

**THE DEFINITION AND INTERPRETATION OF TERRESTRIAL ENVIRONMENT
DESIGN INPUTS FOR VEHICLE DESIGN CONSIDERATIONS
(Final Version 10/24/05)**

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Abstract

The description and interpretation of the terrestrial environment (0-90 km altitude) is an important driver of aerospace vehicle structural, control, and thermal system design. NASA is currently in the process of reviewing the meteorological information acquired over the past decade and producing an update to the 1993 Terrestrial Environment Guidelines for Aerospace Vehicle Design and Development handbook. This paper addresses the contents of this updated handbook, with special emphasis on new material being included in the areas of atmospheric thermodynamic models, wind dynamics, atmospheric composition, atmospheric electricity, cloud phenomena, atmospheric extremes, sea state, etc. In addition, the respective engineering design elements will be discussed relative to the importance and influence of terrestrial environment inputs that require consideration and interpretation for design applications. Specific lessons learned that have contributed to the advancements made in the acquisition, interpretation, application and awareness of terrestrial environment inputs for aerospace engineering applications are discussed.

Introduction

Atmospheric phenomena play a significant role in the design and operation of aerospace vehicles and in the integrity of the aerospace systems and elements. Terrestrial environment design criteria guidelines are based on statistics and models of atmospheric and climatic phenomena relative to various aerospace design, development, and operational issues.

Aerospace vehicle design guidelines are provided in the handbook for the following environmental phenomena: winds; atmospheric models and thermodynamic properties; thermal radiation; U.S. and world surface extremes; humidity; precipitation, fog, and icing; cloud phenomena and cloud cover models; atmospheric electricity; atmospheric constituents; aerospace vehicle exhaust and toxic chemical release; tornadoes and hurricanes; geologic hazards; and sea state. Information on mission analysis, prelaunch monitoring, and flight evaluation relative to terrestrial environment Inputs is also provided.

In general, the document does not specify how the designer should use the terrestrial environment data in regard to a specific aerospace vehicle design. Such specifications may be established only through analysis and study of a particular vehicle design problem. Although of operational significance, descriptions of some atmospheric conditions have been omitted since they are not of direct concern for an aerospace vehicle system's design, the primary emphasis of this handbook. Induced environments (vehicle caused) may be more critical than the natural environment for certain vehicle operational situations. In some cases, the combination of natural and induced environments will be more severe than either environment alone.

The terrestrial environment criteria guidelines presented in the handbook were formulated based on discussions with and requests from engineers involved in aerospace vehicle development and operations. Therefore, they represent responses to actual engineering problems and not just a general compilation of environmental data. The NASA Centers, various other Government agencies, and their associated

contractors responsible for the design, mission planning, and operational studies use this handbook extensively.

Terrestrial Environment Importance

It is important to recognize the need to define the terrestrial environment very early in the design and development cycle of any aerospace vehicle. This is especially true for a new configuration. Using the desired operational capabilities, launch locations, and flight profiles for the vehicle, specific definitions of the terrestrial environment can be provided which, if the aerospace vehicle is designed to accommodate, will ensure the desired operational capability within the defined design risk level. It is very important that those responsible for the terrestrial environment definitions for the design of an aerospace vehicle have a close working relationship with program management and design engineers. This will ensure that the desired operational capabilities are reflected in the terrestrial environment requirements specified for design of the vehicle.

An aerospace vehicle's response to terrestrial environment design criteria must be carefully evaluated to ensure an acceptable design relative to desired operational requirements. The choice of criteria depends upon the specific launch and landing location(s), vehicle configuration, and expected missions(s). Vehicle design, operation, and flight procedures can be separated into particular categories for proper assessment of environmental influences and impact upon the life history of each vehicle and all associated systems. These include categories such as (1) purpose and concept of the vehicle, (2) preliminary engineering design, (3) structural design, (4) control system design, (5) flight mechanics, orbital mechanics, and performance (trajectory shaping), (6) optimization of design limits regarding the various natural environmental factors, and (7) final assessment of natural environmental capability for launch and flight operations.

Another important matter that must be recognized is the necessity for having a coordinated and consistent set of terrestrial environment requirements for use in a new aerospace vehicle's design and development. This is particularly important where diverse groups are involved in the development, and is of utmost importance for any international endeavor. A "central control point" having responsibility for the definition and interpretation of the terrestrial environment inputs is critical to the successful design and operation of any new aerospace vehicle. Without this control, different terrestrial environment values or models can be used with costly results, in terms of money, time, and vehicle performance. This central control point should also include responsibility for mission analysis, test support requirements, flight evaluation, and operational support relative to terrestrial environment requirements.

