COMBINED ASCENT LOADS FOR LAUNCH VEHICLE ANALYSIS
Revision J

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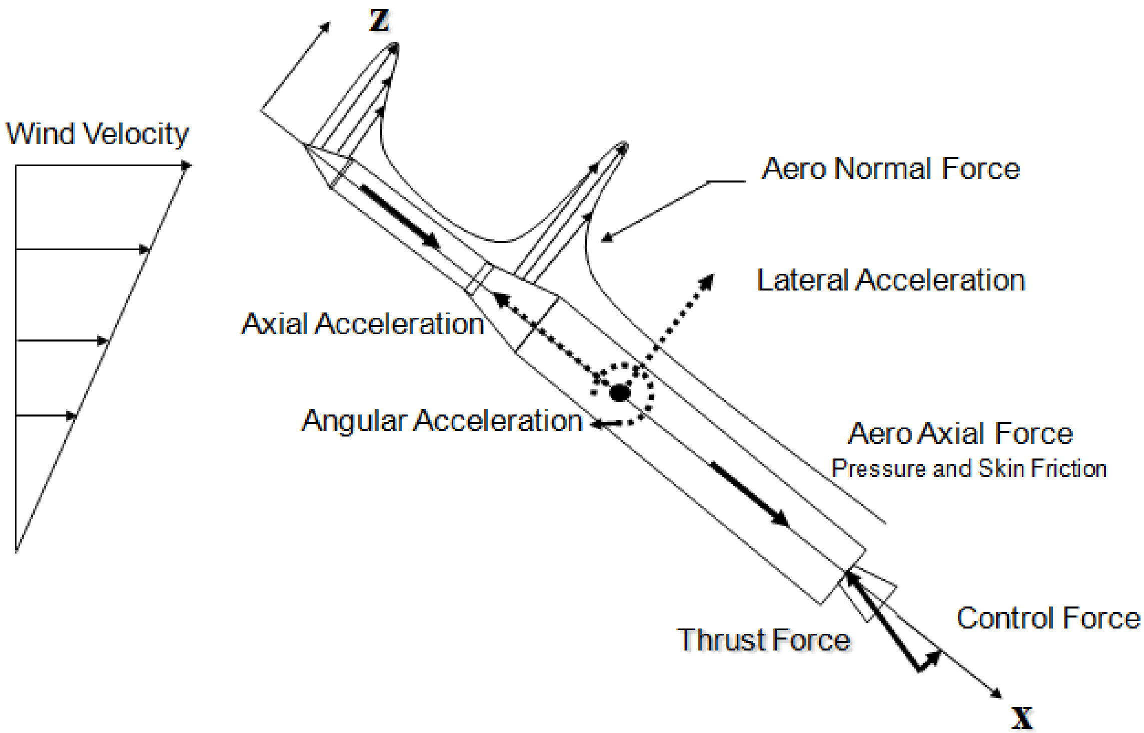

Figure 1. Major Sources of Aero-Mechanical Loads

Introduction

Launch vehicles are subject to the following loads during ascent:

1. Static Aeroelastic (STEL)
2. Gust
3. Buffet
4. Thrust Oscillation (TO)

Bending, shear, and axial loads must be derived as a function of vehicle length.

The response of the vehicle to these loads must be determined as part of the controls analysis and for stress analysis.

STEL

All rocket vehicle bodies are flexible to some degree. A rigid body analysis may result in significant errors in load intensity, especially for slender bodies, or for highly maneuverable vehicles which operate primarily in the atmosphere.

The movement of air-loads due to the elastic body, or the aerodynamic-elastic interaction, must be considered. The vehicle flexibility changes the local angle of attack and control deflection through redistribution of the air-loads. There is a further effect on the moment due to inertia of the off-set vehicle weights, or moment due to axial loads when the vehicle is deflected. These latter effects are typically small, but must be addressed for long, slender, flexible vehicles.

STEL is typically performed with the vehicle in its trimmed condition, where the forces and moments are balanced such that there is no rotation about the center-of-gravity.

STEL may include steady wind pressure with frequency content below 1 Hz.

Furthermore, these effects should be determined for selected points of the worst-case conditions from the Monte Carlo ascent simulations. The simulations should included dispersions on the vehicle angle-of-attack and on the dynamic pressure.

Gusts

A common practice is to separate gusts from winds. Gusts are often considered to act normal to the vehicle axis, and are assumed to be represented by simple discrete time functions. In other cases, gusts are treated statistically by power spectral techniques.

