NASA Technical Memorandum 108511

Importance of the Natural Terrestrial Environment With Regard to Advanced Launch Vehicle Design and Development

S.D. Pearson, W.W. Vaughan, G.W. Batts, and G.L. Jasper

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June 1996

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IMPORTANCE OF THE NATURAL TERRESTRIAL ENVIRONMENT WITH REGARD TO ADVANCED LAUNCH VEHICLE DESIGN AND DEVELOPMENT

ENGINEERING IMPORTANCE

Mr. Dan Goldin, the Administrator of the National Aeronautics and Space Administration (NASA), has expressed the importance of developing a new, less expensive launch vehicle. The United States has not developed a new rocket engine in 25 years. NASA hopes a new engine and new launch vehicle will reduce launch costs per pound of payload to orbit by an order of magnitude. Among other elements, early definition and interpretation of the natural terrestrial environment for the design and development of a new launch vehicle will help avoid either a costly redesign or a launch vehicle with significant operational constraints.

The terrestrial environment is an important forcing function in the design and development of a launch vehicle. The scope of the terrestrial environment includes the following phenomena: Winds; Atmospheric Thermodynamic Models and Properties; Thermal Radiation; U.S. and World Surface Environment Extremes; Humidity; Precipitation, Fog, and Icing; Cloud Characteristics and Cloud Cover Models; Atmospheric Electricity; Atmospheric Constituents; Vehicle Engine Exhaust and Toxic Chemical Release; Occurrences of Tornadoes and Hurricanes; Geological Hazards; and Sea States. One must remember that the flight profile of any launch vehicle is in the terrestrial environment. Terrestrial environment definitions are usually limited to information below 90 km. Thus, a launch vehicle's operations will always 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 launch vehicle design and development inputs. This definition is a significant role, for example, in the areas of structures, control systems, trajectory shaping (performance), aerodynamic heating and take off/landing capabilities. The launch vehicle's capabilities which result from the design, in turn, determines the constraints and flight opportunities for tests and operations.

Although terrestrial environment is the major environmental driver for a launch vehicle and is the focus of this document, the natural environment above 90 km must be considered for launch vehicles such as Single-Stage-To-Orbit (SSTO) vehicles. The orbital phase of an advanced launch vehicle includes exposure to space environment phenomena such as atomic oxygen, atmospheric density, ionizing radiation, plasma, magnetic fields, meteoroids, etc. plus a few man-made factors such as orbital debris. Specific launch vehicle terrestrial and space environments requirements are normally specified in the appropriate vehicle design ground rules and criteria documentation.

It is important to recognize the need for definition of the terrestrial environment very early in the design and development cycle of any new launch vehicle. This is especially true for a new configuration. Using desired operational capabilities and flight profiles, specific definitions of the terrestrial environment can be provided which, if the launch vehicle is designed to accommodate,

accommodate, will ensure the desired operational capability within the defined risk level. It is very important that those responsible for the terrestrial environment definition have a close working relationship with program management and design engineers to ensure that the desired operational capabilities are reflected in the terrestrial environment requirements specified for design of the vehicle.

A launch 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 mission(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) initial 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 environmental factors, and (7) final assessment of environmental capability for launch and flight operations.

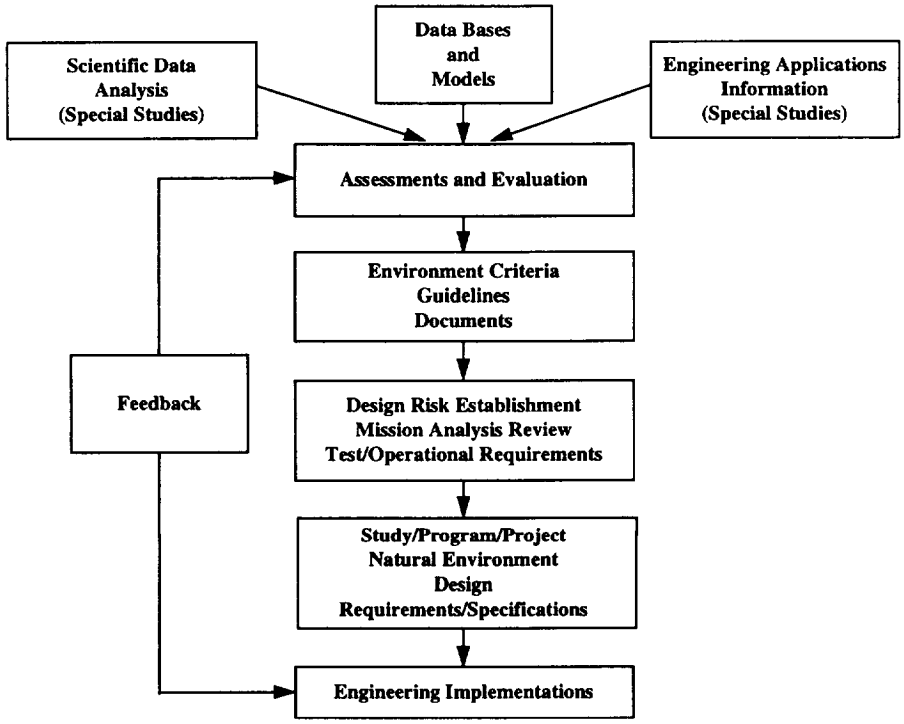
All launch vehicles are developed for specific purposes. Since the desired operational capabilities are sometimes significantly different, trade-offs are necessary. Therefore, it is impractical to take a generic set of terrestrial environment data and apply it to a new launch vehicle's design. The data must be tailored and defined for the intended vehicle's operational requirements.