During the early stages of a new aerospace vehicle's design and development, tradeoff studies to establish sensitivities of various terrestrial environment-forcing functions are important. Feedback from these studies is key to establishing the necessary terrestrial environment requirements for the vehicle's final design. Including a single source (central control point) responsible for the preliminary design tradeoff study terrestrial environment inputs and their interpretation is important. This will preclude a multitude of problems in the final design and development process, and will enable terrestrial environment requirements to be established with a minimum amount of communications problems and misunderstanding of design issues.

The close association between the design and test engineering groups and those responsible (central control point) for the terrestrial environment inputs is key to the success of the vehicle's development process. This procedure has been followed in many NASA aerospace vehicle developments and is of particular importance for any new aerospace vehicle. Figure 1 illustrates necessary interactions relative to terrestrial environment definition and engineering application. Feedback is critical to the process and ability to produce a viable vehicle design and operational capability.

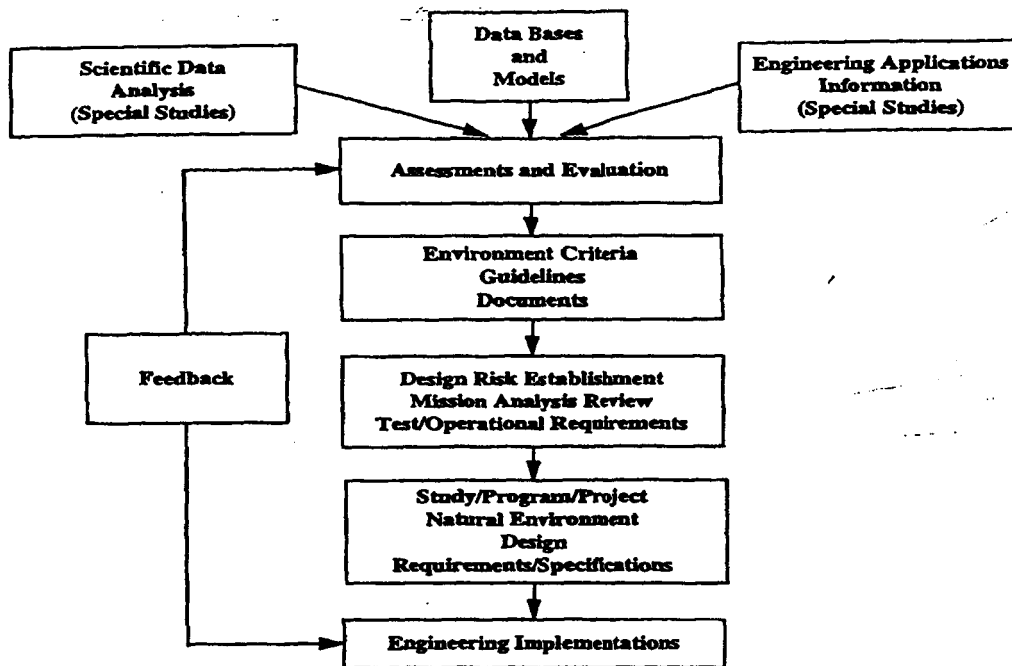


Figure 1. Natural terrestrial environment definition and analysis for aerospace vehicle engineering application.

Finally, although often not considered to be significant, it is of major importance that all new aerospace vehicle design review meetings include a representative from the terrestrial environment group (central control point) assigned to support the program. This will ensure good understanding of design requirements and timely opportunity to incorporate terrestrial environment inputs and interpretations, which are tailored to the desired operational objectives, into the design process. It is also necessary that any proposed deviations from the specified terrestrial environment requirements, including those used in preliminary design tradeoff studies, be approved by the responsible terrestrial environment central control point to ensure that all program elements are using the same baseline inputs. This will also help the program manager understand the operational impact of any change in terrestrial environment requirements before implementation into the design. Otherwise, gross errors and deficiencies in design can result from use of different inputs selected from various diverse sources by those involved in design and other performance studies.

One must remember that the flight profile of any aerospace vehicle includes the terrestrial environment. Terrestrial environment definitions are usually limited to information below 90 km. Thus, all aerospace vehicles' operations will be influenced to some degree by the terrestrial environment with which it interacts. As a result, the definition of the terrestrial environment and its interpretation is one of the key

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aerospace vehicle design and development inputs. This definition is a significant role; e.g., in the areas of structures, control systems, trajectory shaping (performance), aerodynamic heating, and takeoff/landing capabilities. The aerospace vehicle's capabilities which result from the design, in turn, determine the terrestrial environment constraints and flight opportunities for tests and operations.

Terrestrial Environment Issues

For terrestrial environment extremes, there is no known physical upper or lower bound except for certain environmental conditions. For example, 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 used for design must be accepted with the knowledge that there is some risk of the values being exceeded. Since the measurement of many environmental parameters is not as accurate as desired, thereby some theoretical model estimates are believed to be more representative for design use than those indicated by empirical distributions from short periods of record. Therefore, theoretical values have been given considerable weight in selecting extreme values for some parameters; i.e., the peak surface winds. Criteria guidelines are presented for various percentiles based on available data samples. Caution should be exercised in the interpretation of these percentiles in aerospace vehicle studies to ensure consistency with physical reality and the specific design and operational problems of concern.

