Thermal Environments and Margin Guidelines for NASA's X-57 "Maxwell" Flight Demonstrator

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NASA's X-57 project includes development and flight demonstration of new electrified propulsion systems and equipment. The system components are designed to operate without active thermal management, which places increased emphasis on the ambient conditions as well as environmental stress screening for the newly designed equipment. Since the X-57 will not be operated outside of the Dryden Aeronautical Test Range at NASA's Armstrong Flight Research Center, the X-57 team developed a series of reference atmospheres, described in this paper, based on the 2019 Edwards Range Reference Atmosphere to guide system development and testing. These four reference atmospheres include a standard day reference atmosphere that is identical to the 1976 U. S. Standard Atmosphere, a mean operational day atmosphere based on the mean 2019 Edwards Range Reference Atmosphere, and hot and cold day atmospheres based on the ±2σ yearly temperature variations in the Edwards Range Reference Atmosphere. As described herein, these reference atmospheres were then used to develop anticipated operational extremes for thermal cycle testing for the X-57 systems, which were developed from an amalgamation of two standards: SMC-S-016 and DO-160G. The project also adopted thermal margin guidance from SMC-S-016 to set requirements for the development of new electrified propulsion system components.

I. Nomenclature

a	speed of sound
C	Sutherland's constant
h_p	pressure altitude
P	pressure
R	gas constant for dry air
t_i	i^{th} time index for thermal cycle
T	temperature
T_0	reference air temperature
T_v	virtual temperature
γ	specific heat capacity for dry air
μ	viscosity
μ_0	reference viscosity
ν	kinematic viscosity
ρ	dry air density

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II. Introduction

The National Aeronautics and Space Administration (NASA) developed the X-57 "Maxwell" as a flight demonstrator* for Distributed Electric Propulsion (DEP) technology [1]. As part of this effort, the X-57 Project conducted numerous different design, analysis, and testing tasks associated with hardware and software that is intended to operate in an atmospheric environment.

Aircraft performance values are highly dependent on the atmospheric conditions in which the flight occurs. As such, flight projects require the definition of a reference set of atmospheric conditions to conduct design and analysis tasks. In addition to the definition of a baseline reference atmosphere, anticipated extremes in ambient conditions are necessary to develop and analyze aircraft system and subsystem performance, as well as verify that the aircraft and associated subsystems will be able to function appropriately within the expected operating environment. As a corollary, defining the atmospheric extremes also defines the acceptable operating environment for planned tests, allowing the team to define limits for the conduct of a test based on the measured or anticipated environment.

This paper describes the four reference atmospheres used by X-57 Project team members for design, analysis, and verification activities, as appropriate. Together, these four atmospheres are referred to as the X-57 Project Reference Atmospheres. The first reference atmosphere was used to analyze, develop, and communicate aircraft performance to external audiences, and is based on the 1976 U.S. Standard atmosphere [2]. The other three reference atmospheres denote the expected operating atmospheric environment of the actual X-57 aircraft – the typical yearly mean conditions, high-temperature extreme conditions, and low-temperature extreme conditions, respectively. These last three reference atmospheres are based on Range Reference Atmospheres compiled by NASA's Marshall Space Flight Center's Atmospheric Environments Group for use at Edwards Air Force Base [3].

The X-57 subsystems must operate within their respective limitations, which includes the minimum and maximum component operating temperatures. Uncertainty exists with respect to the operating environment and the component temperatures themselves, particularly prior to flight. To address this uncertainty, margin must be introduced into the design and analysis process. This paper also introduces the X-57 Project thermal margin plan, as well as a thermal cycling test methodology to be used for component testing, screening, and qualification.

III. Reference Atmosphere Considerations

Typical reference atmospheres and ambient extremes are defined by the requirements of the end user. The 1976 U.S. Standard Atmosphere [2] is a common reference atmosphere used for many different aircraft design and analysis activities, as it represents a common, internationally agreed upon set of equations to produce standard conditions at different altitudes. However, this does not necessarily represent the extremes of the conditions that may be anticipated at each altitude. As such, the extreme conditions are often adopted based on well-known standards or heuristics applied as a deviation from the reference atmosphere. For example, MIL-HDBK-310 [4] describes climatic extremes that can shape design and test requirements for military systems.

These standards are meant to apply to systems that may operate in extreme environments throughout the world. However, the X-57 aircraft is not intended to operate anywhere other than the Dryden Aeronautical Test Range, which is part of the Edwards Air Force Base complex in Edwards, California. Furthermore, the X-57 ground and flight test activities do not necessarily need to be conducted in all known atmospheric extremes in this area – the team had the option to select test times that avoid some well-characterized extremes (e.g., test shortly after sunrise to avoid the highest daily summer temperatures) or wait for better conditions. Limiting the extremes by too much may conflict with the desire to maintain compact test schedules, so some balance was necessary.

A. Source Data and Resolution

The X-57 Project Reference Atmospheres were derived from two reference atmosphere datasets: the 1976 U.S. Standard Atmosphere [2] as captured in the Public Domain Aeronautical Software (PDAS) repository [5] and the 2019 Edwards Range Reference Atmosphere (ERRA) [6] captured from NASA Armstrong Flight Research Center / Edwards Air Force Base Climatology Data [3] as compiled by NASA Marshall Space Flight Center's Atmospheric Environments Group. The PDAS data is available in U.S. Customary Units from 0 to 65,000 ft mean sea level (MSL) in 1,000 ft increments, as well as in the International Systems of Units (SI) from 0 to 20 km MSL in 500 m increments. Given the 1976 U.S. Standard Atmosphere and the International Standard Atmosphere (ISA) [7] are identical over these ranges, this document hereon refers to the 1976 U.S. Standard Atmosphere as "ISA." The 2019 ERRA includes data at 723 m MSL (near the field elevation of Edwards Air Force Base) and from 1 to 30 km in 500 m increments.

* NASA opted to end the X-57 program prior to any test flights, but many of its unique subsystems have been analyzed, developed, and tested.

The ISA data can be expressed purely in functional form if necessary. However, the ERRA is only provided as a table of data in SI units. To ensure consistency, the reference atmospheres developed in this document are based on tabular data only. The values are provided in the Appendix in both U.S. Customary Units and the International System of Units (SI). Many of the calculations within this section reference U.S. Customary Units, but subsequent tests and profiles often used SI or derivative Metric system units (for example, atmospheric temperatures are typically referenced in degrees Celsius at an altitude expressed in ft MSL).

B. Altitudes

The altitudes for each reference atmosphere are given in terms of pressure altitude. The pressure altitude is defined as the height above a standard datum plane, which corresponds to the pressure associated with the geometric altitudes in the ISA. Pressure altitude (below 36,089 ft) is defined as [8]:

$$h_P = \left[1 - \left(\frac{P}{2116.2}\right)^{0.190284}\right] \times 145366.45 \tag{1}$$

where h_p is the pressure altitude in ft and P is the atmospheric pressure in lb_f/ft^2. The source data include geometric altitude as well as atmospheric pressure; the reported values of h_p in the X-57 Reference Atmosphere Tables are always based on the listed pressure in the source data, converted using Equation (1) above. As such, some small rounding errors are present. For consistency, all reference atmosphere tables are given at the same pressure altitudes.