Another important matter that must be considered is the necessity for having a coordinated and consistent set of terrestrial environment requirements for use in a new launch 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 focused on definition and interpretation of the terrestrial environment inputs is critical to the successful design of any new launch vehicle. Without this control, different terrestrial environment values or models can be used with costly results both in terms of money and time. All this can easily be avoided by establishing very early in the design and development phase a responsible person/group with the authority to control all terrestrial environment inputs for the program. This should 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 launch vehicle's design and development, trade-off studies to establish sensitivities of various terrestrial environment forcing functions are important. Feedback from these studies is key to establishing terrestrial environment inputs for the launch vehicle's final design requirements. Including a source responsible for the preliminary design trade-off study terrestrial environment inputs and their interpretation is important and will preclude a multitude of problems in the final design and development process. This will enable terrestrial environment requirements to be established with a minimum amount of communication problems and misunderstanding of design issues.

The group having the 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 and engineering assessments and updates. This is necessary to ensure accurate and timely terrestrial environment inputs tailored to the program's needs. Assuming design engineers and program management can simply draw on the vast data bases and numerous models of the terrestrial environment currently available in the literature can prove to be a major deterrent to the successful development of the program. The close association between the design and test engineering groups and those responsible for the terrestrial environment inputs is key to the success of this process. This procedure has been followed in many NASA aerospace vehicle developments and is of particular importance for any new launch vehicle. The following diagram illustrates necessary interaction relative to terrestrial environment definition and engineering application.

NATURAL TERRESTRIAL ENVIRONMENT DEFINITION AND ANALYSIS FOR LAUNCH VEHICLE ENGINEERING APPLICATION



Finally, although often not considered to be significant, it is of major importance that all new launch vehicle design review meetings include a representative from the terrestrial environment group 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 trade-off studies, be approved by the

responsible terrestrial environment person/group to ensure that all program elements are using the same baseline inputs. This will help the program manager understand the operational impact of any change in terrestrial environment requirements before implementation into the design. Gross errors and deficiencies in design can result from use of different inputs selected from various sources by the groups involved in design and other performance studies.

TERRESTRIAL ENVIRONMENT ISSUES

Experience gained in developing terrestrial environment design criteria for previous aerospace vehicle programs has proven that to be most effective, the terrestrial environment design criteria for a new launch vehicle should be:

(a) Available at the inception of the program and based on the desired operational performance for the launch vehicle.

(b) Issued under the signature of the program manager and be part of the controlled program definition and requirements documentation.

(c) The design criteria document should specify the terrestrial environment for all phases of activity including pre-launch, launch, ascent, on-orbit, descent and landing.

Terrestrial environment phenomena play a significant role in the design and flight of all launch vehicles and in the integrity of the associated systems and structures. Terrestrial environment design criteria guidelines are based on statistics and models of atmospheric and climatic phenomena relative to various launch vehicle development, operational, launch and landing locations.

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 for design must be accepted with the knowledge that there is some risk of the values being exceeded. The measurement of many environmental parameters is not as accurate as desired. In some cases, theoretical model estimates of design values are believed to be more representative for design use than those indicated by empirical distributions from short periods of record. Therefore, theoretical values are 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 launch vehicle studies to ensure consistency with physical reality and the specific design and operational problems of concern.

Launch vehicles are not normally designed for launch and flight in severe weather conditions such as hurricanes, thunderstorms, and squalls. Environmental parameters associated with severe weather which may be hazardous to launch vehicles include strong ground and inflight winds, strong wind shears and gusts, turbulence, icing conditions, and electrical activity. Terrestrial environment guidelines usually provide information relative to severe weather characteristics which should be included in design requirements/specifications.

Assessment of the terrestrial environment in the early stages of a new launch vehicle development program is advantageous in developing a vehicle with a minimal operational

sensitivity to the environment. For areas of the terrestrial environment that need to be monitored prior to and during tests and operations, this early planning will permit development of the required measuring and communication systems.

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

Good engineering judgment must be exercised in the application of terrestrial environment inputs to launch vehicle design analysis. Consideration must be given to the overall vehicle mission and system performance requirements. Knowledge is still lacking on the relationships between some of the terrestrial environment variates which are required as inputs to the design of launch 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/operational engineer and the respective organization's terrestrial environment specialists. Although, a launch vehicle design should accommodate all expected operational environment conditions, it is neither economically nor technically feasible to design launch vehicles to withstand all terrestrial environment extremes. For this reason, consideration should be given to protection of launch vehicles from some extremes 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 designing which would be necessary to cope with all terrestrial environment possibilities.

In general, terrestrial environment requirement documents do not specify how the designer should use the data in regard to a specific launch vehicle design. Such specifications may be established only through analysis and study of a particular design problem. Induced environments (vehicle caused) may be more critical than terrestrial environments for certain launch vehicle operations. In some cases the combination of natural and induced environments will be more severe than either environment alone. Induced environments are considered in the launch vehicle design criteria documents and should be consulted for such data.

INTEGRATED TERRESTRIAL ENVIRONMENT DEFINITION AND ENGINEERING APPLICATIONS

As previously noted, it is very important for one member of a new launch vehicle design and development team to be a person with knowledge of the terrestrial environment and experience in determining its effects on the launch vehicle. Terrestrial environment data must be formulated and interpreted in terms of vehicle characteristics. This can only be accomplished with the terrestrial environment specialist working with the launch vehicle system design specialists to achieve an optimum design. True optimization is a balancing act between trajectory (performance), control, loads, thermal, and operations where terrestrial environments are the major environmental driver. A launch vehicle design team must include disciplinary members in thermal, control, performance (trajectory shaping), structural, electronic, materials, flight mechanics, etc., it must also include a terrestrial environment specialist to provide a total systems approach.