The gust analysis should include tuning gusts at various altitudes. In addition, a discrete $(1-\cos\omega t)$ gust environment should be considered, per Reference 1. The $(1-\cos\omega t)$ function can be tuned to the critical bending frequency of the vehicle. The tuning is performed by varying the length of the gust.

The gust frequency f_G is

$$f_G = \frac{V_{RW}}{L_G} \tag{1}$$

where

V_{RW}	is the relative wind velocity
L_G	is the gust length

Note that

$$\omega = 2\pi f_G \tag{2}$$

Gusts are particular concern in the jet stream.

The strongest jet streams are the polar jets, at around 7–12 km (23,000–39,000 ft) above sea level, and the higher and somewhat weaker subtropical jets at around 10–16 km (33,000–52,000 ft).

Further information on gusts models is given in Appendix A.

<u>Buffet</u>

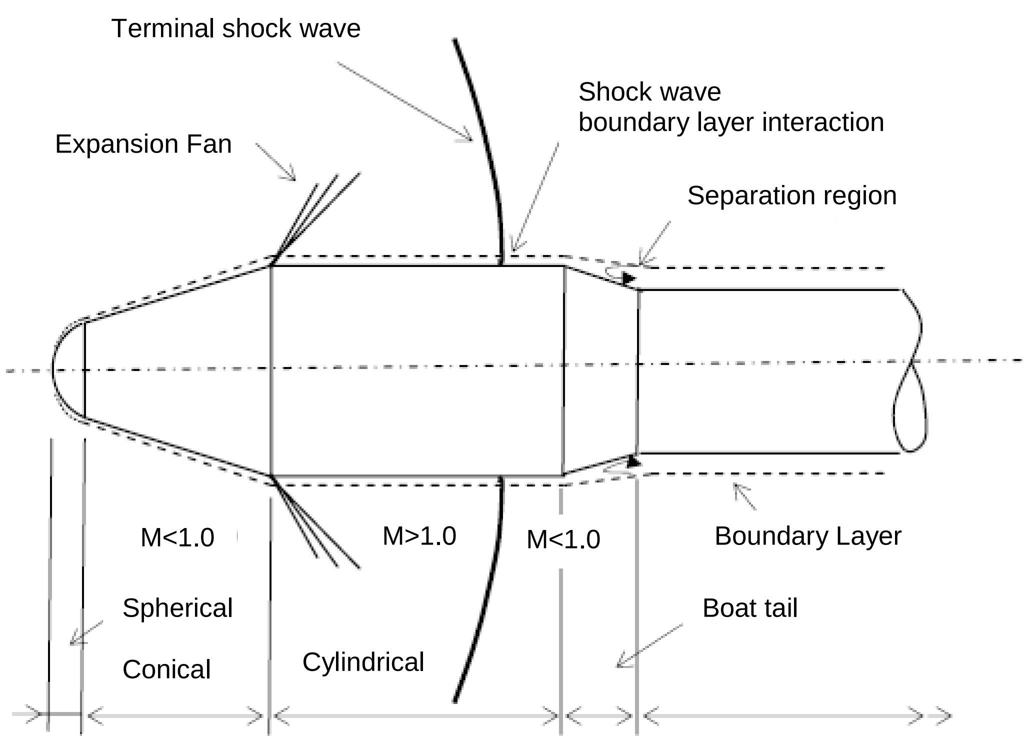

Figure 2. Schematic Flow Field on Payload Fairing at Transonic Mach Number (Ref. 9)

Aerodynamic transonic buffet loads are due to the pressure against the vehicle skin from shock wave/turbulent boundary layer interaction and separated flows.[1]

Separated flows may be induced by the shock wave/turbulent boundary layer interaction.

Separated flow can also be due to angle-of-attack, surface roughness, or geometrical protuberances.

Buffeting environments may be derived based on wind tunnel test data and Computational Fluid Dynamics (CFD) analysis supplemented by flight test data.

Further information on wind tunnel testing is given in Reference 7.

Thrust Oscillation

A thrust oscillation can occur in the cavity of a solid rocket motor due to standing waves formed by vortex shedding in the exhaust gases.

In addition, liquid engine stages can have pogo oscillations.

Further information is given in Reference 4 and 5.

