https://doi.org/10.5028/jatm.v11.1088 ORIGINAL PAPER

The Role of Terrestrial and Space Environments in Launch Vehicle Development

Dale L. Johnson[1], William W. Vaughan[2,*]

Vaughan WW https://orcid.org/0000-0003-1982-1506

How to cite

Johnson DL; Vaughan WW (2019) The Role of Terrestrial and Space Environments in Launch Vehicle Development. J Aerosp Technol Manag, 11: e4719. https://doi.org/10.5028/jatm.v11.1088

ABSTRACT: Natural (Terrestrial & Space) Environment (NE) phenomena play a significant role in the design and flight of aerospace vehicles and in the integrity of the associated aerospace systems and structures. Natural environmental design criteria guidelines described here are based on measurements and modeling of atmospheric and climatic phenomena relative to various aerospace vehicle development and mission/operational procedures, and for vehicle launch locations. Both the terrestrial environment (0-90 km altitude) and the space environment (Earth orbital altitudes) parameters and their engineering application philosophy are given with emphasis on launch vehicle-affected terrestrial environment elements. This paper also addresses the basis for the NE guidelines presented, the interpretation of the guidelines, and application to the development of launch or space vehicle design requirements. This paper represents the first of three on this subject.

KEYWORDS: Terrestrial environment, Space environments, Launch vehicle environment, Aerospace vehicle, Design requirements, Risk, Atmospheric parameters.

INTRODUCTION

Natural (Terrestrial & Space) Environment (NE) phenomena play a significant role in the design, development, and operation of all aerospace launch vehicles (LVs). Winds, turbulence, hydrometeors, atmospheric density, temperature extremes, ionizing radiation, orbital debris, and the other environmental phenomena pose a threat to the integrity of the vehicle structures, avionics, control, and other systems. Thus, the NE forms a fundamental constraint to a vehicle's design and operability. Design engineers must address this constraint in terms of robust design, operational mitigation, and mission risk. To be successful, a launch vehicle program must take an aggressive, coordinated, and consistent approach to managing the influence of natural environmental phenomena (terrestrial and space) in a vehicle's development cycle.

Because the initial concept development phase sets the program's goals for operational range, location, payload weight, vehicle robustness, operability, and acceptable mission risk (factors that are all highly constrained by the NE), careful consideration of the NE is especially important within that phase. A thorough understanding of all the natural environmental phenomena is essential to the development of a realistic and achievable definition of vehicle capabilities at the top level. This section describes the interactions of the NE with the key vehicle engineering elements and serves as a starting point for specifying appropriate NE information for any LV design. Because the launch and much of the flight profile for any LV occurs in the terrestrial environment (usually defined as below 56 nmi (90 km) altitude), this atmospheric region generally dominates the natural environmental design criteria. These criteria are based on statistics and models of natural environmental phenomena relative to various operational capabilities and requirements of aerospace vehicles, engine tests, vehicle launch locations, flight profiles, and orbits. The scope of the terrestrial environment includes the

1.National Aeronautics and Space Administration – Marshall Space Flight Center (retired) – Huntsville/AL – USA.
2.National Aeronautics and Space Administration – Marshall Space Flight Center (emeritus) – Huntsville/AL – USA.
Correspondence author: williamwvaughan@aol.com
Received: Jan. 31, 2019 | **Accepted:** Mar. 26, 2019
Section Editor: Rosa Marques

following NE phenomena, which cause forces and other effects on every LV. Therefore, the vehicle design engineers must include these effects in their design. Constraints must be placed on the operation of the vehicle depending on the risk of exceeding the NE design values: winds; thermal radiation; humidity; atmospheric electricity; atmospheric constituents; sea states; geological hazards; atmospheric thermodynamic models and properties; US and world surface environment extremes; precipitation, fog, and icing; cloud characteristics and cloud cover models; vehicle engine exhaust and toxic chemical release; occurrences of tornadoes, hurricanes, and severe weather

As indicated in Table 1, these NE phenomena may significantly affect multiple areas of vehicle structures, control, trajectory shaping (performance), aerodynamic heating, take-off and landing capabilities, and all other systems, subsystems, and disciplines. Note that winds and gusts (column 1) affect the system and the mission analysis (row 1) but do not affect manufacturing (row 3), as one would expect.

Table 1. Key terrestrial environment parameters versus vehicle engineering systems (X) and mission phase (P).

Launch vehicle system and subsystems (X)	Winds and gusts*	Atmospheric Thermodynamic properties	Atmospheric constituents	Solar or thermal radiation	Atmospheric electricity	Clouds and fog	Humidity	Precipitation or hail	Sea state	Severe weather	Geologic hazards	Mission phase (P)
System	XP	XP	XP	XP	XP	XP	XP	XP	XP	XP	X	Mission analysis
Propulsion/engine sizing	X	XP	P		X		XP			X		Manufacturing
Structures/airframe	XP	XP		X	XP		P	XP	X	XP	P	Testing
Performance trajectory/G&N	XP	XP	P1**	P	XP	P	P	P	P	P	P	Transportation and ground handling
Aerodynamics	XP	XP	P1	P	P		P	P	P	P		Rollout/on-pad
Thermal loads/ aerodynamic heating	XP	XP	P1	XP	P	P	P	P	P	P		Prelaunch/DOL countdown
Control	XP	XP	P1	P2***	XP	P	P	P		XP		Lift-off/ascent
Loads	XP	XP			P	P		P	XP	XP		Stages recovery/fly back and RTLS/TAL/AOA†
Avionics	P	P	X	X	XP	P	X	P		XP		Flight
Materials	X	XP	XP	XP3††	X		X	X	X	X		Orbital
Electrical power	P	P	X		XP	X		XP		P		Descent
Optics	P	XP	XP1	XP	XP	P	XP	P	P			Landing
Thermal control	P	XP	P1	XP	P		P	XP	P	P		Postlanding
Telemetry, tracking, and communication	P	XP	XP1	P	XP	XP	P	XP	P	XP	P	Ferry/transportation
	P				P		P	P		P	P	Facilities/support equipment
	P	P	P1		P		P	P			P	Refurbishment
Mission operations	XP	XP	XP1	XP	XP	X	XP	XP	X	XP	XP	Storage