Lessons learned show that it is very beneficial to establish teaming early in the design process to avoid time consuming and costly redesigns at later stages of development. During the very early stages of the design definition for a new launch vehicle, desired operational characteristics are developed. Given that the launch vehicle will operate in the terrestrial environment, design consideration must be given to the operational environmental conditions. Assessments made early in the development program for the launch vehicle will prove advantageous in maintaining an economical program and obtaining a launch vehicle with acceptable operational sensitivity to the environment. Also, for those terrestrial environment parameters that need accurate and timely monitoring prior to or during operations of the launch vehicle, early assessments will permit development of any necessary new environment measurement system(s) to support tests and operations.

In many cases, it is impossible to clearly define limiting extreme values for a particular terrestrial environment parameter that may occur during the desired lifetime of the launch vehicle. It may not be technically or economically feasible to design a launch 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 lifetime for the launch vehicle. Because of these and other considerations, a value less than the extreme may be a more appropriate design input. The terrestrial environment specialist has the responsibility to provide the program manager and chief engineer 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 launch vehicle program manager and the chief engineer have a good understanding of the operational risks due to the terrestrial environment.

Certain procedures prove to be effective in addressing specific questions on the terrestrial environment conditions for the planning of a new launch vehicle design. There are several environment parameters of interest for each of the launch vehicle's operational phases. The

phases are: (1) pre-launch, (2) launch, (3) return to launch site, (4) abort once around, (5) on-orbit and (6) end of mission landing. Most standard statistical summaries of terrestrial environment variables are tabulated for single variables or a combination of a few variables such as cloud ceilings and visibilities and they require parametric statistical summaries. Interest is not only in the probability of each of the several terrestrial environment variables taken separately, but also in the probability that at least one of several variables will be of concern for a particular operational phase or several phases. For example, if there is a launch constraint due to several terrestrial environment parameters of which any one is a No-Go condition, then the probability of interest is the probability that any one of the constraints will occur.

The purpose of terrestrial environment statistical analysis (mission analysis) is to address the following questions relative to assumed or assigned environmental constraints for the operational phases of a new launch vehicle.

1. What is the probability that the designated environmental constraints will (will not) occur during a particular monthly reference period?

2. What is the probability that the designated environmental constraints will (will not) occur for N consecutive days at a particular time of day during a monthly reference period?

3. Once the designated environmental constraint has occurred (has not occurred) for 1, 2, 3, ... J consecutive days at a particular time of day, what is the probability that the given constraints will continue for N additional days?

Valid answers to these questions have practical applications to any new launch vehicle program development in the following interrelated areas:

1. Establishing terrestrial environment design criteria

2. Operational planning

3. Establishing launch and flight operational rules

4. Program decisions on cost-trade assessments.

ENGINEERING AND TERRESTRIAL ENVIRONMENT AREAS OF CONCERN

It is important that the need for definition of the ground, ascent, on-orbit, and descent launch vehicle operational terrestrial environments be recognized early in the design and development phase of a launch vehicle program. Engineering technology is constantly changing. Current trends in engineering design have increased launch vehicle susceptibility to terrestrial environment factors. Based on past experience, the earlier the terrestrial environment specialists become involved in the design process, the less the potential for negative environmental impacts on the program downstream, through redesign, operational work-arounds, etc.

The following tables provide a reference guide for the terrestrial environment specialist and others on the design team for a new launch vehicle program. This information summarizes potential terrestrial environment areas of engineering concern when first surveying a launch vehicle project. Table I provides a breakout of typical terrestrial environment concerns with respect to four engineering areas: structures, avionics, flight systems and operations. A checklist is provided in Table II which will help identify those terrestrial environment areas of greatest concern for a new launch vehicle program.

The information in this document compliments that given in NASA Technical Memorandum 4511, "Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1993 Revision". NASA TM 4511 describes the terrestrial environment and the areas of effect on a launch vehicle's design, development, and operations. Tables III and IV provide a breakout of the terrestrial environment and the major engineering areas of interaction for a launch vehicle system. One of the key functional areas of terrestrial environment interest lies with the ascent structural and control characteristics of a launch vehicle. The terrestrial environment areas of concern in design will vary with the launch vehicle configuration and launch and landing site(s). They are also different for expendable versus reusable vehicles.

The information given in NASA Technical Memorandum 4527, "Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development", provides an excellent overview of on-orbit natural environment phenomena which require design consideration for launch vehicle configurations such as the Single-Stage-To-Orbit vehicle. NASA Reference Publication 1350, "The Natural Space Environment: Effects on Spacecraft" includes a description of the on-orbit space environments and the major engineering areas of interaction for a launch vehicle system.

Natural Terrestrial Environments
Areas of Concern

- Vehicle Structures
  - Wind/Wind Shear/Turbulence Definitions
  - Site specific Vector Wind Profile models for ascent and descent structural design, tank sizing, and performance
  - Ground winds for lift-off and landing
  - Atmospheric models for ascent and descent trajectories required for performance and thermal protection systems

- Avionics
  - Wind and atmospheric variability models and databases for guidance and control systems design

- Flight Mechanics/Trajectory Optimization
  - Balance between loads, control, trajectory, thermal, etc.