Aerospace vehicles are not normally designed for launch and flight in severe weather conditions such as hurricanes, thunderstorms, ice storms, and squalls. Environmental parameters associated with severe weather that may be hazardous to aerospace vehicles include strong ground and in-flight winds, strong wind shears and gusts, turbulence, icing conditions, and electrical activity. Terrestrial environment guidelines usually provide information relative to those severe weather characteristics that should be included in design requirements and specifications if required to meet the program's mission operational requirements.

Knowledge of the terrestrial environment is also necessary for establishing test requirements for aerospace vehicles and designing associated support equipment. Such data are required to define the fabrication, storage, transportation, test, and preflight design condition and should be considered for both the whole vehicle system and the components which make up the system. This is one of the uses of guideline data on terrestrial environment conditions for the various major geographic locations applicable to the design of a new vehicle and associated supporting equipment.

The group having the central control point responsibility and authority for terrestrial environment design requirement definition and interpretation must also be in a position to pursue environment input-related applied research studies, engineering assessments, and updates. This is necessary to ensure accurate and timely terrestrial environment inputs tailored to the program's needs. Design engineers and program management that assume they can simply draw on the vast statistical databases and numerous models of the terrestrial environment currently available in the literature, without interpretation and tailoring to specific vehicle design needs, can prove to be a major deterrent to the successful development and operation of an aerospace vehicle.

Although ideally a vehicle design should accommodate all expected operational environment conditions, it is neither economically nor technically feasible to design an aerospace vehicle to withstand all terrestrial environment extremes. For this reason, consideration should be given to protection of vehicles from some extremes. This can be achieved by use of support equipment and specialized forecast personnel to advise on the expected occurrence of critical terrestrial environment conditions. The services of specialized forecast personnel may be very economical in comparison with more expensive vehicle designs that would be necessary to cope with all terrestrial environment possibilities.

The terrestrial environment is a very major environmental driver for an aerospace vehicle's design and is the focus of this handbook. However, the natural environment above 90 km must also be considered for aerospace vehicles. The orbital operating phase of an aerospace vehicle operating includes exposure to the space environment, such as atomic oxygen, atmospheric density, ionizing radiation, plasma, magnetic fields, meteoroids, etc., plus a few man made environments, such as orbital debris. Specific aerospace vehicle terrestrial and space environments design requirements are normally specified in the appropriate vehicle design criteria documentation.

Good engineering judgment must be exercised in the application of terrestrial environment requirements to an aerospace vehicle design analysis. Consideration must be given to the overall vehicle mission and system performance requirements. Knowledge is still lacking on the relationship between some of the terrestrial environment parameters that are required as inputs to the design of aerospace vehicles. Also, interrelationships between vehicle parameters and terrestrial environment variables cannot always be clearly defined. Therefore, a close working relationship and team philosophy must exist between the design and operational engineer and the respective organization's terrestrial environment central control point specialists.

Terrestrial Environment Handbook Content Example

Introduction:

The terrestrial example chosen for this paper is an engineering application that is associated with Section 14 on Sea State. The global sea state wave/wind model chosen as the base model for the Terrestrial Handbooks Section 14 is the 2003 update by Ian Young (Young, 2003) from the 1996 "Atlas of the Oceans: Wind and Wave Climate", by Young and Greg Holland (Young, 1996). The ocean atlas data base was doubled (1985-1995) for the 2003 update. This new model, along with other models and data bases, was utilized to arrive at results for the following example.

Background/Procedure:

The example being illustrated is with regard to a hypothetical manned space vehicle that is launched from Kennedy Space Center (KSC), Florida and then experiences problems during initial ascent which would result in an aborted mission into the Atlantic Ocean along its trajectory. The question being addressed is with respect to what natural environment parameters might exist that would affect the vehicle recovery and/or its crew rescue. For mission planning purposes, what would be the best months or the worst months to launch, with respect to the natural environment, should an abort occur? Waves, wind, sea/air temperature, visibility, clouds and fog are all important terrestrial parameters that need to be considered in planning any spacecraft sea-rescue mission scenario. A typical 51.6 degree inclination orbit, for a vehicle launched from LC39 at KSC was chosen. The ground track is presented graphically in Figure 2.

In order to establish some natural environment design limits for the launch vehicle, wave height, along with sea and air surface temperature maximums and minimums are the key natural environment parameters that will need to be established by the vehicle program. Likewise, the key natural environment parameters which affect survivability and rescue at a given splash down location are: Sea state, (i.e., the height and wavelength of the waves) along with the associated descent/surface winds (speed and direction); sea surface temperature of the water; air temperature at the splash down location; precipitation; visibility/cloud cover (including super cooled stratus and low cumulus, fog and thunderstorms), and, of course, the elapsed time between splash down and crew rescue.