The project ceiling for the X-57 is 15,000 ft MSL. The project reference atmospheres extend slightly above this geometric altitude to enable adequate interpolation. The floor of all X-57 Project Reference Atmospheres is defined as 0 ft h_p. This requires extrapolation of points below 2,372 ft (723 m) MSL for all data derived from the ERRA. For lower altitudes, the pressure altitude is set as an independent variable to the levels in the ISA. The corresponding temperatures for these lower altitudes are increased by 11.63°R, which is the estimated temperature difference between the ISA and the ERRA at 2,372 ft MSL. The "hot" and "cold" X-57 Project Reference Atmospheres assume temperature standard deviations below 2,372 ft MSL equal to those at the ERRA surface.

C. Temperature Corrections

The ISA is derived from dry air assumptions, whereas the ERRA is based on measured air data that includes some moisture. The ERRA data includes ambient temperature and vapor pressure, which is used to compute atmospheric density. Virtual temperature (T_v) is the temperature dry air must have so that the dry air density equals the measured density (with water vapor present). The virtual temperature from the ERRA [9] is provided in lieu of the ambient temperature (T) for the X-57 Project Reference Atmospheres to account for the dry-air assumptions embodied in many derivative analyses by the X-57 project.

Any temperature corrections (e.g., "hot" or "cold" day) made from the ISA or 2019 ERRA data assume dry air and an ideal gas. Given that the pressure altitude is defined for each X-57 Project Reference Atmosphere, the air pressure is known. The density of air is calculated as:

$$\rho = \frac{P}{RT_v} \tag{2}$$

where ρ is the dry air density, T_v is the dry air temperature, and R is the gas constant for dry air, assumed as 1716.2 ft-lb_f/slug°R. The speed of sound is found from:

$$a = \sqrt{\gamma R T_v} \tag{3}$$

where a is the speed of sound and γ is the specific heat capacity ratio for dry air, assumed as 1.4.

D. Viscosity Modeling

The ERRA data does not report measured viscosity. Since this data is necessary for several different domains, it is calculated for the X-57 Project Reference Atmospheres based on the other parameters. The X-57 Project Reference Atmospheres use data derived from Sutherland's Viscosity Law when viscosity is not explicitly provided as part of the reference data set (e.g., anything other than ISA conditions). The gas viscosity is calculated as follows [10]:

$$\mu = \mu_0 \left(\frac{0.555T_0+C}{0.555T_v+C}\right)\left(\frac{T_v}{T_0}\right)^{\frac{3}{2}} \tag{4}$$

where μ is the viscosity of air in slug/ft-s; μ_0 is the reference viscosity of air at reference temperature T_0, which are assumed as 3.8158x10^{-7} slug/ft-s and 524.07°R, respectively; and C is Sutherland's constant, assumed as 120°R for standard air. The kinematic viscosity ν is found from:

$$\nu = \mu/\rho. \tag{5}$$

IV. X-57 Project Reference Atmospheres

The X-57 Project References Atmospheres were developed based on the ISA and ERRA as appropriate. A total of four reference atmospheres were established – standard day, mean operational day, hot day, and cold day. The temperature profile of the four atmospheres is shown in Fig. 1, and the specific values of each reference atmosphere are discussed in the subsections that follow.

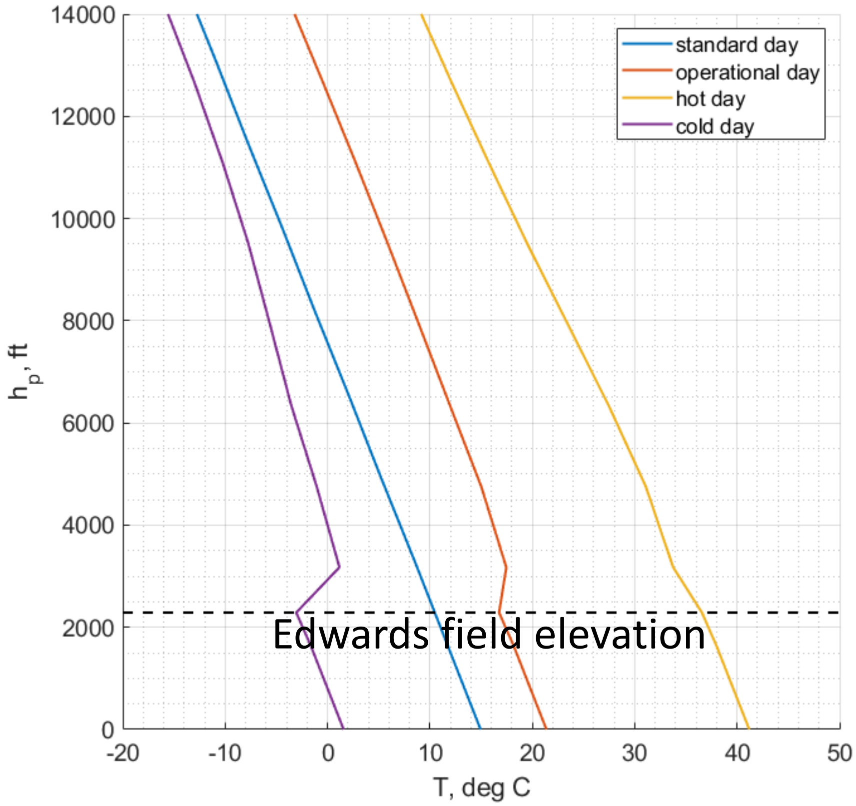

Fig. 1 Temperature profiles of X-57 Project Reference Atmospheres to 14,000 ft MSL.

A. Standard Day Reference Atmosphere

The X-57 Project Standard Day Reference Atmosphere is based entirely off the ISA. It is defined over a pressure altitude of 0 to 17,413 ft. This reference atmosphere was intended primarily for communication of X-57 performance parameters to external audiences. It is a useful reference atmosphere for comparison to the performance of other aircraft or aircraft subsystems since the ISA is a typical reference condition. Table 4 in the Appendix provides the values associated with the X-57 Project Standard Day Reference Atmosphere in U.S. Customary Units, and Table 5 provides the same in SI units.

B. Mean Operational Day Reference Atmosphere

The X-57 Project Mean Operational Day Reference Atmosphere is based on the yearly average ("month 13") ERRA parameters. It is defined over a pressure altitude of 0 to 17,413 ft. This reference atmosphere was intended primarily for calculating X-57 performance parameters for X-57 mission performance planning. Table 6 in the

Appendix provides the values associated with the X-57 Project Mean Operational Day Reference Atmosphere in U.S. Customary Units, and Table 7 provides the same in SI units.