- Flight Systems Design/Analysis
  - Assess applicability of wind and atmospheric models and databases for conceptual flight systems design, design trade studies and performance analysis
  - Consultative services related to natural environments for systems integration

- Operations
  - Ground
    - Atmospheric parameterization for ground operations, transportation, assembly and preflight to yield risks of adverse weather conditions

  - Flight
    - Launch and landing probabilities assessments relative to atmospheric conditions (e.g., thunderstorms, ground winds, flight winds, and range safety constraints)

Table I

Natural Terrestrial Environments
Launch Vehicle Project Checklist

GENERAL INFORMATION
- Anticipated Mission(s)
- Space Vehicle Type
- Description of Space Vehicle Operational Objectives
- Expected Launch turn around time (days)
- Proposed Launch and Landing Site(s)
- Anticipated On-Pad Stay Time
- Planned Recovery Site(s)
- Design Lifetime for Reusable Elements
- Launch Vehicle
- Shape of Structure (attach diagram)
- Upper Stages
- Suborbital/Orbital Capabilities
- Return from Orbit Constraints

WINDS
- Ground
- Ascent
- Descent

HYDROMETEOR/AEROSOLS/CONSTITUENTS
- Precipitation (all types)
- Cloud and Fog Characteristics
- Contaminants/Particles
- Optical Surfaces
- Atmospheric Chemistry

ATMOSPHERIC ELECTRICITY
- Static Discharges
- Lightning Protection
- Electrical Fields

THERMODYNAMIC PROPERTIES ASCENT AND ENTRY
- Max-Q Altitude Region
- On-Pad Requirements
- Radiation/Temperature
- Aerobraking
- Overall Thermal Protection Design
- Storage
- Reference Atmosphere Model

ANTICIPATED OPERATIONAL CONSTRAINTS
- Thunderstorms
- Ground Winds
- Ascent Winds
- Temperature/Density
- Cloud Cover/Visibility
- Electrical Fields
- Precipitation (all types)
- Environmental Effects

Table II

NATURAL TERRESTRIAL ENVIRONMENTS

	ELEMENTS	PROGRAM STAGES	MODELS/DATABASES
ATMOSPHERIC CONSTITUENTS	Gases, Blowing sand/dust, Sea salt, Atmospheric chemical contaminants/particulates	Design-Ground handling/transportation, Storage	Climate statistical models, U.S. Standard Atmosphere
ATMOSPHERIC ELECTRICITY	Thunderstorm electricity, Lightning, Static electricity	Design-Ground handling/transportation, Storage, Mission planning, Vehicle design/prelaunch/launch/landing	Climate statistical models, Bond strap model
CLOUDS and FOG	Cloud formation process, Cloud distribution, Scattering, Extinction properties, Fog density	Mission planning, Vehicle design/prelaunch/launch/landing	Global cloud model, ISSCP database, NIMBUS database Climate statistical models
HUMIDITY	Vapor concentration/vapor pressure/temperature	Design-Ground handling/transportation, Storage, Vehicle prelaunch	4-D Atmospheric model GRAM 95
PRECIPITATION	Rainfall rates/raindrop size, Snow loads/particle size, Hail, Icing	Design-Ground handling/transportation, Storage, Mission planning, Vehicle design/prelaunch/launch/landing	MISAP, Precip. statistical databases
SEA STATES	Wave height, Ocean temperature/currents	Shipping planning, Shipping	Sea state model
SEVERE WEATHER	Tornadoes, Tropical storms, Hurricanes, Earthquakes	Design-Ground handling/transportation, Storage, Mission planning, Vehicle design/prelaunch/launch/landing	Climate statistical models
THERMAL RADIATION	Solar radiation: direct/diffuse/absorber/scattered	Design-Ground handling/transportation, Storage, Vehicle design, Prelaunch, Inflight	Solar radiation model
THERMODYNAMIC PROPERTIES	Atmospheric temperature/pressure/density	Design-Ground handling/transportation, Storage, Vehicle design/prelaunch/launch/landing, Inflight, Aerobraking	GRAM 95, U.S. Standard Atmosphere, Range Ref. Atmos. (RRA)
WINDS	Ground winds, Inflight winds, Wind shear, Turbulence/gusting	Design-Ground handling/transportation, Storage, Vehicle design/prelaunch/launch/landing, Inflight, Aerobraking, trajectory shaping	Wind databases, Vector wind models, GRAM 95, U.S. Standard Atmosphere, MISAP, RRA

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Table III

TERRESTRIAL ENVIRONMENT EFFECTS

	TERRESTRIAL ENVIRONMENTS				
SPACE VEHICLE SUBSYSTEMS	**Atmospheric Constituents**	**Atmospheric Electricity (Lightning)**	**Clouds and Fog**	**Humidity**	**Precipitation**
Avionics	Contamination of Components	Upsets Due to EMI from Charging, L/V Charging		Contamination of Components	
Electrical Power		Power Surges			
GN&C		Control System Electronics			
Materials	Contamination of Surfaces	Selection			
Optics	Contamination and Sensor Degradation		Performance of Sensors		
Propulsion		Inadvertent Ignition		Performance	
Structures		Bonding of Structure			
Telemetry, Tracking, & Communications	Optical Sensing	EMI Due to Arcing	Optical Sensing		Performance Errors
Thermal Control					
Mission Operations	Ground Handling, Storage	Ground Handling, Transportation	Launch and Landing Decisions	Transportation, Ground Handling, Mission Planning	Ground Handling, Mission Planning, Launch Decision

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Table IV

TERRESTRIAL ENVIRONMENT EFFECTS

	TERRESTRIAL ENVIRONMENTS				
SPACE VEHICLE SUBSYSTEMS	**Sea State**	**Severe Weather**	**Thermal Radiation**	**Thermodynamic Properties**	**Winds**
Avionics			Thermal Design		
Electrical Power					
GN&C				Ascent and Reentry Trajectory Shaping	Torques, System Design, Trajectory Biasing
Materials	Selection	Damage Due to Hydrometeors	Material Performance	Reentry Heating, Material, Degradation	Selection Relative to Stress, Loads
Optics			Influences Optical Design	Necessary for Optical Designs	
Propulsion		Thermal Stress to Solid Rocket Systems		Performance, Fuel Requirements, System Design	Performance, Engine Torques, System Design Exhaust Byproduct Transport
Structures	Impact Loads	On-Pad Stress	Thermal Induced Stress	Dynamic Pressure/Laods	Loads, Stress, Fatigue, Overturning Moments
Telemetry, Tracking, & Communications		Performance Errors		Possible Tracking Errors	
Thermal Control			Thermal Control System Design	Thermal Loads/Heating During Reentry	
Mission Operations	S/C Recovery, Booster Recovery, Shipping	Mission Planning influences, Transportation, Storage, Launch/Entry Decision	Prelaunch and Launch Decisions	Mission Planning	Fuel Handling Hazard, Mission Planning Influences, Transportation, Launch Decision