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Calculations along a ground track at approximately every 10 degrees longitude were done producing monthly (or seasonal) natural environment results. The three references (NAVAIR, 1969; NAVAIR, 1971; and NAVAIR, 1978) indicate that the mean percent frequency values were assembled from 'all'

available data and that no diurnal results were calculated. The sea state/wave data along with in-depth discussion of sea temperatures and surface winds were extracted from the four other sources (Young, 1996; Young, 2003; Caires, 2004; and Smith, 1998). The eight north latitude/west longitude ground track sites used in this study were:

<u>Site#</u>	<u>Lat.N/Long.W</u>
1 -	28.5°/80°
2 -	35°/70°
3 -	42°/60°
4 -	47°/50°
5 -	50°/40°
6 -	51.5°/30°
7 -	52°/16°
8 -	51°/4°

Sea State (Waves/Wind):

Since the Young Atlas of 2003 gave only mean monthly wave conditions, we used the C-ERA-40 (Caires, 2004) 30 year period of record (POR) significant wave height 90% quantiles for the worst sea state month (January) over the Atlantic Ocean. This model gave significant wave heights (H_s) between 7 and 8 meters which can extend over the entire north Atlantic between 45° to 65° N lat, and 45° to 5° W long, as shown in figure 3. This is equivalent to a Beaufort wind number of 8 and represents a high sea state (with associated winds of 34 to 40 knots). From the MSFC data Atlas (Young, 2003), the 50 year extreme wave height at the location 50°N, 38°W is 21.9±1.6 meters (71.9±5.2 feet).

From NAVAIR 1969, Gale force winds (winds ≥ 4 knots (17.5 m/s)) representing a Beaufort number of ≥ 8 along the ground track were determined and indicated a percent frequency of 17 to >20% during December/January/February at sites 5 and 6. The summer months May through August presented no Gale problems. Likewise, cold sea surface mean temperatures (of <40°F) prevailed from December through May at site 4 (30°F mean in February). Mean seasonal sea swell height probabilities ≥ 2 feet (≥ 7 m) were given, which indicated that during Fall (November) and Winter (February) the frequency probability ranges from 25 to >30% at sites 5, 6, and 7. Spring (May) and Summer (August) months had probabilities ranging from 15 to >20% at sites 6 and 7.

Sea Surface Temperature:

Using the NOAA NWS Environmental Modeling Center's 30 year normal sea surface temperature data (Smith, 1998) for January (December is about as cold), one can see from figure 4 where in the north Atlantic would give the coldest sea-surface temperatures. January sea temperatures are normally colder than 5°C (41°F) along the flight track over to ~45°W longitude, and do not get any warmer than 10°C (50°F) along its entire Atlantic flight path. The coldest January mean ambient temperatures along the ground track occur in the vicinity of Newfoundland with temperatures near -7°C (20°F). A splashdown of a few hundred miles downrange can make a substantial difference in the normal January sea/air temperatures found near Newfoundland. The sea surface temperature can increase by 13°F if splash down occurs just 500 statute miles (805 km) further downrange.

Air Temperature, Visibility/Clouds, Precipitation Results:

Both the surface air temperature equal to or below freezing ($\leq 0^\circ\text{C}$) along with the occurrence of supercooled stratus/low cumulus and frozen precipitation also peak out in the winter months, especially at the site 4 lat/long location. In January and February there is a 40 percent frequency of occurrence of mean air temperatures being at or below 0°C at this site (35% in March and 22% in December). The other 7 lat/long sites offer less of a probability of occurrence. The percent frequency of supercooled stratus and low cumulus was done by season and indicated a 20% frequency of occurrence in Dec/Jan/Feb

at site 4, with a 15% frequency in Mar/Apr/May also at this site. Sites 3 and 5 gave 15% in Dec/Jan/Mar, as did site 5 in Mar/Apr/May. Total clouds (sky ≥ 8) frequency also peak out to >80% at sites 3 to 5 from Dec through Apr. However, 70 to >80% mean total cloud frequencies also exist for basically all months of the year, for sites 3 through 7. Frozen precipitation occurs at a 15 to 20% frequency from Dec through Feb at site 4, with lesser values at other sites. Mean precipitation tends to occur more frequently in the winter months (Nov thru Mar) with a frequency of 30 to 35% at sites 4 through 7. However, even the warmer months (of April thru October) give a 20 to 30% mean frequency of precipitation occurrence centering around sites 5 thru 7.