C. Hot Day Reference Atmosphere

The X-57 Project Hot Day Reference Atmosphere is based on the yearly average ("month 13") ERRA parameters, with a temperature correction corresponding to two standard deviations (+2σ) of the reported ERRA standard deviation for T_v. It is defined over a pressure altitude of 0 to 17,413 ft. This reference atmosphere was intended primarily for analysis and sizing of X-57 performance parameters and subsystems for the hottest conditions expected during X-57 operations. Table 8 in the Appendix provides the values associated with the X-57 Project Hot Day Reference Atmosphere in U.S. Customary Units, and

Table 9 provides the same in SI units.

D. Cold Day Reference Atmosphere

The X-57 Project Cold Day Reference Atmosphere is based on the yearly average ("month 13") ERRA parameters, with a temperature correction corresponding to two standard deviations (-2σ) of the reported ERRA standard deviation for T_v. It is defined over a pressure altitude of 0 to 17,413 ft. This reference atmosphere was intended primary for analysis and sizing of X-57 performance parameters and subsystems for the coldest conditions expected during X-57 operations. Table 10 in the Appendix provides the values associated with the X-57 Project Cold Day Reference Atmosphere in U.S. Customary Units, and Table 11 provides the same in SI units.

V. X-57 Thermal Margin Plan

The thermal margin plan defines the thermal margins for the electrical components. To develop thermal margin allocations and thermal cycling test profiles, the X-57 project leveraged the guidance provided by the Air Force Space Command [11] for test requirements of passive thermal hardware. The margin methodology is shown in Fig. 2. Here, the Thermal Uncertainty Margin describes the uncertainty of the modeling methods used to estimate the temperatures of the components throughout the mission and is the same as the Acceptance Test Margin. All flight hardware should be tested to the acceptance temperature levels. Any unit that needs to be used for flight and design qualification testing will be tested to the protoqual temperature levels. Ideally, all components will have a dedicated unit that undergoes qualification testing to verify the quality of the design. Design and analysis should be completed to ensure the component never reaches the component temperature limit minus the margins (the red bar in Fig. 2). When the thermal margin plan is applied to testing, test conditions should be set with the margins added.

In Fig. 2, Bar 1 (Left) shows that analysis produces the best estimate of the worst-case hot and cold temperatures of the component in the expected operating environment. The red color in each bar indicates the predicted temperature range that the electronic components will reach during operation. The yellow part of Bar 1 adds thermal uncertainty of 11°C (per SMC-S-016 guidance) to both the minimum and maximum predicted temperatures.

Bars 2-4 on the thermal margin graph in Fig. 2 are used to test hardware after it is built. The acceptance test will include a thermal uncertainty margin, which involves testing ± 11 °C beyond the maximum and minimum predicted temperatures. The protoqual test margin will exceed the maximum and minimum predicted temperatures by ± 16°C, while the qualification test margin will exceed the maximum and minimum predicted temperatures by ± 21 °C. The protoqual and qualification test margins were derived directly from the SMC-S-016 guidance.

Analysis uncertainty comes from several sources including error in measurement of the environment, assumptions about the system(s) being analyzed, errors in estimated heat load, etc. Additional uncertainty comes from part-to-part variation, material property ranges, and other manufacturing-related tolerances. Together, this uncertainty is bundled into the thermal uncertainty margin, which is added onto the analytical estimate as shown in Bar 1. The thermal uncertainty margin is determined by experience in matching analysis to test. For spacecraft, that is captured in the SMC-S-016 document [11]. The standard that applies directly to aircraft is DO-160G [12]; however, it does not include any uncertainty margin, hence the project elected to use SMC-S-016 guidance.

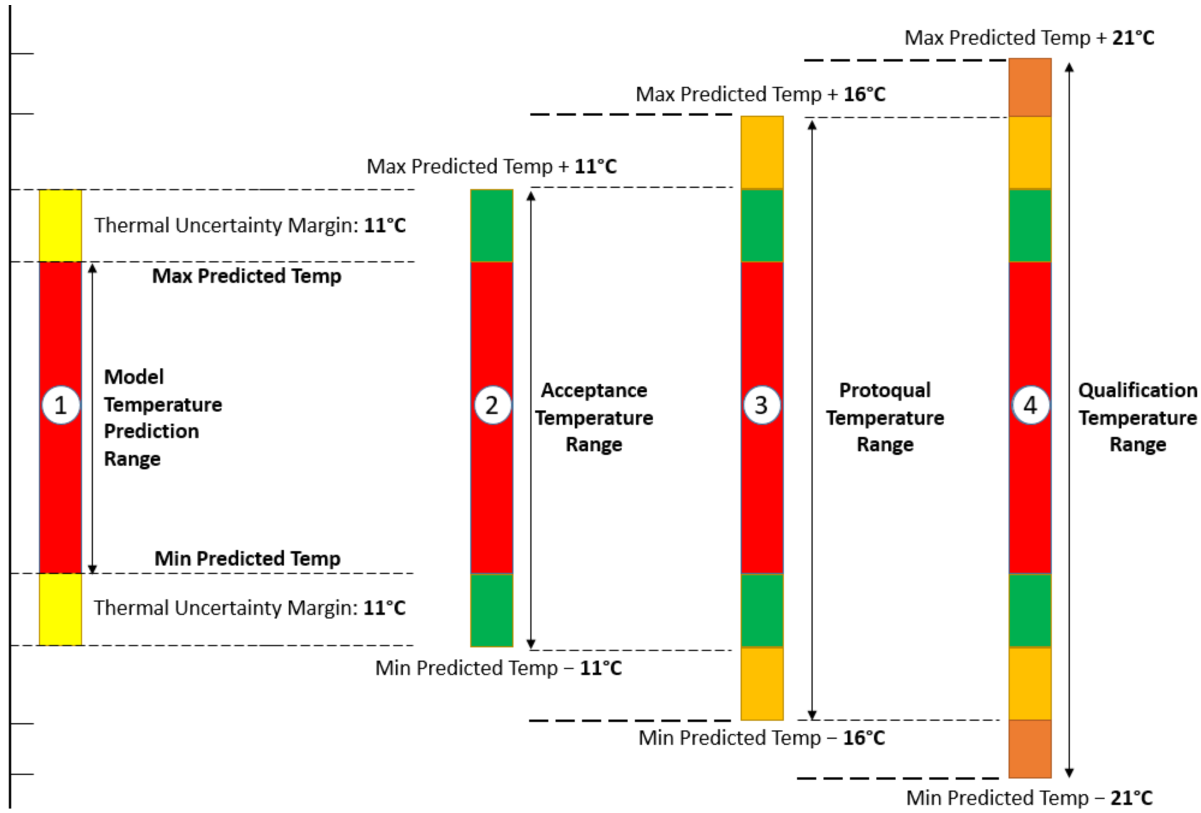

Fig. 2 X-57 Thermal Margin Plan definitions and levels.