*May include either ground wind or ascent wind models; **P1 – May also include environmental parameters of blowing sand or dust, atmospheric contaminants, salt air, salt water, and fungi; ***P2 – May also include ice or frost formation with possible impact on craft. †RTLS = Return to Launch Site; TAL = Transatlantic Landing; AOA = Abort Once Around. ††P3 – May also include albedo, electro-radiation, meteoroids, and space debris.

In turn, a vehicle's NE operational capabilities resulting from the design determine the NE constraints and flight opportunities for tests and operations. Although the terrestrial environment is the major natural environmental driver for a launch vehicle, the space environment above 56 nmi (90 km) for all LVs that go into orbit must be considered. The orbital phase includes exposure to space environmental phenomena such as atomic oxygen, atmospheric density, ionizing radiation, plasma, magnetic fields, meteoroids, and man-made orbital debris. Ionizing radiation is a consideration even for vehicle elements that do not reach orbit.

MANAGING THE EFFECTS OF THE NATURAL ENVIRONMENT ON THE LAUNCH VEHICLE

DEVELOPMENT PROCESS

Three important factors dominate the management of the NE role in LV development:

1. A launch vehicle is designed for specific purposes with specific operational capabilities. The differences from prior vehicles are often significant, so that new design trade-offs against the NE are necessary. If the shortcut of adapting NE design criteria from a prior program is taken, the new vehicle may have many of the same NE operational constraints as the old.
2. Natural environment parameters – wind, temperature, and other atmospheric parameters – will, on rare occasions, reach values outside the NE limits set for the design and operation of any vehicle. Thus, selecting proper NE criteria always involves the evaluation and acceptance of NE risk for the characteristics of the vehicle in question. This type of risk is managed by developing robustness within the design, by operational controls, and by accepting NE operational constraints.
3. The NE influences the entire vehicle and ground operations system, and mitigating its effects usually involves trades and compromises among several vehicle subsystems or compromises in vehicle operability. Thus, within the project office, NE issues are primarily within the domain of the lead systems engineer. This engineer should follow the process in Table 2 to ensure that all NE phenomena and issues are addressed in the design phase and appropriate NE design criteria are established to ensure the required LV operational capability relative to the NE.

Table 2. The process* of bringing inputs from the NE into LV development.

Step	Considerations and comments
1. Determine the mission statement or profile	After established, the NE team can consider the initial NE criteria
2. Initiate the NE model and statistical database selection process	NE team obtains and analyzes the NE databases pertaining to mission profile (site, trajectory, flight frequency, etc.)
3. Define preliminary, mission-focused NE inputs for the first concept cycle through interactions between the NE team and project engineering (and management)	Preliminary NE criteria provided to engineering for initial engineering studies and trades
4. Continue (iterate) NE interaction with engineering in developing program baseline NE definitions with the ultimate goal of arriving at a set of final NE design requirements that complete the mission model and vehicle concept, given proper risk analysis	Engineering feedback to NE team will enhance the exactness of NE design criteria to use
5. Document the final NE design requirements in a Natural Environment Design Criteria document	Project management (in collaboration with the NE team) to prepare controlled documentation of NE design criteria

*After establishing the project office and NE team connection, and the NE team/engineering working group.

Design teams should follow these steps to ensure the LV will withstand the required NE influences from the time it leaves the manufacturing plant until it injects the payload into orbit (expendable LV) or returns safely to the landing site (reusable).

THE FLOW OF THE PROCESS FOR DETERMINING NATURAL ENVIRONMENT DESIGN CRITERIA

Figure 1 is a block diagram illustrating the flow of the process within a program involving NE-related work and inputs during the formulation phase for the design, development, and operations of a new LV. However, before beginning this NE process, a connection with the project office personnel needs to be made to develop an effective team involving management, engineering, and the NE personnel. Since NE design criteria are needed in the first cycle of the vehicle concept development process, and, because the NE interaction helps determine the feasibility of the basic vehicle concept, the NE team should be an integral part of the design team and coordinate with the project to begin work as near program inception as possible. Noted is that perhaps 80% of the total natural environmental definition effort and inputs should occur during the vehicle formulation phase. The obvious reason for the early start is that the environmental definition and conceptual definition must occur simultaneously to evolve a credible LV with minimal operational constraints due to the NE.