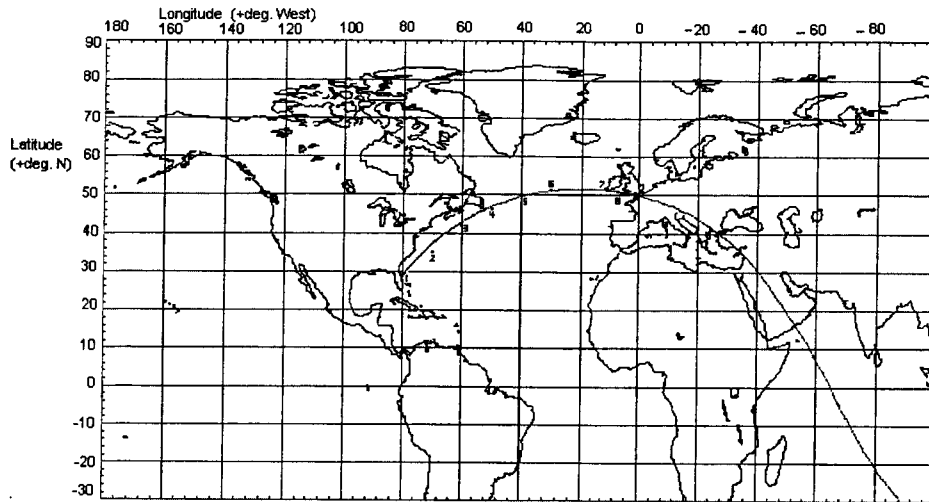


Figure 2. Typical 51.6 degree orbit inclination launch (ground track) from KSC, FL.

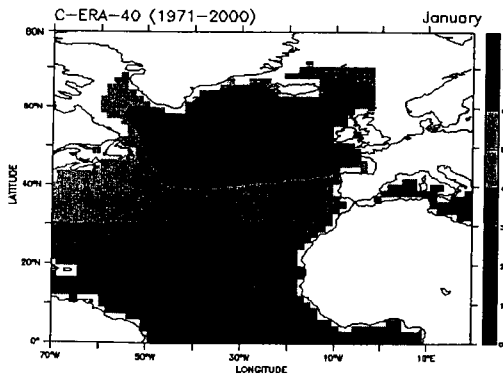


Figure 3. North Atlantic January Significant Wave Height in meters, 90% Quantiles. Cairns (2004)

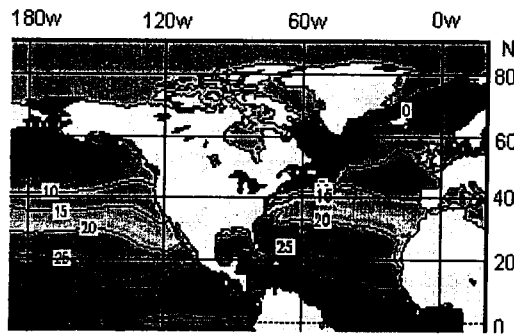


Figure 4. NOAA 1961-1990 January Normal Sea Surface Temperature (°C). Smith (1998)

One Solution: By taking into account that if a winter-time abort situation might arise during initial ascent, the crew vehicle should steer toward the right (or south) to avoid the harsher wave, wind, sea/air temperature conditions that might exist along that initial ground path track. Plan to avoid splashing down near Newfoundland and in the north Atlantic between longitudes 63°W and 40°W. Also, since search and rescue capabilities will vary along the trajectory ground path, possibilities may exist to land the crew in regions which are more accessible for rescue. This could shorten the elapsed time between splash down and crew rescue, thus enhancing survivability.

Fog and Thunderstorm Results:

When considering possible launch abort scenarios, one might think that by just avoiding the winter months (November through March) and only launching between late spring and early fall might be more appropriate with regard to the natural environments influence. However, various other natural environment parameters need to be considered here. The percent frequency of fog in any form and of thunderstorms is higher in the north Atlantic Summer months than in the Winter months. Regarding fog, the site 4 location has the highest frequency percentage of 60% which peaks out in July. The months May through August also offer >40% frequency of occurrence of fog at site 4. Site 3 peaks at 40% in July, while site 5 peaks at 30% in July. The occurrence of fog during the winter months, though less, is between 10 and 20% at site 4. See table 1 which presents the average percentage frequency of fog as a function of the time during that month.

Thunderstorm days were recorded by month, and also peak out during the summer months along this ground track. Site 1 near KSC gives the highest average number of days for thunderstorms with 20 (or a 65% monthly frequency) during June and July, and with 10 to 15 days from May through September. Site 2 is next highest with 7 days in July and August (6 in September and 4 in May and June). Site 3 peaks at 5 in August and 4 in July. The remainder of the northern Atlantic sites offer only 1 or 2 thunderstorm days during any month of the year, except as one nears the British Isles the number increases slightly to 3 in July at site 7 (and 4 at site 8). Table 1 also presents the thunderstorm percentage frequency results along the ground track. This table clearly shows the Summer time maxima for both north Atlantic fog and thunderstorms.

Table 1. North Atlantic Fog and Thunderstorm Percentage Frequencies by Month. (To show the higher frequency during Summer time). * All table values are in percent.