A. Environmental Zone Temperatures

The thermal environments for the X-57 components are grouped into zones, which are based on regions of the aircraft that will experience similar local conditions (e.g. air temperature, pressure, vibration). These zones are used to estimate the ambient conditions for component testing, as applicable. The acceptance temperature limits are shown in Table 1, and the corresponding zones is shown in Fig. 3.

Table 1 Environmental Zone Equipment and Ambient Acceptance Temperature Ranges

Zone	Zone Description	Equipment	Acceptance Range, ℃
1	Cockpit	Equipment Pallet, Multifunction Display, Controller Aera Network Relay Box, Fiber Optic Bus Extender, Audio Annunciator, Throttle Encoder, Electromechanical sensors	-15 to 48
2	Cabin	Traction Battery, Battery Controller Module, Contactor Pallet	-15 to 48
3	Tail	Accelerometers	-27 to 48
4	Wing	Traction Bus, Avionics Bus, Electromechanical sensors, Synchronous Versatile Input Module	-27 to 48
5a	High Voltage Cruise Nacelles	Cruise Motor Controller High Voltage Components, Miniature Data Acquisition Unit, Fiber Optic Bus Extender	-27 to 68
5b	Low Voltage Cruise Nacelles	Cruise Motor Controller Low Voltage Components	-27 to 48
6	Cruise Motors	Cruise Motors	-27 to 68
7	High Lift Nacelles	High Lift Motor Controllers, Miniature Data Acquisition Unit	-27 to 48
8	High Lift Motors	High Lift Motors	-27 to 48

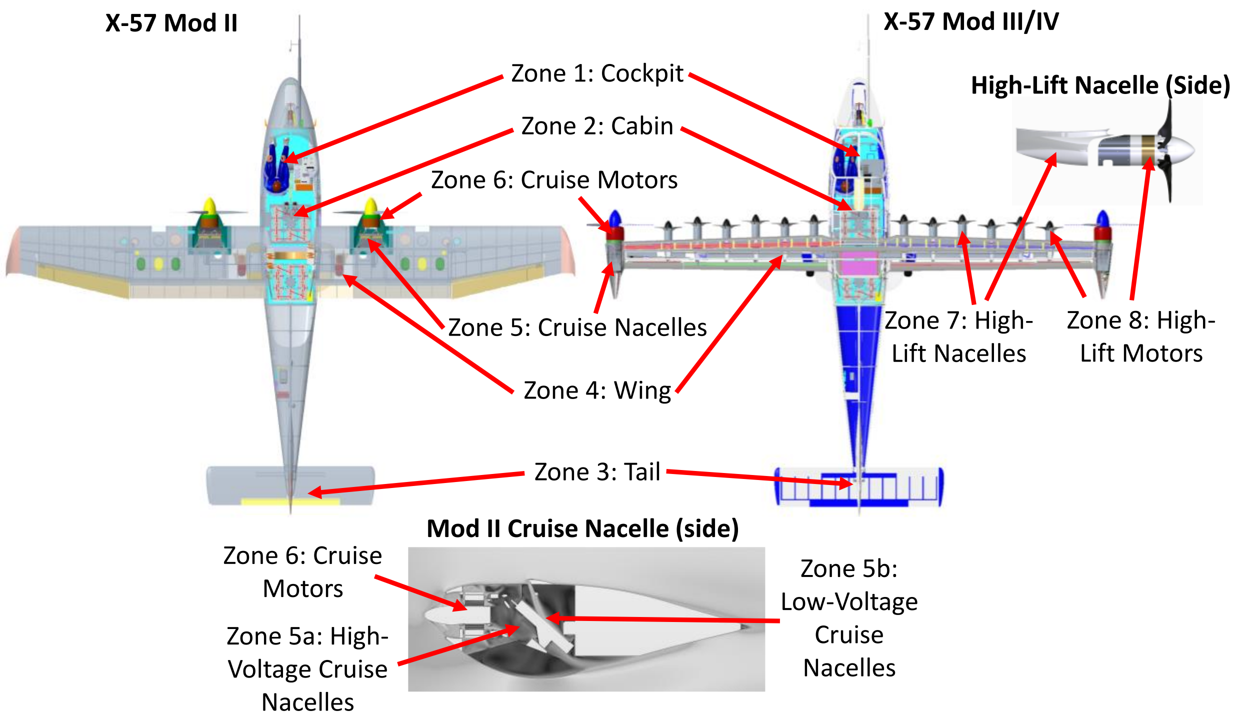

Fig. 3 Environmental zones used to define ambient environments for X-57 component testing.

The lower bounds assume X-57 Project Cold Day atmospheric temperatures at a pressure altitude of 14,000 ft MSL,* except in Zones 1 and 2. For these zones, the cold temperature is from the X-57 Project Cold Day temperature at ground level (about 2,300 ft MSL) because any operations above ground level imply the aircraft is flying, and the equipment in the cabin will provide a temperature that is higher than atmospheric ambient conditions.

The upper bound is based on thermal analysis in the X-57 Project Hot Day atmosphere. The Zone 1 through Zone 2 high temperatures are based on the cabin conditions at ground level, as this is where the highest temperature conditions are recorded, and the heat addition of active components in these zones is not large. The Zone 5 temperature range is derived from analysis of the cruise motor in the Mod II configuration where the maximum average temperature aft of the motor is 57°C,† which becomes 68°C with 11°C of uncertainty margin. This is the highest temperature that the cruise nacelle high voltage components experience, so it is set as the high temperature for Zone 5a in the Mod II configuration. Zone 5b is isolated from Zone 5a (in Mod II) and trends more with the ambient temperature due to the low thermal loads of the components in this zone. Zone 6 is also set to 68°C as the high temperature because the aft windings of the cruise motor are predicted to see 57°C air and an 11°C temperature margin is added. Ultimately, the thermal tests should consider detailed analysis where appropriate, such as the analysis carried out for the Mod II cruise nacelles [13]. Zones 7 and 8 will be cooled by atmospheric air.

B. Thermal Cycle Test Profile

Thermal cycle testing is used to determine if electrical equipment can survive multiple environmental extremes that may occur during a vehicle's lifetime, as well as screen out issues associated with manufacturing defects and workmanship issues. The thermal cycle test profiles are referenced from both the SMC-S-016 [11] and DO-160G [12] documents. SMC-S-016 is written for spacecraft vehicles and systems, while DO-160G applies to aircraft systems and equipment. Referencing both documents for the thermal cycle test helped to establish a clear, detailed test profile that can be easily followed and completed.

