-HDBK-310, which does not assume a normal (or any other) distribution for the temperatures. Fig. 4 compares temperature profiles at EAFB, with frequency-of-occurrence days calculated in the same manner as MIL-HDBK-310, using data from NOAA's Integrated Global Radiosonde Archive [22]. On the cold side, the -2σ values lie between the 1% and 10% cold days. This is roughly in line with the 4.55% frequency associated with a 2σ event, assuming a normal distribution. On the hot side, the +2σ values are nearer to the 20% hot day at lower altitudes, but they exceed the 1% hot day at altitudes greater than 2,000 m. At some altitudes, the +2σ temperatures exceed the maximum observed temperatures, which indicates a non-normal distribution of temperatures skewed toward the right.

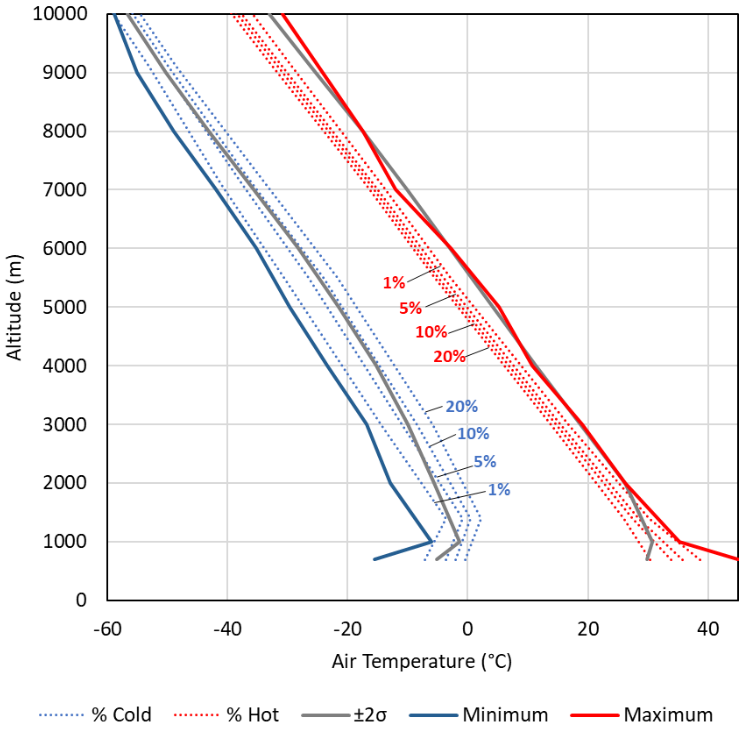


Fig. 4 Air temperatures at EAFB for various altitudes. Minimum and maximum from Ref. [21]. ±2σ from Ref. [20].

B. Thermal Radiation and Solar Flux

MIL-HDBK-310 provides values of solar flux as a function of time of day for worldwide and regional surface environments. The maximum value for the worldwide 1% hot day is 1,120 W/m^2. For cold days, solar flux is considered negligible. The definition of these solar flux values is not clear, but it could be assumed that they represent total solar radiation (direct normal incident plus diffuse). The standard mentions long wave radiation to the cold sky but does not provide guidance on sky temperatures. For ground temperatures, it is noted that they can "attain temperatures 15 to 30 °C higher than that of the free air, depending upon radiation, conduction, wind, and turbulence." Solar flux values are not provided at altitude.

Similarly, NASA TM-2008-215633 lists solar flux values as a function of time of day. These are provided for two regions encompassing various NASA-relevant locations in the western and eastern United States. The data include 95th percentile and extreme values for the months of June and December. They include total radiation for various surface orientations as well as diffuse radiation. Sky temperature is also tabulated for various locations. Recommended design high and low values for solar flux are given with a maximum value of 1,145 W/m^2 for direct horizontal incident flux. Design high and low values for sky temperature are 10 °C and -34 °C, respectively. Other useful information includes variation of solar flux with altitude and estimates of surface temperature differentials with varying emittance, air temperature, and wind speed. Solar flux extremes are also provided for KSC, EAFB, and WSMR in the NEDD and detailed solar flux and sky temperature cycles for KSC are provided in the DSNE.