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Table IV (cont'd)

WIND ENVIRONMENT INTERACTIONS RELATIVE TO LAUNCH VEHICLE DESIGN

Wind is usually the most important terrestrial environment parameter influencing the design of a launch vehicle (Fig. 1). Because it has temporal and spatial variations, representation of the wind data in a simple and concise form is not possible for all purposes of design and operation of a launch vehicle. Caution must be exercised in the employment of wind data to ensure consistency with the physical interpretation relative to the specific launch vehicle design problem. Given the importance of wind inputs for launch vehicle design, wind input has been selected to illustrate the importance of terrestrial environment considerations in the launch vehicle design and development process.

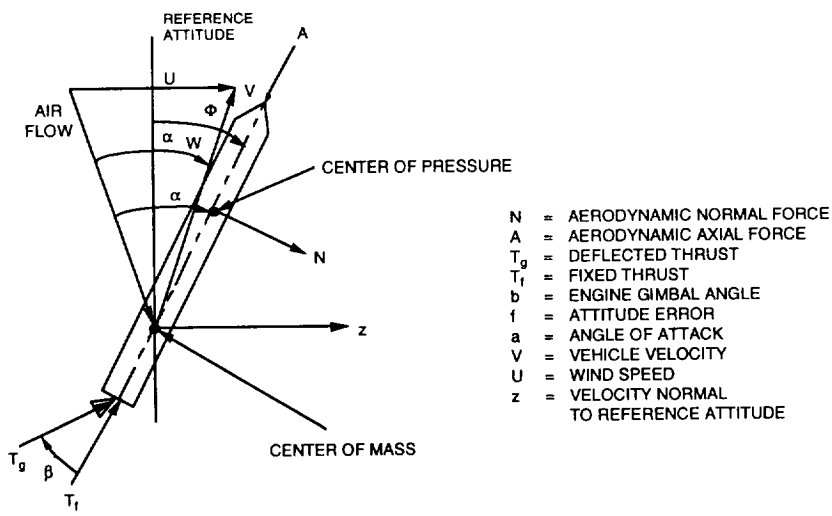

Figure 1. Rigid launch vehicle dynamic model

The term 'design' is used here to include not only the detail parts of the several stages, but also the choice of the structural system of the airframe, choice of the overall configuration, and selection of trajectory (optimization). Such decisions as whether to require fins for stabilization, permissible vehicle slenderness ratio, location of propellant tanks, and even requirements for ground handling and launch equipment are often based on the effects on the launch vehicle of ground winds as well as in-flight winds.

Ground Winds

Wind is a vector quantity which varies in both space and time, so the wind loads should be considered as a dynamic input to the vehicle structure. From the aerodynamic point of view, the problem falls in the category of viscous separated flow around a bluff body. Although such flows have been studied for many years, there does not exist an adequate approximation to aerodynamic transfer functions to relate the dynamic wind vector to the dynamic load on the body. Therefore, quasi-steady assumptions must be used.

To simplify the problem, the near-surface wind profile is broken down into steady and unsteady components (Fig. 2), with the resulting static and dynamic loads superposed. The second order loads which result from the interaction of the static and dynamic wind components are often neglected in the present state of the art.