Combined Loads Formula, Reference 1

The following is taken from Reference 1, Appendix B, paragraph 2.5.1.

$$\text{ASCENT LOADS} = 1\ \text{STEL} + 1/3\ \text{GUST} + 0.335\ \text{BUFFET} + \text{MEAN TO}$$

$$+\sqrt{(2/3\ \text{Gust})^2 + (0.665\ \text{Buffet})^2 + (\text{TO} - \text{Mean TO})^2} \tag{3}$$

[1] In contrast, laminar, attached flow generates much lower aerodynamic pressure.

Combined Loads Formula, Reference 6

The following is taken from Reference 6, VII.M-16 for the total moment M_{total} .

$$M_{total} = 1M_{STEL} + 1/3M_{Gust} + 0.415\ M_{Buffet}$$

$$+\sqrt{(2/3\ M_{Gust})^2 + (0.585\ M_{Buffet})^2 + (M_{Dispersions})^2} \tag{4}$$

The dispersions are tolerances on thrust, dynamic pressure, autopilot gains, wind air-load distributions, etc.

Uncertainty Factors

Table 1. Typical Uncertainty Factors

Analysis	Uncertainty Factor
Maneuvering	1.5
STEL, axial & lateral	1.25
Gust	1.3
Buffet (loads)	1.2
Buffet (acceleration)	1.5

Additional Load Cases

A typical vehicle may is exposed to the following events prior to ascent:

1. Base drive and ground winds during roll-out
2. Prelaunch ground winds
3. Thrust mismatch at liftoff for a vehicle with multiple engines and/or solid motors
4. Ignition overpressure (IOP)

References

1. NASA Loads and Structural Dynamics Requirements for Spaceflight Hardware, Lyndon B. Johnson Space Center, JSC-65829 RFI Release 1.
2. NASA SP-8099 Combining Ascent Loads.
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5. T. Irvine, Vibration in Rocket Vehicles due to Combustion Instability, Revision E, Vibrationdata, 2008
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7. T. Irvine, Notes on Wind Tunnel Testing, Vibrationdata, 2010.
8. R. Blevins, Flow-Induced Vibration, Second Edition, Krieger Publishing Company; Malabar, Florida, 2001.
9. R.C. Mehta, Numerical Study of Flow Field Visualizations over a Payload Shroud at Transonic Speeds, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2009.

APPENDIX A

Reference 3, Excerpt

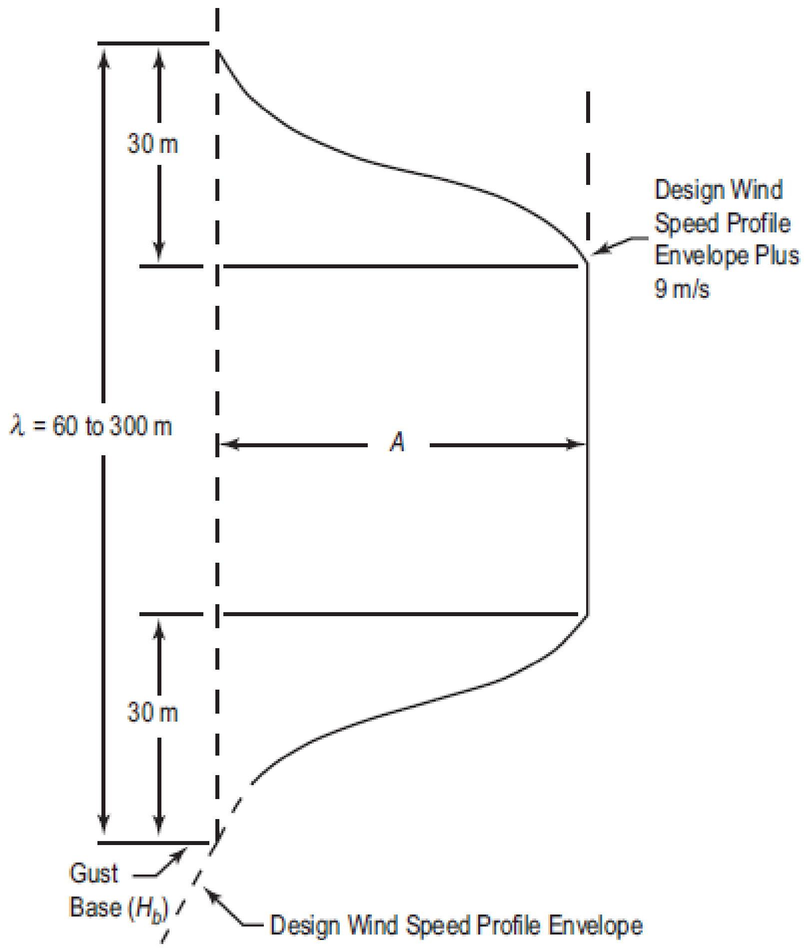

Figure 2-17. Relationship between discrete gust and/or embedded jet characteristics (quasi-square wave shape) and the design wind speed profile envelope.