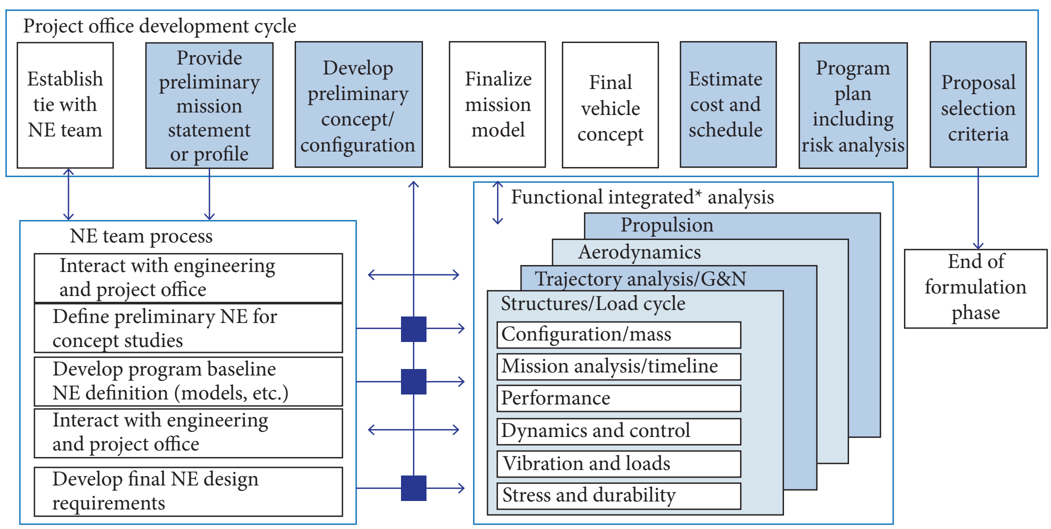

Figure 1. Concept development for launch vehicles showing the role the NE team plays in the development of engineering systems in the project cycle. *Can also include control, thermal, avionics, and materials.

Establishing a technical NE team should occur very early in the project development process, because they need to provide NE straw-man criteria (terrestrial and space environmental data drawn from generic sources but specific to a launch site) to support the first concept design cycle relative to the mission requirements. The NE single point of contact is responsible for all NE criteria and their interpretation within the program. This person is responsible to provide coordinated and consistent NE inputs across the program lifetime, and over all phases of the vehicle's mission profile. Without this control, different NE values or models could be used with results costly in money and time. This control of NE inputs is particularly important where the vehicle design involves diverse groups (even international). All engineering design areas (systems and subsystems) should be using the same NE (design requirement) inputs. After these two initial procedures are in place, the NE flow process can proceed as follows.

Vehicle and Mission Profile Needed to Select Natural Environment Databases and Develop Preliminary Natural Environment Inputs

Steps (1) to (3) of the NE design process (Table 2) involve a successive series of iterations, through which the NE team becomes familiar with the desired, but evolving, operational capabilities, flight and mission profiles, vehicle systems and their capabilities, and every aspect of the mission for which the LV is being developed. The NE team can then develop successively refined specific definitions of the terrestrial and space environments to use in vehicle design and tune them to ensure the desired operational capability of the LV within the defined (or desired) design risk level.

Mature Natural Environment with Engineering Trades and Document

The vehicle engineering team evaluates the LV's response to the evolving NE design criteria to ensure an acceptable design exists relative to the vehicle's desired operational requirements (step (4) of Table 2). Because they interact with the conceptual design's operability, risk, and launch site requirements, the NE criteria must evolve very quickly away from the preliminary focused mission and toward a very specific set of terrestrial environmental design criteria to be applied to the new vehicle's design. This evolution occurs simultaneously with and is part of the repeated cycles that refine the vehicle concept. The process involves most, if not all, of a vehicle's subsystems. In the final step of the process (step (5) of Table 2), the team specifies the refined NE criteria in a controlled document that becomes part of the System Requirements Definition. In the next section, the programmatic steps for determining NE criteria in a new LV program are discussed. If these NE design criteria are not considered or implemented, the vehicle program may be significantly constrained from an operability perspective.

DATA SOURCES AND CONSIDERATIONS FOR DEVELOPING NATURAL ENVIRONMENT CRITERIA

Over the last 50 years, NASA Marshall Space Flight Center (MSFC) has provided general and specific NE criteria for designing and developing various NASA (and joint NASA/Department of Defense (DoD)) projects and vehicles. Johnson (2008), Pearson *et al.* (1996), Smith and Adelfang (1998), Smith *et al.* (1982), Vaughan and Brown (1983), Von Braun (1967) and Potter (1984) document various terrestrial environment (0 to 49 nmi (0 to 90 km) altitude) guidelines for engineering to use (with the proper interpretation) when starting a new project such as a launch or space vehicle. In particular, Johnson (2008) compiled a great amount of general guideline criteria for the terrestrial environment that have been used in many NASA and other organization's aerospace vehicle programs (Vaughan and Johnson 2013; 2014). Similarly, Anderson and Smith (1994) document design guidelines for the general space environment (>49 nmi (>90 km) altitude). However, in most instances, very specific NEs need to be generated or tailored to meet a vehicle's design requirements. Usually, these specific natural environments are created for a project's controlled requirements (or specifications) document. References Smith and Adelfang (1988), Geissler (1970), Leslie and Justus (2008), Adelfang *et al.* (1994), Johnson Space Center (1998), Johnson (1994), Justus *et al.* (1990), Adelfang and Smith (1998), and Smith and Austin (1983) give representative examples of these terrestrial and space environments.

The relationship and interaction between the NE parameters and the various engineering systems and elements are important. Various references (Johnson 2008; Pearson *et al.* 1996; Ryan *et al.* 1996; Ryan 1992; 1996; Blair *et al.* 2001; Carter and Brown 1974) identify these relationships, and Table 1 summarizes them. A series of over 100 NASA Space Vehicle Design Criteria monographs published in the late 1960s and 1970s under the NASA SP-8000 series is available online from NASA (NASA n.d.). These SP-8000 series documents are regarded as guides to design but not as design requirements. They contain various engineering criteria, along with terrestrial, space, and planetary criteria.