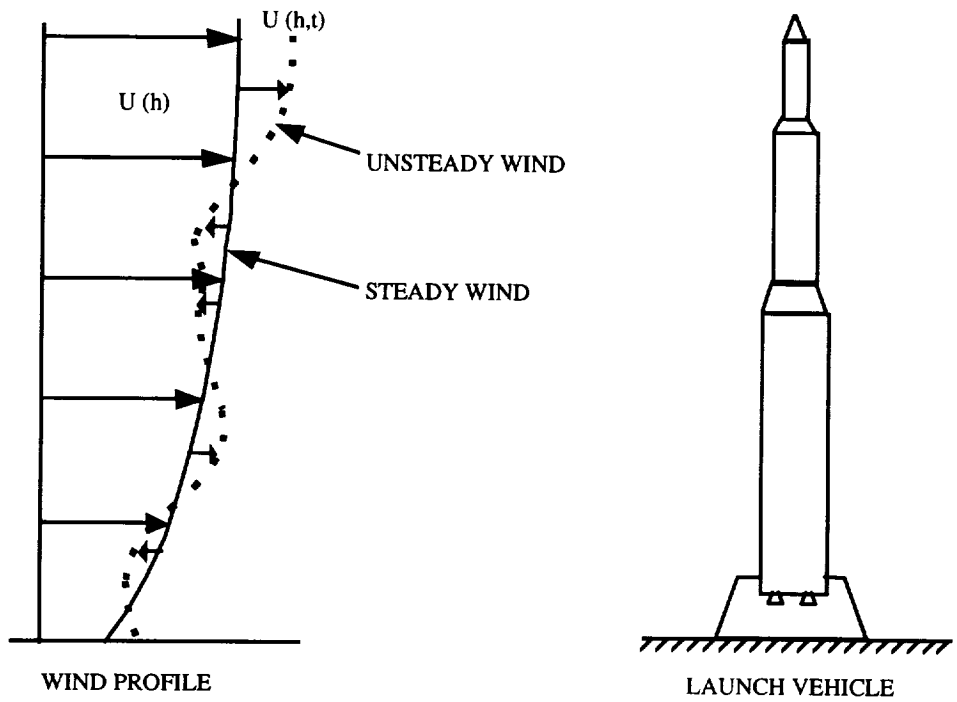

Figure 2. Launch vehicle exposed to ground winds

Static and dynamic loads due to winds can be combined vectorially to obtain the final load (Fig. 3). This method is believed to provide a conservative estimate. Since most of these loads can be determined to some extent in the design phase, the structural integrity of the vehicle will be, in general, jeopardized only by unexpectedly large vortex shedding loads. In this case, a study must be made of launch pad operations to determine the time frame of vehicle exposure and the associated risk of structural damage or launch delay. It must be emphasized that difficulties of this type should be anticipated for any new vehicle configuration and continuing appraisal made of possible launch operations and schedules from the earliest conception of the design. Extended exposure to the wind field of the unprotected vehicle should be avoided and the risk associated with any proposed on-pad stay time schedule should be established. This risk includes not only structural damage but the possibility of schedule slip or failure to obtain a desired launch date or time.

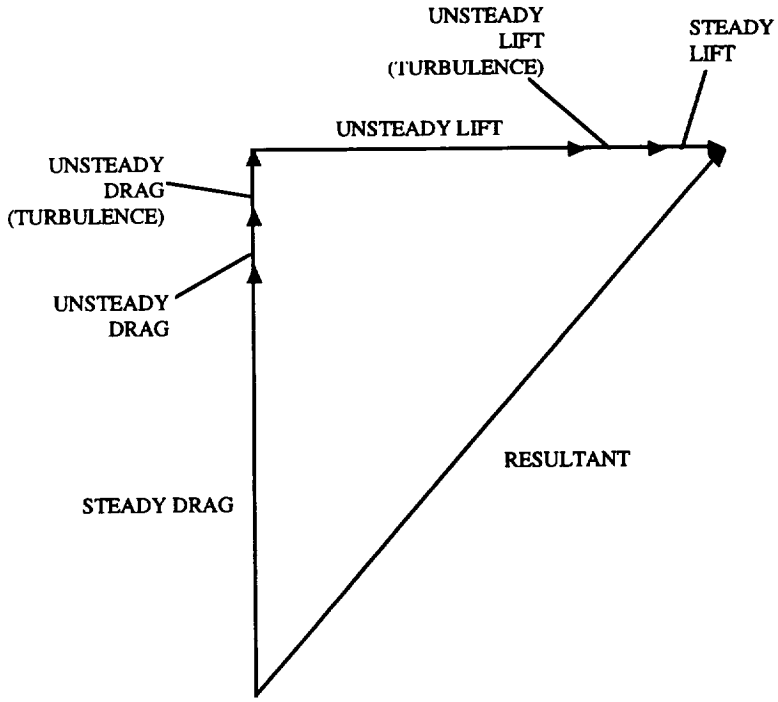

Figure 3. Total wind loads on launch vehicle

Wind has a significant effect on the launch vehicle during the period from just before release of the hold-down mechanism until the vehicle has completely cleared the launch tower structure. The major wind problem in launch analysis is that of drift of the vehicle during initial ascent. It is assumed for these analyses that the vehicle at lift-off is in an undeflected state such that its initial motion is vertical. Under these conditions bending moments induced on the vehicle are smaller than those experienced at later flight times, or in the hold-down position before launch, when ground winds may surpass the allowable values for launching. Very large forces and moments can be induced in the vehicle if it collides with the tower or vehicle hold down mechanism. However, since this is not a design condition, but a possible condition for catastrophic failure of the vehicle, no analysis is usually made of the loads induced by such a collision.

A symmetrical launch vehicle was analyzed for classical vortex shedding using both analytical and scale model testing. Being essentially a cylinder, the vehicle showed clear vortex shedding problems, particularly since it must spend up to 30 days on the pad exposed to ground winds. As a result, a system was designed which damped the vehicle against the test stand. Also, a wind velocity criterion was used which required installation of the damper when above critical wind levels were being predicted. Also, dampers were used during any free standing time on the pad. Figure 4 shows the maximum ground winds (speed) versus bending moment capability. There is also a smaller bending effect due to the Sun's radiation and differential heating on the vehicle structure. Figure 5 translates these critical wind velocities by azimuth for two vehicle configurations.