2.3.7.2 Classical NASA Discrete Gust Model.

Assuming that a design wind speed profile envelope without a wind shear envelope is to be used in a design study, the classical NASA model defines an associated discrete gust of variable length from 60 to 300 m. The leading and trailing edges conform to a 1-cos buildup and decay within an altitude interval of 30 m, as shown in figure 2-17. The plateau region of the gust can vary in thickness from zero to 240 m. An analytical expression for the value of this gust (u_g) as a function of height, H, above natural grade is given by

$$u_g = \frac{A}{2}\left\{1 - \cos\left[\frac{\pi}{30}\left(H - H_b\right)\right]\right\}, \quad H_b \le H \le H_b + 30 \text{ m},$$

$$u_g = A, \quad H_b + 30 \text{ m} \le H \le H_b + \lambda - 30 \text{ m},$$

and

$$u_g = \frac{A}{2}\left\{1 - \cos\left[\frac{\pi}{30}\left(H - H_b - \lambda\right)\right]\right\}, \quad H_b + \lambda - 30 \text{ m} \le H \le H_b + \lambda, \tag{2.73}$$

where H_b is the height of the base of the gust above natural grade, λ is the gust thickness ($60 \le \lambda \le 300$ m), and A is the gust amplitude in meters per second.

The gust amplitude is a function of H_b, and, for design purposes, the 1-percent risk gust amplitude is given by

$$A = 6 \text{ m/s}, \quad H_b < 300 \text{ m}$$

$$A = \frac{3}{700}\left(H_b - 300\right) + 6, \quad 300 \text{ m} \le H_b \le 1000 \text{ m}$$

and

$$A = 9 \text{ m/s}, \quad H_b > 1000 \text{ m} \tag{2.74}$$

APPENDIX B

The following excerpt from Reference 8 is concerned with aircraft response to gust.

Reference 8, Excerpt

Certain simplifying assumptions are useful in computing the response of the aircraft to gusts:

1. The aircraft is a rigid body
2. The aircraft horizontal velocity is constant
3. The gust is normal to flight
4. The aircraft does not pitch
5. Quasi-steady aerodynamic analysis can be used
6. Two-dimensional aerodynamics can be used

Two discrete gust time-histories of practical interest are the abrupt gust and the FAA gust.

The vertical velocity v for time t > 0 is

$$v(t > 0) = \begin{cases} V_o \ , & \text{abrupt gust} \\ \dfrac{Vg}{2}\left(1 - \cos\left(\dfrac{2\pi U t}{25c}\right)\right) , & \text{FAA gust (1988)} \end{cases} \tag{B-1}$$

where

U	is the aircraft forward velocity
c	is the chord length of the wing
V_o	is the vertical gust constant velocity
V_g	is the design gust velocity

Consider random continuous gusts. The von Karman vertical gust spectrum (1961) is widely used for aircraft design.

The velocity power spectral density $S_V(f)$ is

$$S_V(f) = v_{rms}^2 \left(\frac{2L}{U}\right) \frac{1 + \frac{8}{3}(2\pi a f L/U)^2}{\left[1 + (2\pi a f L/U)^2\right]^{11/6}} \tag{B-2}$$

f	is the frequency (Hz)
v_{rms}	is the root-mean-square vertical velocity, equal to 85 ft/sec between 0 and 30,000 ft, and then decreasing linearly to 30 ft/sec at 80,000 ft
L	2500 ft, an integral length scale of turbulent eddies (FAA, 1988)
a	1.330 is the von Karman constant
U	is the forward aircraft speed

APPENDIX C

OTIS 4 Trajectory Optimization Program

The Optimal Trajectories by Implicit Simulation program (OTIS) is a general-purpose program, which is used to perform trajectory performance studies. A user can simulate a wide variety of vehicles such as aircraft, missiles, re-entry vehicles, hypervelocity vehicles, satellites, and interplanetary vehicles. The vehicle models used in OTIS are defined by user inputs; there are no embedded, vehicle specific aerodynamic or propulsion models. OTIS is primarily a point mass, three-degree of freedom (3DOF) simulation program for single vehicles. Options allow six-degree of freedom (6DOF) simulations and several types of limited multiple vehicle problems. The program name is derived from one of the program's methods used to solve differential equations, which was distinctive at the time of OTIS' origin. Trajectory integration can be specified as implicit, explicit or analytic. Flight paths can be generated with respect to any of the major bodies in the solar system. Trajectory generation, trajectory targeting and trajectory optimization can all be accomplished using this program.