The project thermal cycle test profile is the suggested baseline test profile and can be modified for the needs of specific components. For the X-57, the thermal cycle testing included a minimum of seven cycles, with the first cycle

* The highest operational altitude for the X-57 is driven by supplemental oxygen requirements for the pilot, which is as high as 14,000 ft MSL without supplemental oxygen due to the short cruise duration (less than 30 minutes).
† Higher temperatures can be seen in specific areas of the motor, such as the region just aft of the stator cooling slots, but this is referring to the highest average temperature.

shown in Fig. 4 and subsequent cycles in Fig. 5. The first and subsequent cycles of thermal cycle test are outlined in tabular form in Table 2 and Table 3, respectively, where the time steps labeled on each profile in the figures correspond with the time step labels in the tables. The first cycle shown in Fig. 4 includes portions with the equipment turned off when ramping to the ground survival hot and cold temperatures. The equipment is turned on when the operational hot and cold temperatures are reached. Since there is no ground survival demonstration for the subsequent cycles, the equipment is operational throughout so cycling only occurs between hot and cold operational temperatures for these profiles as shown in Fig. 5. Together, these test profiles were intended be used for acceptance and protoqual testing.

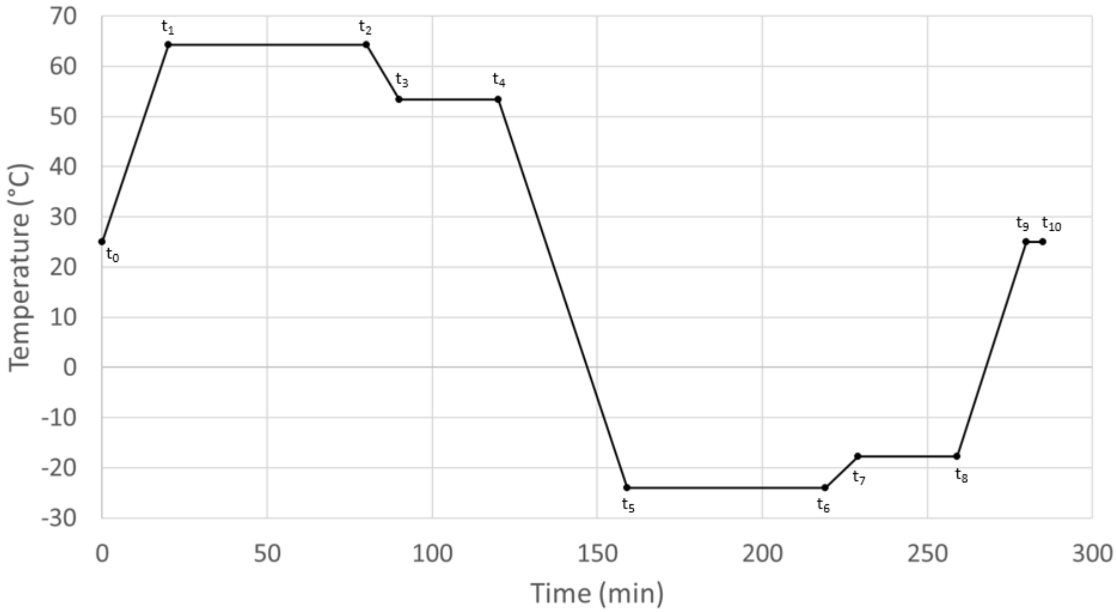

Fig. 4 Profile for first cycle of X-57 thermal cycle testing.

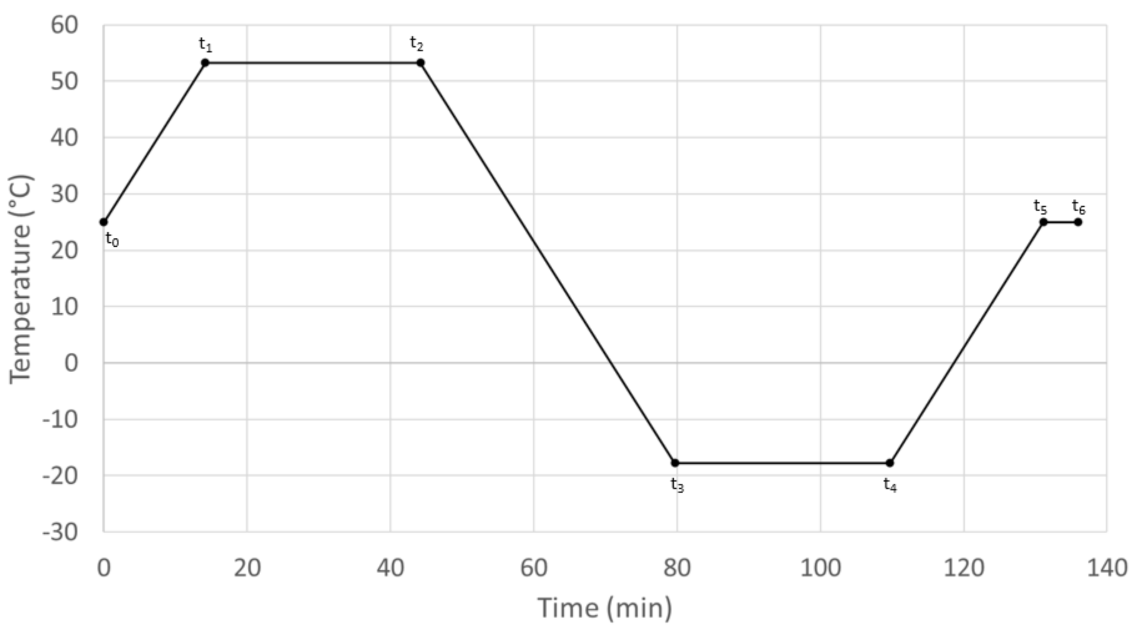

Fig. 5 Profile for subsequent (repeated) cycles of X-57 thermal cycle testing.

Table 2 Procedure for first cycle in X-57 thermal cycle testing

Step	Segment	Equipment status	Segment Duration (min)	Elapsed Time (min)	Initial Temp (°C)	Final Temp (°C)
t_0	Start	NOT OPERATING	0.0	0.0	25.0	25.0
t_1	Ramp to Ground Survival High Temperature	NOT OPERATING	20.0	20.0	25.0	64.3
t_2	Ground Survival High Temperature Hot Soak	NOT OPERATING	60.0	80.0	64.3	64.3
t_3	Ramp to Operating High Temperature	NOT OPERATING	10.0	90.0	64.3	53.3
t_4	Operating High Temperature	OPERATING	30.0	120.0	53.3	53.3
t_5	Ramp to Ground Survival Low Temperature	NOT OPERATING	39.0	159.0	53.3	-24.0
t_6	Ground Survival Low Temperature Cold Soak	NOT OPERATING	60.0	219.0	-24.0	-24.0
t_7	Ramp to Operating Low Temperature	NOT OPERATING	10.0	229.0	-24.0	-17.8
t_8	Operating Low Temperature	OPERATING	30.0	259.0	-17.8	-17.8
t_9	Ramp to Ambient Temperature	OPERATING	21.0	280.0	-17.8	25.0
t_{10}	Ambient Temperature	OPERATING	5.0	285.0	25.0	25.0