III. Subsystem Requirements

This section details additional thermal-related requirements for subsystems and specific components that are part of, or interface with, the thermal management system, including batteries, fuel systems, and electronic components.

A. Batteries and Electronic Components

Regulations do not generally specify requirements for the thermal management system (TMS) directly; determining appropriate requirements relies mostly on considering the role of the TMS in the ability of batteries and electronic components to meet environmental requirements. Other standards, such as MIL-STD-2218 (inactive for new design) and MIL-HDBK-251, provide guidance and best practices for designing and testing thermal management systems [24].

In reference to storage batteries, 14 CFR 25.1353 requires that "safe cell temperatures and pressures must be maintained during any probable charging or discharging condition. No uncontrolled increase in cell temperature may result when the battery is recharged" for the conditions of "maximum regulated voltage or power", "during a flight of maximum duration", and "under the most adverse cooling condition likely to occur in service". From this, it is clear that the TMS must be able to maintain the battery cell temperature within safe limits during normal and any probable abnormal charging or discharging condition. For the SUSAN Electrofan, charging and discharging conditions are related primarily to the power distribution system onboard the aircraft; failure or disruptions to this system must be considered in the design of the thermal management system. Compliance with these requirements "must be shown by test unless experience with similar batteries and installations has shown that maintaining safe cell temperatures and pressures presents no problem." (14 CFR 25.1353 (b).(2)) Development of the initial SUSAN design would require testing; subsequent design changes may be able to leverage the initial testing.

AC 20-184 identifies DO-311 and DO-347 as acceptable means of compliance for the CFR sections concerning lithium batteries [26-27]. DO-311 states that battery design must prevent thermal runaway, i.e., "the occurrence of self-sustaining, uncontrolled increases in temperature or pressure." DO-347 defines test methods for demonstrating thermal runaway containment. The NASA standard for battery safety aboard crewed space vehicles [28] requires that lithium-ion battery designs be evaluated to understand the severity of a worst-case single-cell thermal runaway and its propensity for cell-to-cell propagation. Both NASA and DoD best practices are to design battery systems to prevent propagation [29].

In addition to normal operation, the functionality of TMS in potential failure modes must be considered. Per 14 CFR 25.1351, electrical components involved in generating or transmitting power, including "associated control, regulation, and protective devices" must be designed so that "no failure or malfunction of any power source can create a hazard or impair the ability of remaining sources to supply essential loads". From the perspective of the TMS, which could be considered a protective device, there would be a requirement that the TMS be capable of providing sufficient thermal management to functioning power sources in the event of a failure of one power system.

If the TMS is considered a component of the electrical system (and the argument could be made for that) or located in a designated fire zone and used during emergency procedures, 14 CFR 25.869 would also apply, requiring that the TMS "meet the applicable fire and smoke protection requirements" (for component of electrical systems) or "at least fire resistant" (for locations in a designated fire zone). With thermal runaway being a concern for batteries, the area around the batteries may be considered a designated fire zone. Nickel-Cadmium batteries are specifically called out in 14 CFR 25.1353 to "have provisions to prevent any hazardous effect on structure or essential systems" that could be caused by thermal runaway, as well as a system to monitor and disconnect the battery in the event of "battery failure" (such as thermal runaway). It is expected that similar requirements could be levied on other battery types in the future. Additionally, MIL-STD-2218 recommends that "all force cooled equipment shall be provided with an over-temperature indication and protected with thermal interlocks to prevent damage to the equipment due to overheating."

The third potential failure source applicable to the TMS is lightning. 14 CFR 25.1316 contains requirements that "each electrical and electronic system that performs a function, for which failure would prevent the continued safe flight and landing of the airplane, must be designed and installed so that (1) the function is not adversely affected during and after the time the airplane is exposed to lightning; and (2) the system automatically recovers normal operation of that function in a timely manner after the airplane is exposed to lightning." Preliminary thermal analysis indicates that components critical to flight (such as the batteries and electrical components) would exceed temperature limits for proper functionality without thermal management; therefore, the TMS should be capable of providing adequate thermal management to the components in the event of a lightning strike.