Theoretical Natural Environment Product Considerations

Because, in some cases, the measurements of some natural environmental parameters are not as extensive as desired, it is believed that theoretical model estimates of environmental values can be more representative in design use than those indicated by empirical distributions from relatively short periods of record. Thus, theoretical values are given considerable weight in selecting extreme values (or other percentiles) for some parameters such as peak surface wind speed. However, caution should be exercised when interpreting these theoretical percentiles as design requirements in LV studies, to ensure consistency with physical reality and to the specific design and operational problems.

Severe Weather Impact Considerations

Launch vehicles are not designed for launch and flight in severe weather conditions, such as hurricanes, thunderstorms, microbursts, downbursts, and squalls. Natural environmental phenomena associated with severe weather that may be hazardous to a launch vehicle (or in ground processes) include strong, steady-state ground and in-flight winds, strong wind shears and gusts, turbulence, hail and icing conditions, and electrical activity. These adverse weather conditions should be factored into the vehicle's launch constraints and design risk requirements and specifications if the vehicle may fly through them, or may be exposed to these environments during rollout or while on the launch pad.

Induced Environment Considerations

Induced environments (vehicle caused) may be more critical than terrestrial environments for certain LV operations. In some cases, the combination of natural and induced environments will be more severe than either environment alone. The LV design criteria documents should be consulted for data on induced environments.

SCHEDULE CONSIDERATIONS

Natural Environment Databases Needed Early

Vehicle design engineers need various NE criteria early in the concept development phase for any proposed launch and landing sites and along the proposed flight trajectories. If the required NE databases needed to develop these criteria are not available in the archives, instrumentation must be installed and measurements taken over a substantial period. This data collection, then, may result in the delay of adequate NE design criteria definition for the formulation design phase, and also affect the program's vehicle risk analysis.

Natural Environment Mission Analyses Needed Early

Early on, atmospheric mission analysis calculations regarding mission planning purposes for the proposed launch site (and landing site) are also needed. This probabilistic method of using numerous threshold values for NE parameters (constraints) helps to determine the total system operability. This process can also be used to validate the NE design criteria and a vehicle's operational capabilities relative to risks, for example, of launch delay.

Common Natural Environment Inputs Needed for Procurement Process

Natural environments criteria drive costs and operational capability for a launch vehicle. Thus, a uniform set of NE design criteria prior to any competitive procurement is required in order to provide a common baseline and level playing field for the proposal development process.

DOCUMENT THE NATURAL ENVIRONMENT DESIGN CRITERIA

Because the description of NE parameters and models may be complex, designers may require a substantial NE document that is intimately linked with the top-level operability, risk, and system capability requirements. A vehicle cannot meet these design requirements unless the concept and ultimately, the design, are fitted to a properly selected set of NE criteria.

Thus, the usual practice on major space vehicle programs, which includes any LV, is to specify the NE parameters in a separate controlled document or subdocument called Natural Environment Design Criteria.

These NE criteria are then incorporated into the System Requirements Definition (SRD) as an applicable document, issued under signature of the program manager and baselined as part of the controlled Program Definition and Requirements documentation.

This approach works quite well, as long as the NE design criteria are complete and provide only one set of parameters and models for each application, maintained under technical NE configuration control. This will help ensure proper and consistent NE inputs in all phases of the vehicle's development program.

In general, a terrestrial environment requirements document does not specify how the designer should use the NE criteria in regard to the designer-specific, LV characteristics.

Natural environment specifications are established only in collaboration with the NE Team Lead and through specific NE analysis involving study of a particular design problem.

NATURAL ENVIRONMENT CRITERIA AND PRODUCTS FOR APPLICATIONS IN VEHICLE ENGINEERING DESIGN

Thus far, our discussion has centered on the philosophy for developing the NE design criteria and the concurrent close interaction with the concept development engineering activities. Next, how NE parameters and models are selected is discussed. This process must consider all phases of a vehicle's lifecycle: prelaunch preparation activities, launch, on-orbit, reentry, landing, and post- landing. Table 3 identifies those NE areas of greatest concern in a new LV program. This table gives the engineering team more details on which major systems the NE affects, and which engineering parameters receive the most effect. Note that Table 3 is not inclusive of all NE and engineering relationships. There are other minor vehicle elements or engineering parameters relating to the various NE parameters, which are not included here. The engineering team should review this information when they first survey an LV project, because it provides a reference for the terrestrial environment specialist and others on the design team.

In addition to the information in Table 3, one must be aware of the NE-related material typically found in the Launch Commit Criteria (LCC) associated with the various ranges. Vandenberg Air Force Base (VAFB) lists various critical weather constraints pertaining to prelaunch and to day-of-launch (DOL) activities for the DoD's Athena, Atlas, Delta, Minuteman, Multi Service Launch System (MSLS), Peacekeeper, Pegasus, Taurus, and Titan LVs. Thunderstorms, surface winds, and temperatures are the main terrestrial parameters of interest during prelaunch. On the DOL, solar conditions, surface winds, cross winds, turbulence, takeoff and landing minimums, surface temperature, precipitation, upper-level winds (surface to 80,000 ft (24,384 m)), and wind shear (30,000 to 45,000 ft (9144 to 13,716 m)) are key parametric examples. The exact terrestrial environmental conditions (weather constraints) may vary depending on the vehicle and its configuration or mission profile. See DeSordi (2000) for more details.