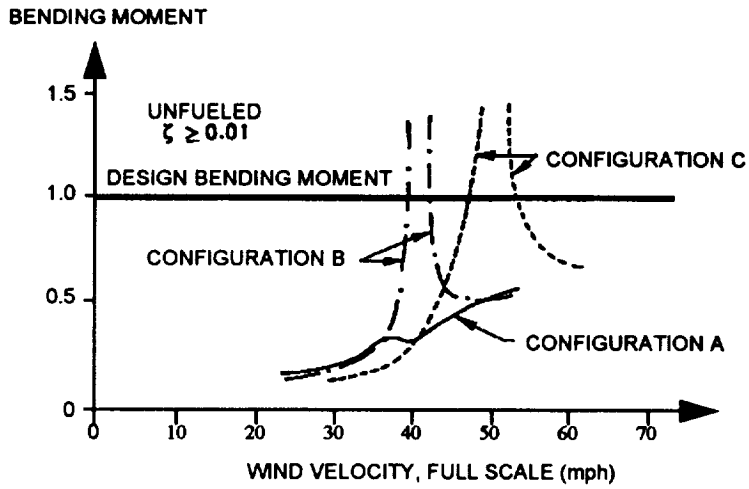

Figure 4. Maximum ground wind loads for a selected launch configuration

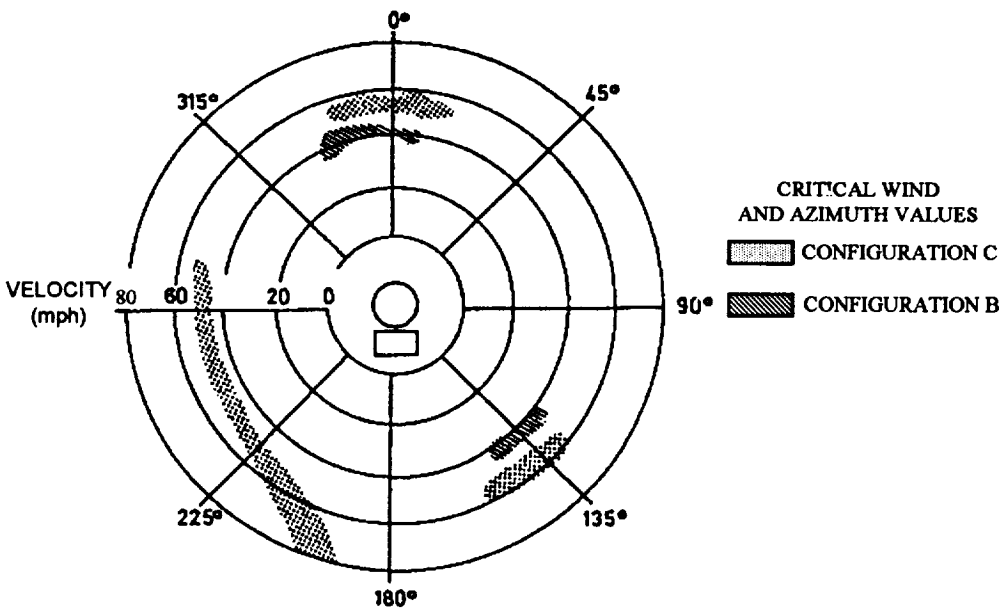

Figure 5. Dependence of ground wind loads on azimuth angle

A non-symmetrical launch vehicle configuration may not be susceptible to classical vortex shedding; however, it falls into the arena of the classical stop sign flutter, named from road signs fluttering at certain critical frequency wind speeds. Scale model wind tunnel tests are needed to verify the stop sign flutter potential. The flutter limit may be determined relative to the pad vehicle interface stiffness. Final design may show no stop sign flutter problem due to the naturally large torsional stiffness arising from the vehicle configuration and the holddown/supports.

In-flight Winds

A symmetrical vehicle derivative used to launch a new payload configuration further exemplifies a wind gust elastic body response coupling problem. In this example, the new payload was placed forward of the last stage with a nose cone on the front instead of the usual payload. This change in external configuration changed the aerodynamic distribution, thus the response to winds. This apparently small configuration change had a substantial effect on the resulting loads.

One symmetrical launch vehicle configuration without wind biasing had approximately a 95 percent launch probability, and greater than 99 percent with wind biasing. The vehicle flew with wind biasing for added margin. This assessment was made using synthetic wind profiles. Using the Monte Carlo approach and the measured Jimsphere wind profile ensembles, the unbiased case was greater than 99 percent. With the new payload, the launch vehicle configuration had less than a 50 percent launch probability without wind biasing and 80 percent with wind biasing using the synthetic profiles. Verification and operational analysis for the new payload configuration was accomplished using the Monte Carlo approach. The results are shown on Figure 6 for one flight time, both with and without wind biasing giving 65 percent and 98 percent probability, respectively. As a result, the problem was solved using wind biasing and verified using Monte Carlo response analysis. The new payload configuration flew with a very good launch probability as a result of the wind bias profile and the change to a more realistic verification analysis approach. The lesson is clear, small changes can easily eat up large margins. Analysis must be refined to match the engineering problem requirements.

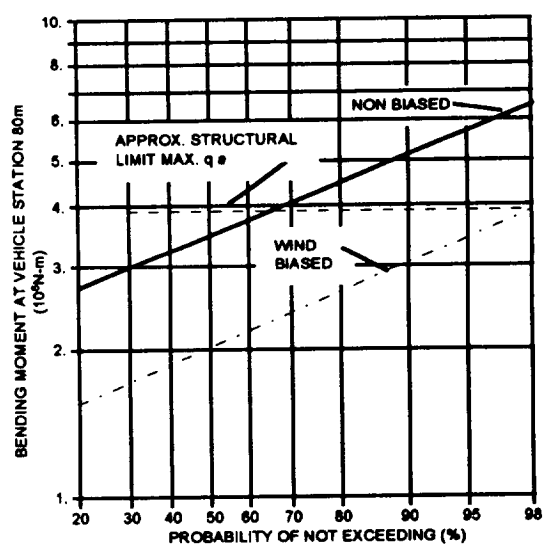

Figure 6. Maximum bending moment at a selected new payload configuration launch vehicle station versus probability of not exceeding for March sample of Jimsphere winds.

Guidance System: The ascent wind profile effects come into play when the guidance system attempts to meet the objective of maximizing payload. There are two ways in which the

flight-mechanical effect of optimizing the lift-drag-direction relationship for a trajectory through the Earth's atmosphere and gravitational field. The second factor, on which the wind has a direct influence, is the effect of flight path on the vehicle bending moment and hence on structural weight. Bending moment is caused by control forces, i.e., engine gimbaling, and by aerodynamic side forces induced by winds acting against the side of the vehicle and vehicle maneuvering. The size of bending moments on a vehicle determines in part the structural strength requirements and, thus, the structural weight of the vehicle. With all other factors considered equal, higher structural weight results in lower payload. Therefore, in choosing the optimal flight path, the guidance system must consider not only the flight-mechanical aspects, but also the wind-induced bending moments, rigid body aerodynamics, aerodynamics lift and vehicle overturning moment contribution to the drift and, thus, flight path optimization.