In the event of a failure of the TMS, MIL-STD-2218 recommends designing equipment to be capable of handling a loss of cooling for a period of 10 minutes (tailorable to the specific aircraft mission as needed) and to be able to "meet specified performance with a coolant flow rate equal to 75 percent of the design flow rate for a period of 30 minutes" (also tailorable).

B. Fuel Tanks

Fuel is being considered as a coolant fluid for use on the SUSAN Electrofan aircraft. If the fuel is heated during transit from the fuel tanks to the engine, the temperature limits are defined by the engine. If the fuel is recirculated back to the fuel tank after absorbing heat from the components, fuel tank temperature limits apply. The lower temperature limit of the fuel in the tanks is determined primarily by the freezing temperature of the fuel, with some margin built in. A heater may be required to maintain the temperature above this lower limit; alternatively, heat extracted from components may serve to maintain the fuel temperature.

Temperature of the fuel in the tank is dictated on the upper end by the flammability requirements of 14 CFR 25.981 and Appendix N. The allowable temperature is determined by the highest temperature that allows a safe margin below the lowest expected autoignition temperature of the fuel. The type of fuel used, as well as any additives, will determine the autoignition temperature. Part of the certification of an aircraft includes "demonstrating that no temperature at each place inside each fuel tank where fuel ignition is possible will exceed" (14 CFR 25.981 (a).(2)) that allowable temperature. Per AC 25.981-1D, the FAA has accepted 400 °F as the maximum surface temperature inside fuel tanks for kerosene type fuels, like Jet A [30]. Also relevant to the thermal management system, since the fuel will be used in that system, it must also be demonstrated that "an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations of failures not shown to be extremely improbable, taking into account the effects of manufacturing variability, aging, wear, corrosion, and likely damage" (14 CFR 25.981 (a).(3)).

Additional requirements levied by 14 CFR Part 25 include the restriction that "no fuel tank Fleet Average Flammability Exposure on an airplane may exceed three percent of the Flammability Exposure Evaluation Time" (14 CFR 25.981 (b)). Since the wings for SUSAN are expected to be composite and integration of the fuel into the thermal management system would introduce heat into the fuel, the analysis must be based on an assumed Equivalent Conventional Unheated Aluminum Wing Tank, "an integral tank in an unheated semi-monocoque aluminum wing of a subsonic airplane that is equivalent in aerodynamic performance, structural capability, fuel tank capacity, and tank configuration to the designed wing" (14 CFR 25.981 (b).(3).(i)).

Introduction of a means of mitigating the "effects of an ignition of fuel vapors with that fuel tank such that no damage caused by an ignition will prevent continued safe flight and landing" (14 CFR 25.981 (c)) renders the additional requirements discussed in the above paragraph moot. However, these design features must be protected "to ensure the continued effectiveness of those features, and prevent degradation of the performance and reliability" (14 CFR 25.981 (d)) of those features. Inspection and test procedures, maintenance intervals, and life limits must be provided as part of the type certification.

IV. Thermal Analysis Requirements

There are numerous sources of uncertainty in thermal analysis, particularly in parameters like contact conductances, convection coefficients, optical properties, and component heat loads. Typical means of managing uncertainty are correlating models with test data, designing to worst-case conditions, applying thermal uncertainty margin, or a combination of these. NASA has many standards across the agency among its centers setting thermal margins for space projects [31-34] and has endorsed and employed military standards as well [35, 36]. However, none of these standards are strictly applicable to aeronautics projects. The margin philosophies in these standards are all similar and, in most cases, accompany thermal testing requirements as the thermal margins are used to derive test environment temperatures. This is in contrast to aeronautics standards like DO-160 and MIL-STD-810, which recommend fixed test environment temperatures based on expected flight environments [37]. The thermal uncertainty margin in the NASA standards varies from 5 °C to 17 °C with additional design margin (as part of a hardware qualification and acceptance program) from 5 °C to 20 °C. In most cases, these margins can be reduced as the project matures or as models are correlated with test data.