NATURAL ENVIRONMENT TEAM PRODUCTS

Natural Environment Design Criteria Document

The NE Design Criteria document is the key NE product supporting vehicle design and development. This document must address all phases of vehicle operations and flight: prelaunch (evaluation of launch preparations and on-pad stay), launch and ascent (structures and control systems, tower clearance, and other launch hardware and activities), return to launch site, abort once around, booster recovery (land or sea), in flight, on-orbit (for systems and crew protection), descent and landing, post landing, and return to launch site. This document must also be tailored through a process of many iterations to the overall design risks or operational capabilities of a vehicle. Because the program generally has poor concept definitions at the beginning of the process, generic or synthetic descriptions of the NE are given first. Then the processes of design iterations, mission analysis, and NE data analysis evolve the final NE design criteria that match the program's mission goals and operational needs.

The NE design criteria and the associated design requirements that are entered into the system specification document are the primary formal products of the design formulation phase. However, several other important NE products – also the result of the many iteration processes – play an important part in the concept formulation process, even though they may not always find their way into formal program documentation. The following NE products should be considered in any NE design application.

Mission Analysis for Natural Environments

Mission analysis for NE is a time-dependent, statistical analysis of launch and landing go/no-go frequency, based on actual or assumed weather-related vehicle and range safety constraints. The analysis develops a picture of operational delay risks for vehicle operations caused by the surface-observed, NE parameters. In the vehicle concept formulation phase, the engineering team uses the mission analysis results to identify the important terrestrial environment constraints and vehicle soft spots, and carry them into trade studies of how best to mitigate their effects. Results can also serve as a basis for evaluating the operations portion of full lifecycle costs. Eventually, these results support the assertion that the vehicle concept is sufficiently robust that they can expect it to meet its performance goals. Usually, the results are provided informally on an ongoing basis as charts or white papers based on the various trades and iterations.

Table 3. Various terrestrial environment effects on mission phases, vehicle elements, and engineering parameters.

Atmospheric parameters	Effects on		
	Mission phases	Vehicle or launch elements	Engineering parameters
Most atmospheric parameters	Mission planning	Most	Most
Ground winds	Prelaunch (& on pad)	Loading on erect vehicle and supporting structures	Vehicle loads
–	–	Shield vehicle from flying debris (from high winds)	Shield design
–	–	Vehicle vortex shedding vibration	Damper design
Lightning	Prelaunch	Vehicle integrity (damage)	Avionics/structure
Precipitation	–	Materials (TPS)	Structural design
Temperature	–	SRB (fuel temperature-PMBT)	Propellant and engine performance
Solar UV radiation	–	Vehicle unequal bending	Vehicle/structure loads
Ground winds	Launch	In design of vehicle with supporting structure	Vehicle deflection
–	–	Vehicle vortex shedding vibration	Vehicle dynamics
–	–	Vehicle twang loading	Vehicle dynamics & design
–	–	Tower clearance	Vehicle drift
Severe weather	–	Lightning and wind problems from thunderstorms or hurricanes	Avionics/ structure
Visibility and clouds	–	Countdown delay	Mission/schedule delay
Triggered lightning	–	Strike rising vehicle	Avionics/control/structure
Wind aloft; gust & wind shear	In-flight (boost)	Trajectory shaping	Vehicle trajectory
–	–	Structural loading	Vehicle structures and GN&C description
–	–	Bending moments (forces)	Vehicle structures and GN&C description
Atmospheric model (ρ vs. altitude)	–	Launch aerodynamic heating	Vehicle trajectory shaping
Winds aloft	Booster (flyback) & orbiter (RTLS, TAL)	Vehicle wind loads	Vehicle design
Atmospheric models	Booster (flyback)	Aerodynamic heating	Vehicle trajectory shaping
Sea state	Booster recovery	Rough seas on booster recovery & boat	Structure
Winds aloft and atmospheric models (ρ vs. altitude)	Staging	Bending moments/aerodynamic heating	Vehicle loads/structure integrity/ materials
(See orbital section)*	Orbital	(See orbital section)*	(See orbital section)*
Atmospheric model (ρ vs. altitude)	Orbiter return	Reentry aerodynamic heating	TPS description (ablative)
Atmospheric model (ρ extremes/envelope)	Orbiter return	Reentry aerodynamic heating	TPS design (reradiative); performance
Avoidance of severe winds	Descent and landing	Forecast and monitor aloft and surface winds	Vehicle design/trajectory
Triggered lightning	–	Strike descending vehicle	Avionics/control/structure
Atmospheric model (ρ perturbations)	–	Control, fuel	Vehicle weight/trajectory
Winds aloft	Ferry	Vehicle wind loads	Vehicle design
Severe weather	–	Vehicle integrity	Avionics/structure

*The orbital section will be presented in Paper #2 of this 3 part series'.

In addition, two formal project office documents can use this information: the Concept of Operations Description and the Design Risk Description. For terrestrial environment extremes, there is no known physical upper or lower bound, except for certain environmental conditions, e.g., wind speed does have a strict physical lower bound of zero. Essentially all observed extreme conditions have a finite probability of being exceeded. Consequently, terrestrial environment extremes for design must be accepted with the knowledge that some risk exists of the values being exceeded. Consult Smith *et al.* (1982) for more details concerning the application of the Atmospheric Parametric Risk Analysis (APRA) program in mission planning studies.

Natural Environment Wind and Atmospheric Models

Design engineering should focus on wind, thermodynamic, and other terrestrial environment parameters and phenomena in the initial design of any LV, whether they are considering its situation on the ground, in ascent, or upon return. This section presents and describes these various NE effects and the models engineers need to consider in basic LV design studies.