For the OTIS developers, trajectory analysis consists of simulating and optimizing vehicle trajectories. Programs, such as OTIS, are used to predict how a vehicle will perform or to determine how to best fly a given vehicle. The resulting data allow a variety of studies to be accomplished including vehicle & sub-system design trades, guidance studies, error analyses and mission planning.

OTIS is a Fortran program.

OTIS4, developed by NASA GRC and Boeing, was released in 2008.

APPENDIX D

POST II

The Program to Optimize Simulated Trajectories II (POST II) is a generalized point mass, discrete parameter targeting and optimization program. POST II provides the capability to target and optimize point mass trajectories for multiple powered or unpowered vehicles near an arbitrary rotating, oblate planet. POST II has been used successfully to solve a wide variety of atmospheric ascent and reentry problems, as well as exo-atmospheric orbital transfer problems. The generality of the program is evidenced by its multiple phase simulation capability which features generalized planet and vehicle models. This flexible simulation capability is augmented by an efficient discrete parameter optimization capability that includes equality and inequality constraints.

POST II increases the trajectory simulation capability of the original POST computer code and provides a state-of-the-art software tool. POST II contains many basic models (such as atmosphere, gravity, propulsion and navigation system models) that are used to simulate a wide variety of launch, orbital, and entry missions. As indicated above, POST II can support multiple vehicles in a single simulation, each with independently defined environments, vehicle and attracting body characteristics. Thus, each vehicle can have its own guidance, navigation, and control system for completely independent, onboard autonomy. Conversely, effects of multi-body and interaction forces that depend on the relationship of one vehicle to another can be included.

Additionally, POST II can support 3DOF and 6DOF trajectories within the same simulation; not only can each vehicle trajectory support different degrees-of-freedom, but also each trajectory segment within a given simulation can be either 3DOF or 6DOF. The internal structure for variable value storage was adjusted in POST II to permit efficient storage of multiple vehicle/simulation information as well as update coding structure to current standards. This usage of variable structures also increases POST II portability to other platforms. Variable structures (and substructures) also provide code efficiency by allowing the same FORTRAN routines to be used for engineering calculations (e.g., aerothermodynamic heating, aerodynamic forces, propellant flowrates, attitude angles, etc.) of all vehicles by simply exchanging the data of one vehicle for another during the simulation. New input enhancements provide N-dimensional tables, multiple criterion to identify trajectory phase completion, Boolean logic for these multiple criterion, and the ability to use variable (instead of constant) values to trigger events, as well as increase code portability between various computer platforms and operating systems.

Several features related to the multiple vehicle capability of POST II enable trajectory simulations not previously possible in a single POST run. POST II provides the ability to initialize multiple vehicles from the state of another during the simulation. That is, an additional vehicle can be initialized by providing input deltas to another vehicle's state (position, velocity, attitude, and attitude rate) at any event in the simulation. This capability also includes a mechanism for transferring some or all of the parent vehicle's angular momentum to the children vehicles. Also, the ability to activate and/or deactivate any number of vehicles at any event in the simulation is included. The standard POST II input options are available to initialize the state of any vehicle being activated. POST II maintains and increases the user's ability to modify certain subroutines for specific applications. The software is constructed such that user provided code can be included to provide vehicle aerodynamic data, atmosphere model, and even optimization capability. While POST II provides very adequate models for including these data and functions, the user has substantial flexibility to include mission specific models as well as company proprietary representations and functionality. Additionally, support for statistical analysis approaches (such as Monte Carlo dispersion analyses) is also provided.

APPENDIX E

Missile DATCOM

Missile DATCOM is a widely used semi-empirical datasheet component build-up method for the preliminary design and analysis of missile aerodynamics and performance. It has been in continual development for over twenty years with the latest version scheduled for release in January 2006. It has been traditionally supplied free of charge by the USAF to American defense contractors. The code is considered ITAR and should not be distributed outside of the country

The 1997 version is available free of charge in a supplement CD of the book "Design Methodologies for Space Transportation Systems", by Walter E. Hammond. The book was published in 2001, by AIAA.