Control System: The most significant terrestrial environment element affecting control system design is upper altitude winds in the high dynamic pressure region (10-15 km altitude). The control system functions primarily to maintain a prescribed flight path as generated by guidance on preprogrammed attitude tilt commands. Off-nominal values of vehicle parameters and the presence of winds will cause the flight path to differ from that anticipated by the guidance system. Ideally, the control system should minimize this difference. However, there is a cost incurred in attempting to respond precisely to the guidance commands, and the cost appears in terms of bending moments and resulting structural loading on the vehicle plus drift and later thermal loads when the vehicle corrects for flight path deviations. The fact that winds are acting on the vehicle could make this cost excessive. Winds aloft are frequently of such a large magnitude, especially in the maximum dynamic pressure region, that large dispersions in guidance-system-prescribed attitude and flight path angles occur. In order for the control system to decrease these dispersions, large bending moments are imposed on the vehicle. If a controller is being designed for an already-designed vehicle structure, these loads can be so large that the vehicle would exceed its design loads and break up. On the other hand, if the control system design is for a vehicle in the preliminary design stage so that structural requirements are yet to be established, the large bending loads can result in excessively complex, heavy, or expensive structural configurations. Consequently, because of the in-flight winds, bending moments on the vehicle become the overriding consideration in controller design.

The original solid rocket booster on a non-symmetrical launch vehicle configuration had no control capability. Early in the design phase it became clear that the vehicle was uncontrollable without control authority on the solid rocket boosters. As a result, the solid rocket motor nozzle flex bearing, composed of layers of metal and elastomer, was redesigned and baselined. Actuators designed for the vehicle were used as actuation authority. This increased weight, complexity, and cost. In addition, two factors were used very early in the design and development period to take out conservatism, save weight and cost, and improve performance. They are: (1) monthly mean wind biasing was instituted as part of criteria change for generating environments and performance, etc. (past programs had reserved this design requirement as a margin for operation and launch probability increases); and (2) prior programs used the 95-percent wind speed in conjunction with 99 percent wind shear and 99-percent gust as a conditional probability approach. The new launch vehicle configuration used 95-percent wind speed in combination with one half the shear and gust 99-percent levels. Then root sum squaring the other half with the other vehicle

response parameters, again reducing margins. These two design wind conservatisms are not wrong within themselves since it could be shown statistically that these were safe approaches. In addition, prelaunch monitorship of the ascent wind loads provided added assurance of a safe transition through the maximum dynamic pressure region relative to wind loads. However, what these actions did was take out margins for flexibility, operations, and unknown vehicle effects.

The determination of a launch vehicle's response to wind disturbance cannot be reduced to the evaluation of one discrete set of response criteria, such as vehicle loads, but must include many response parameters. The parameters which become design drivers depend upon the vehicle configuration and specific mission. It is not practical to use only one design method for all phases of vehicle design. Different approaches and methods of evaluation must be used as the particular phase demands. The phases include preliminary design, final structural design, guidance and control system design and optimization (preliminary and final), and establishment of limits (constraints) and procedures for launch and flight operations. In each of these phases, three things must be considered:

(1) Choice of methods for analysis and the choice of an analytical dynamic model to describe the launch vehicle characteristics relevant to a particular design phase.

(2) Lack of capability to completely predict the vehicle characteristics—aerodynamic forces, structural weight and thrust, and proper selection of the wind field representation. The final determination of approach to be taken depends upon the design phase and the type of launch vehicle.

(3) Identification of critical constraints depending on the characteristics and missions of the launch vehicle.

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APPROVAL

IMPORTANCE OF THE NATURAL TERRESTRIAL ENVIRONMENT WITH REGARD TO ADVANCED LAUNCH VEHICLE DESIGN AND DEVELOPMENT

Steven D. Pearson, William W. Vaughan, Glen W. Batts, Gwenevere L. Jasper

The Information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classifications Officer. This report, in its entirety, has been determined to be unclassified.

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☆U.S. GOVERNMENT PRINTING OFFICE—1996—733-109/40040

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1996	Technical Memorandum

4. TITLE AND SUBTITLE

Importance of the Natural Terrestrial Environment with Regard to Advanced Launch Vehicle Design and Development

5. FUNDING NUMBERS

6. AUTHOR(S)

S. D. Pearson, W. W. Vaughan*, G. W. Batts**, and G. L. Jasper

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATON REPORT NUMBERS

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-108511

11. SUPPLEMENTARY NOTES

Prepared by Systems Analysis and Integration Laboratory, Science and Engineering Directorate
*University of Alabama in Huntsville;**Computer Sciences Corporation

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The terrestrial environment is an important forcing function in the design and development of the launch vehicle. The scope of the terrestrial environment includes the following phenomena: Winds; Atmospheric Thermodynamic Models and Properties; Thermal Radiation; U. S. and World Surface Environment Extremes; Humidity; Precipitation, Fog, and Icing; Cloud Characteristics and Cloud Cover Models; Atmospheric Electricity; Atmospheric Constituents; Vehicle Engine Exhaust and Toxic Chemical Release; Occurrences of Tornadoes and Hurricanes; Geological Hazards, and Sea States. One must remember that the flight profile of any launch vehicle is in the terrestrial environment. Terrestrial environment definitions are usually limited to information below 90 km. Thus, a launch vehicle's operations will always 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 launch vehicle design and development inputs. This definition is a significant role, for example, in the areas of structures, control systems, trajectory shaping (performance), aerodynamic heating and take off/landing capabilities. The launch vehicle's capabilities which result from the design, in turn, determines the constraints and flight opportunities for tests and operations.

14. SUBJECT TERMS

terrestrial environment

15. NUMBER OF PAGES

30

16. PRICE CODE

NTIS

17. SECURITY CLASSIFICATION	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

National Aeronautics and
Space Administration
Code JTT
Washington, DC
20546–0001