As an example, a set of idealized or synthetic ground and in-flight wind models that characterize such features as wind magnitude versus height, gust factors, turbulence spectra and wind shear phenomena, and vector properties of winds (as winds are normally the driving atmospheric parameter in vehicle design) must be established. See the second part of this paper for vector wind profile model applications (Smith 1976). Later, when adequate vehicle response data are available, simulation of the vehicle's ascent flight and response through high-resolution wind velocity profiles containing an adequate frequency content of gusts, turbulence, embedded jets, and extreme shears to encompass the vehicle's significant frequencies of response (control mode frequencies, first bending mode frequency, liquid propellant slosh modes, and similar frequencies) to these winds is made. This approach also verifies the LV's structural and control system design. The current acceptable practice uses a selection of detailed in-flight wind profiles (resolution to about one cycle per 656 ft (200 m)) obtained by the FPS-16 Radar and Jimsphere balloon measurement technique for the launch site (Vaughan and Johnson 2013). Using anything short of this suggested approach would correspond to the use of some other preliminary design approximation of the NE.

Wind Models. Winds dominate natural environmental factors in the structural and control system design of a launch vehicle, which must withstand various wind forces (steady state versus extreme speed, directional changes, loading, gusts, turbulence, and vertical shear effects). These forces apply to the vehicle on the ground, i.e., enroute to the launch pad, on the launch pad, and in the launch position, and during flight, i.e., ascent, flight, orbit, reentry, landing, and ferry-back.

Table 1 summarized the various wind parameter effects for each mission phase (P) and for various vehicle and launch system elements (X). The exact details including statistics and models of ground winds, winds aloft, and the other terrestrial environment parameters need to be determined by the NE team and presented to the project engineering team – all depending on the required vehicle and mission characteristics. More detail concerning the application of winds as design input criteria for an LV's ascent, flight, and descent is given in the third part of this paper. In considering wind loads and effects, the following definitions hold:

- Steady wind load – wind acts on a vehicle with a constant force
- Turbulence or gust wind load – superimposes varying forces upon the steady wind load
- Vortex shedding – wind phenomenon on a vehicle that creates alternating downwind eddies, thereby exerting cyclic bending forces (base bending moment or vibration) on the vehicle
- Twang loading – wind effect experienced during the base hold-down release to free mode at lift-off.

Atmospheric Models. Atmospheric models contain thermodynamic parameters of atmospheric temperature, pressure, density, and moisture and are also used as input in a vehicle's design analyses. Atmospheric density (ρ) plays a critical role in a vehicle's aerodynamic heating, affecting trajectory, thermal protection system (TPS), and fuel-budgeting studies. Table 1 also presented a summary of the thermodynamic atmospheric parameters and models as a function of mission profile for the various engineering elements and parameters affected.

Range Reference Atmospheres. The engineering team can use Range Reference Atmospheres (RRAs) for the thermodynamic parameters of the atmosphere in DOL flight simulation programs for a launch vehicle. Measured thermodynamic properties aloft made by radiosonde balloon systems, or a standard or reference atmosphere may also be used in the analyses (Johnson 2008; Leslie and Justus 2008; AIAA 2009; Range Commander's Council 1983; US Government 1976; Rawlins *et al.* 2000). Both methods are based on measured data, with the latter being based on climatology. Because atmospheric density is an important parameter in flight simulation studies, and because it varies considerably with location and climatological conditions, recommendation is made to use RRAs developed for the specific launch location rather than the US Standard 1976 (US76) Atmosphere. To date, 29 RRAs in general use have been constructed, most being published at the Range Commanders Council – Meteorological Group. They contain monthly atmospheric thermodynamic and wind parameters (mean and variability) from the surface to either 16 nmi (30 km) or 38 nmi (70 km) altitude for the following global locations: Argentia, Newfoundland, Canada; Ascension Island, South Atlantic; Barking Sands, Hawaii; Cape Canaveral, Florida; China Lake, California; Dugway Proving Ground, Utah; Edwards AFB, California; Eglin AFB, Florida; Eniwetok, Marshall Islands, Pacific; Fairbanks, Alaska; Fort Churchill, Canada; Fort Greeley, Alaska; Fort Huachuca, Arizona; Johnston Island, Pacific; Kwajalein, Marshall Islands, Pacific; Lihue Kauai, Hawaii; Nellis AFB, Nevada; Point Arguello, California; Point Mugu, California; Roosevelt Roads, Puerto Rico; Shemya, Alaska; Taguac, Guam, Pacific; Thule, Greenland; Vandenberg AFB, California; Wake Island Pacific; Wallops Island, Virginia; White Sands, New Mexico; Yuma PG, Arizona Kodiak, Alaska.

Global Reference Atmospheric Model. In most instances, various model atmospheres for thermodynamic parameter needs, by vehicle designers, range from a general US Standard Atmosphere (US Government 1976) to the more specific range-type Reference Atmospheres (Range Commander's Council 1983) mentioned above. However, the NASA MSFC Global Reference Atmospheric Model (GRAM) was originally developed for the Shuttle program mainly for various reentry calculations (Leslie and Justus 2008). GRAM-07 (currently been updated to 'Earth-GRAM 2016, Version 2.0') gives global coverage in three dimensions plus time (by month) (GRAM-07 2016). It presents a monthly mean and variability (σ about the monthly mean) of the thermodynamic parameters (atmospheric temperature, pressure, and density) and winds for a location (vertical profile) or along any given vehicle trajectory.

A Monte Carlo-type calculation can also be obtained from GRAM in that it can generate numerous realistic atmospheric profiles for design or for verification studies. When engineering design calculations involve using the atmosphere above 49 nmi (90 km) altitude in the orbital space environment, the GRAM can be used with the inputs of mean and extreme 10.7-cm solar flux ($F_{10.7}$) values and geomagnetic activity indices (a_p) (unitless), as given in Table 4.