Site No. =	1	2	3	4	5	6	7	8
Lat/Lon =	28.5/80	35/70	42/60	47/50	50/40	51.5/30	52/16	51/4
Month	Fog - TS	Fog - TS	Fog - TS	Fog - TS	Fog - TS	Fog - TS	Fog - TS	Fog - TS
January	3 6.5	3 6.5	4 6.5	>10 3.2	8 3.2	9 6.5	10 6.5	10 3.2
February	3 7.1	4 7.1	6 7.1	>10 3.6	5 3.6	4 7.1	6 7.1	10 <3.6
March	4 13	4 13	7 6.5	11 3.2	9 3.2	10 6.5	10 6.5	>10 3.2
April	4 10	4 10	10 6.7	30 3.3	10 3.3	10 <3.3	5 <3.3	5 3.3
May	3 32	4 13	19 6.5	45 <3.2	15 <3.2	15 <3.2	10 <3.2	>10 6.5
June	2 50	5 13	30 10	50 6.7	20 3.3	20 <3.3	15 <3.3	>10 10
July	1 65	3 23	40 13	60 6.5	30 3.2	30 6.5	18 9.7	10 13
August	1 65	3 23	10 16	>40 6.5	20 6.5	20 6.5	10 6.5	10 9.7
Sept	1 33	3 20	7 10	30 3.3	17 3.3	16 3.3	10 3.3	10 6.7
Oct	1 13	2 9.7	5 6.5	>20 6.5	10 6.5	>10 6.5	10 6.5	10 9.7

Nov	1	10	3	6.7	5	3.3	10	<3.3	10	<3.3	10	6.7	5	<3.3	7	<3.3
Dec	2	6.5	2	6.5	5	3.2	20	3.2	8	<3.2	15	<3.2	10	<3.2	10	<3.2

* - Probabilities >11% are shown in **bold**.

TS – Thunderstorm

Lat – Latitude (N)

Lon – Longitude (W)

Example Summary:

This example has shown that the natural environment parameters do play a part, and do need to be considered, within any vehicle design or mission planning scenario. The Terrestrial Handbook 1001 will provide the engineer or manager with various natural environment statistics, figures, tables, and models that can be utilized in the many engineering vehicle design and development programs.

Terrestrial Environment Areas of Concern

As noted, it is important that the need for definition of the ground, ascent, on-orbit, and descent aerospace vehicle operational terrestrial environments be recognized early in the design and development phase of the vehicle program. Engineering technology is constantly changing. In some cases, the current trends in engineering design have increased vehicle susceptibility to terrestrial environment factors. Based on past experience, the earlier the terrestrial environment central control point specialists become involved in the design process, the less the potential for negative environmental impacts on the program downstream through redesign, operational work-around, etc.

In many cases, it is impossible to clearly define limiting extreme values for a particular terrestrial environment parameter that may occur during the desired operational lifetime of the vehicle. It may not be technically nor economically feasible to design a vehicle to withstand an extreme environment value. However, a lower value may be defined whereby the probability is small that the lower value will occur during the desired operational lifetime of the vehicle. Additional launch delay risks may also be acceptable versus the expense of additional design considerations. Because of these and other considerations, a value less than the extreme may be a more appropriate design requirement. The terrestrial environment specialist has the responsibility to provide the program manager and chief engineer with pertinent information so they can determine the highest risk value that is feasible for the program in that particular environment area. Therefore, it is very important that the aerospace vehicle program manager and the chief engineer have a good understanding of the operational risks due to the selected design terrestrial environment.

The following table 2 provides a reference guide for the terrestrial environment specialist, program management, design engineers, and others on the development team for a new aerospace vehicle program. This information summarizes potential terrestrial environment areas of engineering concern when first surveying a vehicle project. As can be noted from this table, terrestrial environment phenomena may significantly affect multiple areas of an aerospace vehicle's design, and thus operational capabilities, including areas involving structure, control, trajectory shaping (performance), heating, takeoff and landing capabilities, materials, etc. A breakout of typical terrestrial environment concerns with respect to engineering systems and mission phases is shown in the table.