Table 3 Procedure for subsequent (repeated) cycles in X-57 thermal cycle testing

Step	Segment	Equipment status	Segment Duration (min)	Elapsed Time (min)	Initial Temp (°C)	Final Temp (°C)
t_0	Start	OPERATING	0.0	0.0	25	25
t_1	Ramp to Operating High Temperature	OPERATING	14.2	14.2	25	53.3
t_2	Operating High Temperature	OPERATING	30.0	44.2	53.3	53.3
t_3	Ramp to Operating Low Temperature	OPERATING	35.5	79.7	53.3	-17.8
t_4	Operating Low Temperature	OPERATING	30.0	109.7	-17.8	-17.8
t_5	Ramp to Ambient Temperature	OPERATING	21.4	131.1	-17.8	25.0
t_6	Ambient Temperature	OPERATING	4.9	136.0	25.0	25.0

For this project, the ±3σ temperatures from the ERRA were used to define the ground survival temperatures, and the X-57 Project Hot and Cold Day extremes with the appropriate level of margin for the test (summarized in Fig. 2) form the extremes. If the Hot Operational temperature is greater than the Ground Survival Hot temperature, then the dwell from time t_1 to t_2 in Fig. 4 is not necessary. Similarly, if the Cold Operational temperature is less than the Ground Survival Cold temperature, then the dwell at t_5 to t_6 in Fig. 4 is not necessary.

VI. Summary

NASA's X-57 "Maxwell" was developed as a flight demonstrator for distributed electric propulsion and featured numerous electronic systems. The waste heat with from these systems was intended to be removed passively with ambient air. Given that the aircraft was only to be flown from NASA's Dryden Aeronautical Test Range at Edwards Air Force Base, and that the aircraft was not intended as a research vehicle, the X-57 team developed a series of atmosphere profiles that were less aggressive than typically seen for production systems that are expected to operate worldwide at any time and therefore in more significant extremes. These reference atmospheres were based on the Edwards Range Reference Atmosphere at ±2σ temperature extremes. These reference atmospheres are given in the Appendix to this paper and formed the basis of X-57's vehicle performance analysis and thermal performance testing.

Little consensus guidance existed for airborne electrified propulsion system environmental testing for the duration of the X-57 project, so the project team developed unique thermal qualification and margin plans based on guidelines from the Air Force Space Command and other consensus standards for passive electronic equipment. These tailored guidelines included development of a layered margin approach for acceptance, protoqual, and qualification testing, as well as a thermal cycling profile used to test the X-57's critical electronic hardware. The particular extremes used for testing was based on "zones" associated with the hardware's location on the unpressurized aircraft, with the exterior components largely following the extremes of the X-57 reference atmospheres. In some cases, thermal analysis informed changes in temperature limits for these zones, particularly in "zones" where the influence of waste heat from the electrical components raised the local temperature well above the freestream ambient temperature (such as the motor nacelles).

Though the X-57 project ultimately ended prior to flight, these guidelines were used for analysis and testing of X-57 electronic hardware. We hope this guidance associated with thermal margin planning and testing can help others in the burgeoning field of electrified aircraft propulsion. Electrified aircraft propulsion offers exciting opportunities for increased performance, affordability, and even new mission paradigms, but also comes with new challenges that may not be fully addressed by today's standard practices. The intent of this research is to provide public reference information that can be used to assist or inform those efforts that will make it to flight.

Appendix: X-57 Project Reference Atmosphere Tables

The X-57 Project Reference Atmospheres referenced from section IV are provided below in both U.S. Customary and SI units in the sections below.

A. X-57 Project Standard Day Reference Atmosphere

Table 4 X-57 Project Standard Day Reference Atmosphere, U.S. Customary Units

h_p, ft	T_v, °R	P, lb$_f$/ft^2	ρ, slug/ft^3	a, ft/s	μ, slug/ft-s	ν, ft^2/s
0.0	518.70	2,116.2	0.0023769	1,116.5	3.7400×10^{-7}	1.5700×10^{-4}
1,635.7	512.79	1,994.0	0.0022651	1,110.1	3.7072×10^{-7}	1.6356×10^{-4}
2,288.9	510.47	1,946.9	0.0022216	1,107.6	3.6941×10^{-7}	1.6618×10^{-4}
3,174.2	507.34	1,884.4	0.0021637	1,104.2	3.6764×10^{-7}	1.6972×10^{-4}
4,759.6	501.64	1,776.5	0.0020629	1,098.0	3.6446×10^{-7}	1.7691×10^{-4}
6,345.6	496.00	1,673.7	0.0019656	1,091.8	3.6128×10^{-7}	1.8392×10^{-4}
7,930.2	490.38	1,575.9	0.0018720	1,085.5	3.5794×10^{-7}	1.9088×10^{-4}
9,510.6	484.70	1,482.9	0.0017821	1,079.3	3.5410×10^{-7}	1.9864×10^{-4}
11,091.5	479.07	1,394.5	0.0016955	1,072.9	3.5077×10^{-7}	2.0734×10^{-4}
12,673.0	473.40	1,310.3	0.0016121	1,066.6	3.4761×10^{-7}	2.1622×10^{-4}
14,251.5	467.77	1,230.4	0.0015321	1,060.3	3.4444×10^{-7}	2.2493×10^{-4}
15,831.9	462.16	1,154.5	0.0014550	1,053.9	3.4127×10^{-7}	2.3445×10^{-4}
17,413.1	456.49	1,082.3	0.0013809	1,047.4	3.3810×10^{-7}	2.4450×10^{-4}

Table 5 X-57 Project Standard Day Reference Atmosphere, SI Units

h_p, m	T_v, K	P, Pa	ρ, kg/m^3	a, m/s	μ, kg/m-s	ν, m^2/s
0.0	288.10	101325	1.2250	340.3	1.7890×10^{-5}	1.4600×10^{-5}
498.6	284.90	95461	1.1670	338.4	1.7740×10^{-5}	1.5200×10^{-5}
697.7	283.61	93216	1.1449	337.6	1.7676×10^{-5}	1.5441×10^{-5}
967.5	281.90	90225	1.1154	336.5	1.7590×10^{-5}	1.5763×10^{-5}
1,450.7	278.71	85062	1.0631	334.7	1.7435×10^{-5}	1.6434×10^{-5}
1,934.1	275.60	80139	1.0134	332.8	1.7280×10^{-5}	1.7024×10^{-5}
2,417.1	272.42	75454	0.9649	330.9	1.7125×10^{-5}	1.7773×10^{-5}
2,898.8	269.32	71004	0.9183	329.0	1.6971×10^{-5}	1.8465×10^{-5}
3,380.7	266.15	66768	0.8735	327.1	1.6816×10^{-5}	1.9218×10^{-5}
3,862.7	263.04	62737	0.8305	325.1	1.6654×10^{-5}	2.0065×10^{-5}
4,343.8	259.88	58913	0.7895	323.2	1.6498×10^{-5}	2.0933×10^{-5}
4,825.6	256.76	55276	0.7496	321.2	1.6336×10^{-5}	2.1802×10^{-5}
5,307.5	253.61	51821	0.7112	319.2	1.6178×10^{-5}	2.2735×10^{-5}