Shown in Table 4 is the solar flux and geomagnetic activity levels above 49 nmi – 90 km – altitude for use in either spacecraft lifetime or in space craft control studies, because the atmospheric parameters do vary with solar and geomagnetic influences at these thermospheric altitudes. $F_{10.7}$ is the 10.7 cm (4.2-in) wavelength solar flux in units of 10-22 W/m^2/cycles/s.

Below ≈49 nmi (≈90 km) altitude, the atmospheric thermodynamic parameters are not driven by solar or geomagnetic influences, so there is no need to consider or use the inputs of $F_{10.7}$ or a_p values at these lower altitudes. The GRAM program automatically accepts the three solar and geomagnetic inputs (from Table 4) for altitudes > 49 nm (> 90 km) and computes resultant atmospheric temperatures, densities, etc., for use in design. The JB2006 and Marshall Engineering Thermospheric (MET) models are installed within GRAM-07 for orbital calculations. The higher the values of solar flux or geomagnetic activity, the greater will be the magnitudes of the calculated thermospheric temperature and density. These parameters then play a part in vehicle lifetime or in control studies. Johnson (2008) and the American Institute of Aeronautics and Astronautics (AIAA) (2009) Guide to Reference and Standard Atmosphere Models are two good references that summarize the various atmospheric models. MSFC has a website for current solar activity and solar cycle predictions (Dunbar and Graybeal n.d.). Johnson (2008) and the AIAA Guide (2009) present a history of Standard and Reference Atmospheres, including GRAM.

Atmospheres for Reentry and Landing Environments. The reentry and landing natural environments for a space vehicle in the engineering design cycle must be developed for a vehicle or for a landing component, because various extreme NE conditions can exist while landing. Atmospheric density and wind magnitudes, along with their perturbations, can immediately affect the vehicle's structure, control, and the TPS integrity. Similarly, terrestrial environment elements such as visibility, fog, cloud cover, icing, precipitation, sonic boom, and potential triggered lightning (lightning from within a thunderstorm cloud or to the ground, as well as from rare sprite (luminous discharges) occurrences propagating from cloud tops to the ionosphere at ≈43 nmi (≈80 km) altitude) must be considered. If the landing is at sea, then sea state is important. If the landing is on land, surface winds, cross winds, and headwind reversals can be involved.

Table 4. Solar flux and geomagnetic index inputs for use in the GRAM and the MET model.

Solar cycle	162-day mean $F_{10.7}$ solar flux	Daily $F_{10.7}$ solar flux	Three-hourly geomagnetic activity index (a_p)	Local standard time (hr)
For lifetime studies, Use -				
Maximum	244	250	35	1400
Mean	150	150	15	1000
Minimum	70	70	0	0400
For control studies, Use -				
Maximum	250	250	400	1400
Mean	150	150	15	1000
Minimum	70	70	0	0400

The engineering team evaluates and avoids sonic boom formation in determining the reentry trajectory. The TPS materials may also be very sensitive to cloud droplets (liquid or ice particles) during deorbit and reentry. High-altitude (≈46 nmi (≈85 km)) noctilucent or polar mesospheric clouds, and lower altitude (≈14.5 nmi (≈25 km)) nacreous or polar stratospheric clouds, can exist in the Northern Hemispheric summer at high latitudes, well above the conventional cloud decks. For a space vehicle to land safely, other NE areas also need to be added into vehicle design and into mission planning. If a potential landing site has extensive cloud cover, fog occurrence, reduced visibility, or potential precipitation or lightning, it might be advisable to consider another landing site. However, the APRA program can compute the probability of go or no-go, given any or all of these various terrestrial environment threshold conditions. The APRA program is recommended for site selection or in mission planning (Johnson 2008). Table 3 included some landing environments.

Atmospheric Density and Wind Perturbations. Atmospheric density and wind, which are related in the real atmosphere, form atmospheric perturbations, but are usually treated as separate items in vehicle design analyses. For wind, the perturbations involve discrete gusts, shear, and turbulence inputs. However, GRAM can treat the two as one perturbation.

Because atmospheric density is the main driver in aerodynamic heating during reentry and return to Earth, TPS materials will be in contact with varying atmospheric density throughout that reentry regime. Also, discrete, sharp, atmospheric density gradient steps, commonly called "pot holes in the sky", can abruptly affect a reentering vehicle. Density perturbations and wind turbulence influence structures (loads), guidance, navigation, and control (GN&C), TPS, and fuel-budgeting calculations. The GRAM is recommended for calculating the monthly mean and variability of these wind and thermodynamic parameters for reentry and landing. Design studies also include density altitude (atmospheric density adjusted for nonstandard temperature), as well as runway surface winds and turbulence.

CONCLUSION

Any new launch vehicle program or project should consider, early in its development stages, the NE (Terrestrial & Space) guideline applications suggested in this paper. A better understanding and application of the NE and its effect on launch vehicles will enable engineering and program management to more effectively minimize program risks and costs, optimize design quality, and successfully achieve mission objectives. The 2008 Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development (Johnson 2008) provides more detailed terrestrial environment statistics, databases, models, recommendations, etc., for use in the mission planning, design, development, trades, testing, and launch of aerospace vehicles. Two future papers will continue this subject: entitled "Key Terrestrial and Space Environment Sources" (paper no. 2) and "Wind Environment Interactions Relative to Launch Vehicle Design" (paper no. 3).