X	Terrestrial Environment Parameter												P	
	Launch Vehicle Systems (Sub-)	Winds & Gusts	Atmospheric Thermodyn	Atmosph Constit	Solar/ Thermal Radiation	Atmosph Electricity	Clouds & Fog	Humidity	Precip or Hall	Sea State	Severe Weather	Geologic Hazzards		Mission Phase
System	X P	X P	X P	X P	X P	X P	X P	X P	X P	X P	X P	X	Mission Analysis	
Propulsion/ Engine Siding	X	X P	P			X		X P			X		Manufacturing	
Structures/ Airframe	X P	X P		X	X P		P	X P	X	X P	P		Testing	
Performance/ Trajectory/G&N	X P	X P	P	P	X P	P	P	P	P	P	P	P	Transport & Ground Hd	
Aerodynamics	X P	X P	P	P	P		P	P	P	P	P		Rollout/On-pad	
Thermal Loads/ Aerodynamic Heat	X P	X P	P	X P	P	P	P	P	P	P	P		Pre-launch DOL ent dn	
Control	X P	X P	P	P	P	X P	P	P	P		X P		Liftoff/ Ascent	
Loads	X P	X P				P	P		P	X P	X P		Stages Recvry	
Avionics		P	P	X	X	X P	P	X	P		X P		Flight	
Materials	X	X P	X P	X P	X P	X		X	X	X	X		Orbital	
Electrical Power		P	P	X		X P	X		X P		P		Descent	
Optics		P	X P	X P	X	P	X P		P	X P	P	P	Landing	
Thermal Control		P	X P	P	X P	P			P	X P	P	P	Post-land	
Telemetry, Tracking & Communication		P	X P	X P	P	X P	X P		P	X P	P	X P	P	Ferry/ Transport
		P				P			P	P			P	Facil/spt Eq
		P	P	P		P			P	P			P	Refurbishmt
Mission Operations	X P	X P	X P	X P	X P	X P	X	X	X P	X P	X	X P	X P	Storage

Table 2. Natural terrestrial environments and aerospace vehicle development areas of concern.

Some Lessons Learned

The Marshall Space Flight Center Natural Environments Branch and its predecessor organizations have over forty five years experience in the development and interpretation of terrestrial environment requirements for use in the design and operation of aerospace vehicles. During this period, a large number of "lessons learned" have produced the basis for the contents of this handbook. A few of these lessons learned are summarized in the following list:

(1) Title: Wind Vectors Versus Engineering Vector Conventions

- Background. Flight mechanics use of wind vectors and conventional meteorological usage. In case of flight mechanics, vector is stated relative to direction force is being applied. However, for meteorology, the wind vector is stated relative to direction from which wind force is coming.
- Lesson. The proper interpretation and application of wind vectors is important to avoid a 180° error in structural loads and control system response calculations.

(2) Title: Design Requirements, Not Climatology

- Background. While based on climatology and models, both physical and statistical, natural environment requirements are part of the overall vehicle design effort necessary to ensure mission operational requirements are met. Thus, they must be selected and defined on this

basis. Simply making reference to climatologically databases will not produce the desired vehicle performance.

- Lesson. Members of the natural environments group assigned as the control point for inputs to a program must also be part of the vehicle design team and participate in all reviews, etc. to ensure proper interpretation and application of natural environment definitions/requirements relative to overall vehicle design needs.

(3) Title: Early Input of Natural Environment Requirements Based on Interpretation of Mission Purpose and Operational Expectations

- Background. Need to develop natural environment definitions and requirements for a program as soon as possible after one has the level one requirements for the program's mission. Thus, all concerned with the development will have common base with associated control on changes made to natural environment definitions/requirements and associated vehicle operational impacts.
- Lesson. The definition of the natural environment requirements for a vehicle that are necessary to meet the mission requirements is important for all concerned with the program. This provides visibility to all, especially program manager and systems engineers, relative to impact on the operation of vehicle and to natural environment design requirements on the program's mission.

(4) Title: Consistent Input for all Users More Important for Trade-Off and Design Studies than Different Inputs within the Noise Level of Knowledge on Natural Environment Topic

- Background. The natural environment is one of the key drivers for much of the design efforts on an aerospace vehicle's thermal, structural, and materials control. Variations in natural environment inputs used by different design groups can mask critical engineering design inputs if not avoided by consistent and coordinated natural environmental inputs and interpretations for engineering applications.
- Lesson. The need for a focused natural environment group which provides coordinated and consistent environment definitions/requirements/interpretations is key to having all concerned direct their efforts toward the same inputs, thus contributing to engineering applications that can readily be interpreted from a common base.

(5) Title: Ability to Test Planned New or Changes in Natural Environment Requirements Versus Results Important Before Implementing Them as Formal Requirements

- Background. Preliminary assessment of natural environments definitions and requirements must first be accomplished in collaboration with a responsible engineering group in order to identify design drives versus mission requirements. Based on this information, the appropriate natural environment definitions and requirements can be implemented and controlled accordingly.
- Lesson. To avoid problems with the engineering interpretation of natural environment definitions and requirements, the natural environments group responsible must first interact directly with an appropriate engineering group to ensure proper use and interpretation when formally implemented as part of the overall program requirements.