The military standards use 11 °C of thermal uncertainty margin for correlated thermal models and 17 °C of margin for uncorrelated models. These margins are based on spaceflight data collected from several programs [38-41] and represents a two standard deviation (2σ) probability that thermal analysis predictions will fall within the temperatures experienced in flight. Many of these standards also set margins on power for growth allowances, either explicitly or in the form of radiator or fluid systems sizing. Power margins range from 2% to 30% can may depend on project maturity or hardware heritage. Standards like the military standards tend to be conservative to compensate for unknown and unforeseen problems that exist in spaceflight, especially for one-off designs. For projects that are willing to accept more risk, the stack-up of large thermal margins along with worst-case design scenarios can result in overdesign, increased cost and mass, and even lower reliability [42, 43]. Appropriate margin practices in aeronautics are necessary for the design of thermal management systems that are required to move the high heat fluxes seen in electrified aircraft.

For aeronautics, thermal margins are not standardized, and industry design practices are not publicly shared. An analysis similar to Refs. 38-41 would be useful but has not been performed. Some guidance can be found in military and commercial standards, such as MIL-HDBK-251, which states that “conservatism must be the aim of every design for reliable equipment. Consequently, an adequate safety factor should be designed into the equipment.” For semiconductors, this safety factor takes the form of maximum junction temperature derating which is recommended not only for reliability but also to account for analytical error. For analysis with large uncertainties, such as natural convection with direct liquid cooling, the standard recommends a “generous safety factor” of at least 25% on temperature rise. MIL-STD-2218 states that thermal models “shall be capable of predicting part temperature to within ±9°F (±5°C),” which could be interpreted as an uncertainty margin. Similar to power growth allowance in space standards, AIR1277B notes that “a growth cooling capacity of 25% for avionics has been designed into some recent military aircraft [44]. However, experience has shown that this is not necessarily enough to cover all future changes in avionics, especially on fighter aircraft where 100% growth has occurred on some programs.”

Uncertainty Quantification (UQ) is another approach toward addressing uncertainty that is gaining usage in aeronautics. AIAA R-154-2021 Annex E provides an overview of this method, which can be defined as the process of characterizing all major sources of uncertainty in a model or experiment and quantifying their effect on the analysis outcomes [45]. This often involves a propagation and aggregation of probabilistic uncertainties in input parameters to generate a resultant uncertainty in the output results. There have been several studies applying UQ to thermal problems for both aircraft and spacecraft [42, 43, 46-48]. For complex thermal models, reduced order models can be developed for the purposes of UQ [49].

V. SUSAN Thermal Requirements

The previous sections have discussed guidance and recommendations from NASA, FAA, military, and commercial sources on design and analysis requirements for thermal management systems for aircraft. This section covers the approach toward developing the thermal requirements for SUSAN (both full and 25% scale versions) using these sources. These requirements will continue to be developed and refined as the project matures.

Table 1 summarizes the SUSAN thermal requirements. The outside air environment for the full-scale SUSAN is based on a worldwide 20% frequency of occurrence cold day and a 1% hot day from SAE AS210. This aircraft is expected to operate on a worldwide basis and these extremes are fairly close to the environmental envelopes of existing regional aircraft. They also align with the suggested environments in JSSG-2001B and MIL-HDBK-310. For the 25% scale SUSAN, the same frequency of occurrence days are chosen, but are based on regional data for expected flight locations from NOAA databases. This envelope is shown in Fig. 5. Thermal radiation and solar loads for both aircraft are based on extremes values of sky temperature and solar flux in NASA TM-2008-215633. This will be included in analysis where appropriate, taking ground temperature and optical properties into consideration as well.

As electrical component heat loads are one of the larger sources of uncertainty in the SUSAN thermal design, a margin of 25% will be applied to all heat loads for design of the TMS. This margin will be stacked with worst-case environmental conditions and other parameters, e.g., convection coefficients. Additional margin on temperature will be applied for component derating and may be applied for any identified areas of very large uncertainty. However, no global thermal uncertainty margin will be applied as no technically justifiable source for a value of such margin was found for aeronautics. Additionally, the stack-up of 25% heat load margin, worst-case conditions, *and* thermal uncertainty margin is likely overly conservative. UQ may be investigated as a method to refine and potentially reduce these margins.