AUTHOR'S CONTRIBUTION

Conceptualization, Johnson DL; Methodology, Johnson DL; Investigation, Johnson DL; Writing – Original Draft, Johnson DL; Writing – Review and Editing, Vaughan WW; Resources, Johnson DL and Vaughan WW; Supervision, Johnson DL and Vaughan WW.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Stanley I Adelfang, and (the late) Orvel E Smith (both of Stanley Associates) for their most valuable technical and historical terrestrial environment contributions and support. Also to BJ Anderson Dr. Robert E Smith (NASA retired) for their space environment contributions.

REFERENCES

Adelfang SI, Smith OE (1998) Gust models for launch vehicle ascent. Presented at: 36th AIAA Aerospace Sciences Meeting; Reno, USA. https://doi.org/10.2514/6.1998-747

Adelfang SI, Smith OE, Batts GW (1994) Ascent wind model for launch vehicle design. J Spacecraft and Rockets 31(3):502-508. https://doi.org/10.2514/3.26467

[AIAA] American Institute of Aeronautics and Astronautics (2009) Guide to reference and standard atmospheric models (AIAA G-003C-2009). https://doi.org/10.2514/4.867842.001

Anderson BJ, Smith RE (1994) Natural orbital environment guidelines for use in aerospace vehicle development (TM-4527). NASA Technical Memorandum.

Blair JC, Ryan RS, Schutzenhofer LA, Humphries WR (2001) Launch vehicle design process: characterization, technical integration and lessons learned. (TP-2001-210992). NASA Technical Paper.

Carter EA, Brown SC (1974) Natural environment support guidelines for space shuttle tests and operations. (TM X-64864). NASA Technical Memorandum.

DeSordi SP (2000) Weather impacts to launch operations. Presented at: 8th Conference on Aviation, Range, and Aerospace Meteorology; Dallas, USA.

Dunbar B and Graybeal S (n.d.) Marshall Solar Cicle Forecast. NASA. http://sail.msfc.nasa.gov/nse/solar.html

Geissler ED (1970) Wind effects on launch vehicles. Slough: Technivision Services.

GRAM (2016). Earh-GRAM 2016. NASA. https://software.nasa.gov/featuredsoftware/earth-gram-2016

Johnson DL (1994) National aerospace plane (NASP) X-30 natural environment requirements document (Rev. 1.0). (TM-108451). NASA Technical Memorandum.

Johnson DL (2008) Terrestrial environment (climatic) criteria guidelines for use in aerospace vehicle development, 2008 Revision. (TM-2008-215633). NASA Technical Memorandum.

Johnson Space Center (1998) Natural environment design requirements (space shuttle). Houston: NASA.

Justus CG, Campbell CW, Doubleday MK, Johnson DL (1990) New atmospheric turbulence model for shuttle applications. (TM-4168). NASA Technical Memorandum.

Leslie FW, Justus CG (2008) The NASA MSFC Earth global reference atmospheric model – 2007 Version. (TM—2008–215581). NASA Technical Memorandum.

[NASA] National Aeronautics and Space Administration (n.d.) NASA space vehicle design criteria SP-8000. NASA. http://library.msfc.nasa.gov/cgi-bin/lsp8000>

Pearson SD, Vaughan WW, Batts CW, Jasper GL (1996) Importance of the natural terrestrial environment with regard to advanced launch vehicle design and development. (TM-108511). NASA Technical Memorandum.

Potter AE (1984) Environmental effects of shuttle launch and landing. Presented at: 22nd Aerospace Sciences Meeting; Reno, USA. https://doi.org/10.2514/6.1983-2577

Range Commander's Council (1983) Cape Canaveral Florida – range reference atmosphere 0 to 70-km Altitude. (361-83). RCC Document.

Rawlins MA, Johnson DL, Batts GW (2000) A characterization of the terrestrial environment of Kodiak, Alaska for the design, development, and operation of launch vehicles. Presented at: 9th AMS/AIAA Conference on Aviation, Range and Aerospace Meteorology; Orlando, FL.

Ryan RS (1992) The role of failure/problems in engineering: a commentary on failures experienced—lessons learned. (TP-3213). NASA Technical Paper.

Ryan R, Blair J, Townsend J, Verderaime V (1996) Working on the boundaries: philosophies and practices of the design process. (TP-3642). NASA Technical Paper.

Smith OE (1976) Vector wind and vector wind shear models 0 to 27km altitude for Cape Kennedy, Florida and at Vandenberg AFB, California. (TM-X-73319). NASA Technical Report.

Smith OE, Austin Jr. LD (1983) Space shuttle response to ascent wind profiles. J Guidance, Control and Dynamics 6(5):355-360. https://doi.org/10.2514/3.19842

Smith OE, Adelfang SI (1998) A compendium of wind statistics and models for the NASA space shuttle and other aerospace vehicle programs. (CR-1998-208859). NASA Technical Report.

Smith OE, Batts GW, Willett JA (1982) Atmospheric constraint statistics for the space shuttle mission planning. (TP-2069). NASA Technical Paper.

U.S. Standard Atmosphere (1976). The superintendent of Documents, U.S.Government Printing Office, Washington, DC..

Vaughan WW, Brown SC (1983) Natural environment considerations for shuttle system development support. Presented at: Shuttle Environment and Operations Meeting; Washington, USA. https://doi.org/10.2514/6.1983-2663

Vaughan WW, Johnson DL (2013) Aerospace meteorology: an overview of some key environmental elements. J Aerosp Technol Manag 5(1):7-14. https://doi.org/10.5028/jatm.v5i1.188

Vaughan WW, Johnson DL (2014) Aerospace vehicle development applications of atmospheric thermodynamic inputs. J Aerosp Technol Manag 6(1):7-17. https://doi.org/10.5028/jatm.v6i1.279

Von Braun W (1967) That puzzling problem for space launches–weather. Popular Science 191(3):102-104.