(6) Title: Need to Maintain Natural Environment Requirements for Design and Operation of Vehicle as Base from Which Other Requirements are Related Versus

Treating Natural Environment Requirements as One Other Non-nominal Input to be RSS in Final Design Action

- **Background.** By taking this action, it provides a viable and robust operational vehicle capability that will meet the vehicle mission operational natural environment requirements. Otherwise, a vehicle will be produced that will have a lower operational capability based on natural environment conditions. It is the natural environment operational requirements that can be monitored and decisions made regarding launch operations, etc., or, in case monitorship is not practical or an emergency, the vehicle will be functional relative to probable natural environment conditions established on basis of past records and mission requirements.
- **Lesson.** Do not design an aerospace vehicle with the required operational natural environment definitions and requirements incorporated and RSS as part of the non-nominal inputs to the vehicle design decision.

(7) Title: Natural Environment Elements That Cannot be Monitored Prior to Operations Decision Must be Minimum Risk Level Possible Consistent with Mission Capability Requirements, Including Those Natural Environment Elements Needed to Meet Safety and Emergency Situations

- **Background.** For an aerospace vehicle launch, most natural environment elements can be monitored and thus taken into account before launch decision relative to acceptable launch delay risks. The same is true for some on-orbit and deep-space spacecraft operational requirements. In such cases, lower probability occurrence environments may be considered, consistent with mission requirements, along with subsequent savings on design. Vehicle ascent winds through max Q versus reentry winds is an example of lower probability (higher risk of occurrence) versus higher probability (lower risk of occurrence) natural environment design requirements for a vehicle. However, minimum risk of occurrence natural environment environments must be used for design to ensure operational capability when natural environments cannot be measured or monitor ship taken advantage for vehicle operations.
- **Lesson.** It is necessary to carefully analyze the mission requirements relative to vehicle operations and provide the natural environment definitions and requirements accordingly in collaboration with the vehicle program manager to ensure understanding of the implications of environments provided for design.

(8) Title: Maintain Natural Environment Requirements for Design as Separate Document but Integral to Overall Mission Requirements for Vehicle

- **Background.** The natural environment definitions and requirements for the Space Shuttle and Space Station were provided such that they could be controlled and available in separate program documents as part of the overall design requirements documentation. This not only provided direct access for all concerned with use of natural environment inputs into design and mission planning but also provided an easy control of inputs. Changes, where required, were readily possible with the change of one document that had application for all natural environment inputs to the program.
- **Lesson.** Each vehicle development program should have only one natural environments definition and requirements document and it should be an integral part of the overall mission requirements for the vehicle design, development, and operations.

(9) Title: Atmospheric and Space Parameter Analysis Model

- Background. The ability for a program manager to easily access information on the operational impact of a vehicle design change relative to the natural environment is an important tool for decision making. In addition, such a tool provides additional insight into mission planning activities, including launch and landing delay probabilities.
- Lesson. Knowledge by mission managers, chief engineers, mission planners, etc. on the availability of an Atmospheric and Space Parameter Analysis Model is a valuable decision-making tool and should be utilized in making the trade-off decision where the desired operational natural environment is a factor.

(10) Title: Reference Period for Design Statements of Natural Environment Definitions and Requirements Relative to Launch and On-Orbit, etc. Operations

- Background. For launch statements on natural environment definitions and requirements, the worst reference month should be used. This provides an operational capability relative to the natural environment that ensures that for any given month, the desired operational capability will be met. Thus, for the worst month reference period, the minimum risk of launch delay due to natural environment will occur with all other months having less probabilities of launch delay. The same situation exists for natural environments associated with on-orbit operational capability, and deep-space operations. In other words, for these cases the anticipated lifetime in these operational conditions must be taken into account along with the acceptable risk for comprising the mission relative to natural environment conditions exceeding the design requirements.
- Lesson. All launch natural environment definitions and requirements for the design of a vehicle must be made with respect to a worst month reference period. For natural environments associated with on-orbit and deep-space operations, the anticipated lifetime in these operational conditions must be taken into account along with acceptable risks for operations.

(11) Title: Life-Cycle Cost Estimates and Natural Environment Operational Constraints of Vehicle

- Background. Once a vehicle has been developed, the constraints relative to operations in the natural environment should be assessed based on the resulting capability of the vehicle. This is the case for launch, on-orbit, and deep-space aspects of the mission. An Atmospheric and Space Environment Parameter Analysis Model can be especially helpful in this regard. The resulting information should be incorporated into the development of the full life-cycle cost estimates and model for the vehicle program.
- Lesson. Consideration needs to be given to the natural environmental constraints on launch and spacecraft operations when developing full life-cycle cost estimates and models.

(12) Title: Accelerated Schedule Without the Infrastructure

- Background. The decision to accelerate a program development schedule needs to be made in light of in-place competences, resources, and management operations. A number of contributing factors can affect this decision, including recognizing the issues and necessary work involved, availability of natural environment skills within the contractor community and interaction between the NASA program offices interfacing with contractors, and isolation of natural environments skills from systems engineering teams working the program.
- Lesson. Program systems engineering offices should have a "skills checklist" and routinely review government and contractor capabilities to assure all necessary expertise is available and tied in appropriately relative to natural environment and other engineering activities.

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