Subsystem requirements that are relevant to the TMS include requirements for batteries and fuel tanks, which are taken from 14 CFR Part 25 for both aircraft. The battery design and/or TMS will prevent cell-to-cell propagation of thermal runaway, in keeping with NASA best practices and JSC-20793.

Table 1. SUSAN Thermal Requirements

Requirement	Applicable SUSAN Aircraft	Requirement Text	Source
Outside Air Environment	Full Scale	SUSAN shall be capable of ground and flight operations at worldwide 20% Cold Day and 1% Hot Day conditions.	SAE AS210
	25% Scale	SUSAN shall be capable of ground and flight operations at 20% Cold Day and 1% Hot Day conditions based on expected flight locations. (Fig. 5)	Data from NOAA's Integrated Global Radiosonde Archive
Thermal Radiation and Solar Flux	Both	SUSAN shall be capable of ground and flight operations under expected extremes of solar and thermal radiation conditions.	NASA TM-2008-215633
Thermal Margins	Both	The SUSAN TMS shall maintain component temperatures within acceptable limits with a 25% margin on heat load in all operating conditions.	General
Battery Thermal Requirements	Both	SUSAN battery modules must maintain safe cell temperatures during any probable charging or discharging condition and prevent cell-to-cell propagation of thermal runaway events.	14 CFR 25.1353 and JSC-20793
Fuel Temperature	Both	No temperature at each place inside each fuel tank where fuel ignition is possible will exceed allowable limits.	14 CFR 25.981

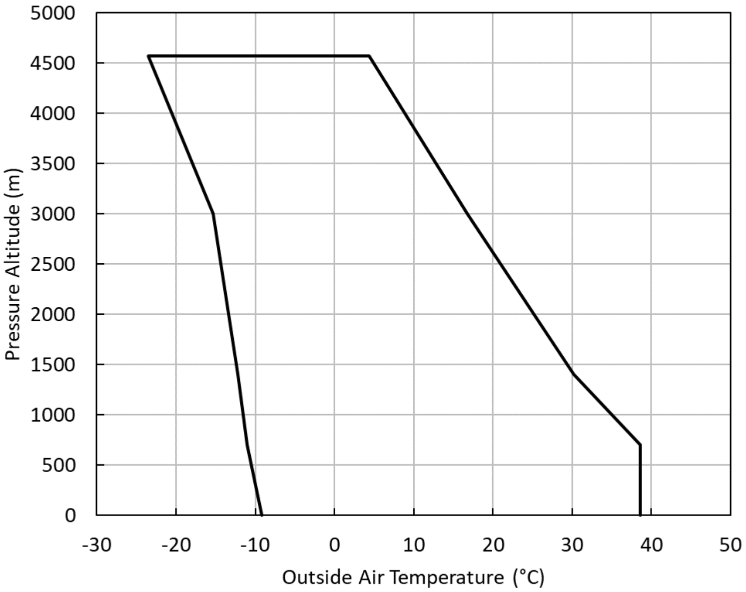


Fig. 5 25% scale SUSAN environmental envelope.

VI. Summary and Conclusion

A review of NASA, military, FAA, and commercial standards and regulations on design and analysis of thermal management systems for aircraft was completed. This was used to inform the development of requirements for the full-scale and 25% scale SUSAN aircraft. Thermal environment requirements for air temperatures were based on the approach taken for airborne military equipment in JSSG-2001B and MIL-HDBK-310. These documents have less definition on thermal radiative environments, so NASA TM-2008-215633 was used to define these environments. No suitable source was found for a global thermal uncertainty margin, as is commonly used in spacecraft thermal analysis. Future investigations comparing analysis predictions to aircraft flight data could be performed to derive such a margin. A conservative 25% margin on heat load was chosen as it is a known source of large uncertainty and is in line with recommendations for power growth allowances used on military aircraft and spacecraft. Thermal requirements for fuel tanks and batteries were also defined. Additional subsystem and TMS component requirements will continue to be developed and refined as the design matures.

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