B. X-57 Project Mean Operational Day Reference Atmosphere

Table 6 X-57 Project Mean Operational Day Reference Atmosphere, U.S Customary Units

h_p, ft	T_v, °R	P, lb_f/ft^2	ρ, $slug/ft^3$	a, ft/s	μ, slug/ft-s	ν, ft^2/s
0.0	530.33	2,116.2	0.0023252	1,128.8	3.8518×10^{-7}	1.6566×10^{-4}
1,635.7	524.42	1,994.0	0.0022156	1,122.5	3.8178×10^{-7}	1.7231×10^{-4}
2,288.9	521.83	1,946.9	0.0021740	1,119.7	3.8028×10^{-7}	1.7493×10^{-4}
3,174.2	523.10	1,884.4	0.0020991	1,121.1	3.8102×10^{-7}	1.8152×10^{-4}
4,759.6	518.68	1,776.5	0.0019958	1,116.3	3.7846×10^{-7}	1.8963×10^{-4}
6,345.6	513.18	1,673.7	0.0019005	1,110.4	3.7527×10^{-7}	1.9746×10^{-4}
7,930.2	507.73	1,575.9	0.0018085	1,104.5	3.7209×10^{-7}	2.0574×10^{-4}
9,510.6	502.26	1,482.9	0.0017204	1,098.5	3.6887×10^{-7}	2.1441×10^{-4}
11,091.5	496.63	1,394.5	0.0016361	1,092.3	3.6556×10^{-7}	2.2343×10^{-4}
12,673.0	490.84	1,310.3	0.0015555	1,086.0	3.6212×10^{-7}	2.3280×10^{-4}
14,251.5	484.95	1,230.4	0.0014784	1,079.4	3.5861×10^{-7}	2.4256×10^{-4}
15,831.9	478.91	1,154.5	0.0014046	1,072.7	3.5499×10^{-7}	2.5273×10^{-4}
17,413.1	472.77	1,082.3	0.0013340	1,065.8	3.5128×10^{-7}	2.6334×10^{-4}

Table 7 X-57 Project Mean Operational Day Reference Atmosphere, SI Units

h_p, m	T_v, K	P, Pa	ρ, kg/m^3	a, m/s	μ, kg/m-s	ν, m^2/s
0.0	294.53	101325	1.1987	344.0	1.8438×10^{-5}	1.5381×10^{-5}
498.6	291.33	95461	1.1418	342.1	1.8279×10^{-5}	1.6009×10^{-5}
697.7	289.90	93216	1.1204	341.3	1.8208×10^{-5}	1.6251×10^{-5}
967.5	290.61	90225	1.0818	341.7	1.8243×10^{-5}	1.6864×10^{-5}
1,450.7	288.15	85062	1.0286	340.3	1.8121×10^{-5}	1.7617×10^{-5}
1,934.1	285.10	80139	0.9795	338.4	1.7968×10^{-5}	1.8345×10^{-5}
2,417.1	282.07	75454	0.9321	336.6	1.7816×10^{-5}	1.9114×10^{-5}
2,898.8	279.03	71004	0.8867	334.8	1.7662×10^{-5}	1.9919×10^{-5}
3,380.7	275.91	66768	0.8432	332.9	1.7503×10^{-5}	2.0757×10^{-5}
3,862.7	272.69	62737	0.8017	331.0	1.7338×10^{-5}	2.1628×10^{-5}
4,343.8	269.42	58913	0.7620	329.0	1.7170×10^{-5}	2.2535×10^{-5}
4,825.6	266.06	55276	0.7239	327.0	1.6997×10^{-5}	2.3479×10^{-5}
5,307.5	262.65	51821	0.6875	324.8	1.6820×10^{-5}	2.4465×10^{-5}

C. X-57 Project Hot Day Reference Atmosphere

Table 8 X-57 Project Hot Day Reference Atmosphere, U.S. Customary Units

h_p, ft	T_v, °R	P, lb_f/ft^2	ρ, $slug/ft^3$	a, ft/s	μ, slug/ft-s	ν, ft^2/s
0.0	565.98	2,116.2	0.0021787	1,166.1	4.0531×10^{-7}	1.8603×10^{-4}
1,635.7	560.07	1,994.0	0.0020746	1,160.0	4.0201×10^{-7}	1.9378×10^{-4}
2,288.9	557.48	1,946.9	0.0020349	1,157.3	4.0056×10^{-7}	1.9684×10^{-4}
3,174.2	552.43	1,884.4	0.0019876	1,152.1	3.9773×10^{-7}	2.0010×10^{-4}
4,759.6	547.60	1,776.5	0.0018904	1,147.0	3.9500×10^{-7}	2.0895×10^{-4}
6,345.6	541.07	1,673.7	0.0018025	1,140.2	3.9131×10^{-7}	2.1709×10^{-4}
7,930.2	533.91	1,575.9	0.0017199	1,132.6	3.8723×10^{-7}	2.2515×10^{-4}
9,510.6	526.76	1,482.9	0.0016404	1,125.0	3.8313×10^{-7}	2.3355×10^{-4}
11,091.5	520.01	1,394.5	0.0015626	1,117.8	3.7923×10^{-7}	2.4270×10^{-4}
12,673.0	513.44	1,310.3	0.0014870	1,110.7	3.7542×10^{-7}	2.5246×10^{-4}
14,251.5	507.14	1,230.4	0.0014138	1,103.8	3.7174×10^{-7}	2.6294×10^{-4}
15,831.9	500.97	1,154.5	0.0013428	1,097.1	3.6812×10^{-7}	2.7414×10^{-4}
17,413.1	494.75	1,082.3	0.0012747	1,090.3	3.6444×10^{-7}	2.8591×10^{-4}

Table 9 X-57 Project Hot Day Reference Atmosphere, SI Units

h_p, m	T_v, K	P, Pa	ρ, kg/m³	a, m/s	μ, kg/m-s	ν, m²/s
0.0	314.34	101325	1.1232	355.4	1.9402×10^{-5}	1.7273×10^{-5}
498.6	311.14	95461	1.0691	353.6	1.9248×10^{-5}	1.8004×10^{-5}
697.7	309.71	93216	1.0488	352.8	1.9179×10^{-5}	1.8287×10^{-5}
967.5	306.91	90225	1.0244	351.2	1.9043×10^{-5}	1.8590×10^{-5}
1,450.7	304.22	85062	0.9743	349.6	1.8913×10^{-5}	1.9412×10^{-5}
1,934.1	300.59	80139	0.9290	347.5	1.8736×10^{-5}	2.0168×10^{-5}
2,417.1	296.62	75454	0.8864	345.2	1.8541×10^{-5}	2.0917×10^{-5}
2,898.8	292.64	71004	0.8454	342.9	1.8344×10^{-5}	2.1698×10^{-5}
3,380.7	288.90	66768	0.8053	340.7	1.8158×10^{-5}	2.2548×10^{-5}
3,862.7	285.24	62737	0.7664	338.5	1.7975×10^{-5}	2.3454×10^{-5}
4,343.8	281.74	58913	0.7286	336.4	1.7799×10^{-5}	2.4428×10^{-5}
4,825.6	278.32	55276	0.6920	334.4	1.7626×10^{-5}	2.5469×10^{-5}
5,307.5	274.86	51821	0.6569	332.3	1.7450×10^{-5}	2.6562×10^{-5}