APPENDIX F

Marshall Space Flight Center, Alabama

Marshall Aerospace Vehicle Representation in C (MAVERIC) is a C-language computer program developed for use in performing high-fidelity simulations of flights and analyses of the guidance and control performances of the X-33 aerospace vehicle and the VentureStar reusable launch vehicle (RLV). A secondary purpose served by MAVERIC is determining indicators of vehicle parameters on realistic flight trajectories.

MAVERIC is in a state of continuing development. It is modular and is designed to be readily modifiable for simulating flights of other conceptual advanced aerospace vehicles; indeed, it has already been modified for use in simulating the flight of an orbital transfer vehicle.

The C computing language was chosen for MAVERIC because the X-33 flight software will be in C. Previous available programs that could have been chosen for the present applications were written in Fortran. These programs were not modular and not easily modifiable for high-fidelity computational modeling of the flight of the X-33.

MAVERIC includes subsystem models for the X-33 and the RLV, plus algorithms for monitoring guidance and control performance and trajectory-reshaping algorithms used to fly X-33 and RLV. A MAVERIC simulation can be started at a point other than liftoff. A simulation can include for all phases of flight from launch to the terminal-area energy-management interface [the interface between (1) re-entry into the atmosphere and (2) gliding flight through the atmosphere toward a landing point].

MAVERIC provides options for mathematical modeling of effects of winds, atmospheres, and dispersion. The Global Reference Atmosphere Model and range reference atmospheres are included. A Monte Carlo capability is provided for use in modeling dispersion. Dispersions that can be modeled include those of atmospheres, winds, propulsion, navigation, aerodynamics, and mass properties. Engine-out termination of flight can also be modeled.

MAVERIC is based on the Tframes modular software developed for the U.S. Army for use in simulating vehicles. Detailed descriptions and documentation for MAVERIC do not yet exist.

Marshall Aerospace Vehicle Representation in C (MAVERIC-II) Computer Program

MAVERIC-II is a generic low-to-high-fidelity vehicle flight simulation program that facilitates the rapid development of flight simulations for launch vehicles and space craft. MAVERIC-II is designed to accommodate multi-staged vehicles, powered serially or in parallel, with multiple engines, tanks and cargo elements. Propulsion may be jet engines or conventional rocket engines, using either liquid or solid propellants. Simulations have been developed for (1) a Lockheed-Martin Two-Stage-To-Orbit reusable concept, (2) the X-37 vehicle, (3) a NASA Langley two-stage bimese reusable concept, and (4) a Saturn V vehicle which serves as a generic non-proprietary simulation design template.

MAVERIC-II includes generic subsystem models for the (1) propulsion system, (2) mass properties, (3) reaction control system, (4) aerodynamic properties, (5) guidance system and (6) navigation system. Capabilities exist to start the simulation at points other than lift-off. Guidance system models are provided with MAVERIC-II, which will accommodate (1) ascent, (2) orbital, (3) coasts, (4) deorbit, (5) entry, (6) TAEM, (7) approach and (8) landing flight phases. Options are included in different wind profiles and atmospheres. The program is written in the C programming language. The Global Reference Atmosphere Model is included, as are range reference atmospheres. Monte Carlo capability exists for dispersion modeling. Dispersions modeled include atmosphere/winds, propulsion, navigation, aerodynamics, and mass properties. One can model engine-out aborts and other failures.

APPENDIX G

Load Indicator

The term "load indicator" has several different meanings depending on the context. Here are some examples, with some overlap, taken from several documents.

1. A load indicator may refer to the product of dynamic pressure and total angle of attack.

2. A flight load indicator (FLI) is used to quantify day-of-launch (DOL) ascent loads as a percentage of allowable load at each station along the length of the launch vehicle.

3. Load indicator models combine the control response with other information about the vehicle, trajectories, and flight events to produce estimates of structural loads at pertinent vehicle locations.

4. Some documents refer to a Moment-Based Load Indicators (MBLI). This is a linearized load indicator that makes use of a Taylor Series Expansion to calculate moment partials dependent on various trajectory parameters.

5. The loads resulting from the force-balance and subsequent scaling are normalized by the vehicle's assumed capability to in order to provide a vehicle load indicator. The vehicle load indicators are provided for a number of different load types at every vehicle x-station. At each x-station the vehicle load indicator gives the user a ratio that indicates how close the vehicle is to its assumed limit load at that x-station. A value above 1.0 indicates that the vehicle has exceeded its assumed limit load at that x-station.