D. X-57 Project Cold Day Reference Atmosphere

Table 10 X-57 Project Cold Day Reference Atmosphere, U.S. Customary Units

h_p, ft	T_v, °R	P, lb_f/ft^2	ρ, slug/ft³	a, ft/s	μ, slug/ft-s	ν, ft²/s
0.0	494.68	2,116.2	0.0024927	1,090.2	3.6440×10^{-7}	1.4618×10^{-4}
1,635.7	488.77	1,994.0	0.0023772	1,083.7	3.6089×10^{-7}	1.5181×10^{-4}
2,288.9	486.17	1,946.9	0.0023334	1,080.8	3.5934×10^{-7}	1.5400×10^{-4}
3,174.2	493.77	1,884.4	0.0022237	1,089.2	3.6386×10^{-7}	1.6363×10^{-4}
4,759.6	489.76	1,776.5	0.0021137	1,084.8	3.6148×10^{-7}	1.7102×10^{-4}
6,345.6	485.29	1,673.7	0.0020097	1,079.8	3.5881×10^{-7}	1.7854×10^{-4}
7,930.2	481.55	1,575.9	0.0019069	1,075.6	3.5658×10^{-7}	1.8700×10^{-4}
9,510.6	477.76	1,482.9	0.0018087	1,071.4	3.5429×10^{-7}	1.9589×10^{-4}
11,091.5	473.25	1,394.5	0.0017170	1,066.3	3.5158×10^{-7}	2.0477×10^{-4}
12,673.0	468.24	1,310.3	0.0016306	1,060.7	3.4854×10^{-7}	2.1376×10^{-4}
14,251.5	462.76	1,230.4	0.0015493	1,054.4	3.4521×10^{-7}	2.2281×10^{-4}
15,831.9	456.85	1,154.5	0.0014725	1,047.7	3.4159×10^{-7}	2.3198×10^{-4}
17,413.1	450.78	1,082.3	0.0013990	1,040.7	3.3785×10^{-7}	2.4149×10^{-4}

Table 11 X-57 Project Cold Day Reference Atmosphere, SI Units

h_p, m	T_v, K	P, Pa	ρ, kg/m³	a, m/s	μ, kg/m-s	ν, m²/s
0.0	274.72	101325	1.2852	332.2	1.7443×10^{-5}	1.3572×10^{-5}
498.6	271.52	95461	1.2251	330.3	1.7279×10^{-5}	1.4104×10^{-5}
697.7	270.10	93216	1.2026	329.4	1.7205×10^{-5}	1.4307×10^{-5}
967.5	274.32	90225	1.1461	332.0	1.7422×10^{-5}	1.5201×10^{-5}
1,450.7	272.09	85062	1.0893	330.6	1.7308×10^{-5}	1.5888×10^{-5}
1,934.1	269.61	80139	1.0357	329.1	1.7180×10^{-5}	1.6587×10^{-5}
2,417.1	267.53	75454	0.9828	327.9	1.7073×10^{-5}	1.7373×10^{-5}
2,898.8	265.42	71004	0.9322	326.6	1.6964×10^{-5}	1.8198×10^{-5}
3,380.7	262.92	66768	0.8849	325.0	1.6834×10^{-5}	1.9023×10^{-5}
3,862.7	260.14	62737	0.8404	323.3	1.6688×10^{-5}	1.9859×10^{-5}
4,343.8	257.09	58913	0.7985	321.4	1.6529×10^{-5}	2.0700×10^{-5}
4,825.6	253.81	55276	0.7589	319.3	1.6355×10^{-5}	2.1552×10^{-5}
5,307.5	250.43	51821	0.7210	317.2	1.6176×10^{-5}	2.2435×10^{-5}

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References

[1] Borer, N. K., Patterson, M. D., Viken, J. K., Moore, M. D., Clarke, S., Redifer, M., Christie, R., Stoll, A., Dubois, A, Bevirt, J., Gibson, A., Foster, T., Osterkamp, P., "Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator," 16th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, (AIAA 2016-3920), June 2016. doi: 10.2514/6.2016-3920

[2] "U. S. Standard Atmosphere, 1976," NASA-TM-X-74335, National Aeronautics and Space Administration, Washington, D.C., October 1976.

[3] "Armstrong Flight Research Center / Edwards Air Force Base Climatology," https://weather.dfrc.nasa.gov/Climatology, accessed 12 December 2022.

[4] "Global Climatic Data for Developing Military Products," MIL-HDBK-310, U. S. Department of Defense, Washington, D.C., June 1997.

[5] "Properties of the U.S. Standard Atmosphere, 1976," Public Domain Aeronautical Software (PDAS), http://www.pdas.com/atmos.html, accessed 9 November 2020.

[6] "Range Reference Atmosphere 2019, Edwards AFB, CA," https://weather.dfrc.nasa.gov/public/data/rcc/RRA_2019_EAFB_mWD.xlsx, accessed 9 November 2020.

[7] "Standard Atmosphere," ISO 2533:1975, International Organization for Standardization, https://www.iso.org/standard/7472.html, accessed 12 November 2020.

[8] "Pressure Altitude," National Oceanic and Atmospheric Administration, https://www.weather.gov/media/epz/wxcalc/pressureAltitude.pdf, accessed 12 November 2020.

[9] "Range Reference Atmosphere, 0-70 km Altitude, Edwards AFB, CA," Document 366-83, Meteorology Group, Range Commander's Council, White Sands Missile Range, New Mexico, August 1983.

[10] "Gas Viscosity Calculator," LMNO Engineering, Research, and Software, Ltd., https://www.lmnoeng.com/Flow/GasViscosity.php, accessed 12 November 2020.

[11] "Space and Missile Systems Center Standard: Test Requirements for Launch, Upper-Stage and Space Vehicles," SMC Standard SMC-S-016, Air Force Space Command, 5 September 2014.

[12] "Environmental Conditions and Test Procedures for Airborne Equipment," DO-160G, RTCA, 8 December 2010.

[13] Borer, N. K., Bui, T., Smith, A. D., "Cruise Propulsion System Thermal Analysis for NASA's X-57 "Maxwell" Mod II Configuration," AIAA AVIATION Forum (AIAA-2023-4273), June 2023.