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Structural Design/ Margin Assessment

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Structural Design/ Margin Assessment

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Office of Management
Scientific and Technical Information Program

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I. INTRODUCTION

Determining structural design inputs and the structural margins following design completion is one of the major activities in space exploration. The end result is a statement of these margins as stability, safety factors on ultimate and yield stresses, fracture limits (fracture control), fatigue lifetime, reuse criteria, operational criteria and procedures, stability factors, deflections, clearance, handling criteria, etc. The process is normally called a load cycle and is time consuming, very complex, and involves much more than structures. It starts with the concept selection (which this report does not deal with, and is probably the one most important activity); moves through flight mechanics analysis, including mission analysis; and performance analysis, which involves many trades and sensitivity studies. It then progresses through control studies, dynamic response analysis, loads determination, heat transfer, etc., before the structural analysis has the correct inputs to determine the design parameters, the design, and resulting verified margins. Each of these areas requires definition of environments for each mission phase as well as variations and expected changes, not only of environments, but of all parameter variations including manufacturing, building, operations, etc. The goodness of the structural design is, therefore, contingent on the adequacy of each part/step of the total process. Many tools and techniques are available for the various parts or steps of the process, and can be found in textbooks, codes, papers, and other publications.

The process is essentially the same whether one is dealing with a launch vehicle, or its components, facilities, payloads, satellites, orbiting platforms, etc. In general, it requires much information to flow from one part to the other. This information flow is one key to project success. Interface control document (ICD), environment definition, constraints, and the like are all a part of this system process. For example, constraints placed on a system, an element, or a component can compromise a design, creating large sensitivities and problems. Another aspect of this process is the determination of the materials' properties.

The key to successful structural design is the proper implementation of the process outlined above. It depends on many factors: leadership and management of the process, adequate analysis and testing tools, data basing, communications, people skills, and training. This report deals with this process and the various factors involved.

A. Materials Characterization

Although not shown explicitly on many flow charts of load cycles, one key to success is materials characterization. Materials characterization is usually stated in some statistical manner such as A-base. The data take several forms depending on the discipline area that uses it. All parts of the structural analysis require the quantification of the stiffness such as axial, torsional, bending, etc. Then the static strength properties of yield and ultimate are required. Special analysis such as fatigue, fracture mechanics, and stability requires additional and further materials characterization. Structural goodness depends on the accuracy of these data. This means not only the use of the standardized accepted data bases, but the generation of special data bases to fit the problems of the design in progress. This means that the structural engineering and the materials engineers/specialists have to be in constant communication and have a working knowledge of each others discipline.

II. GENERAL OR OVERALL APPROACH

The approach chosen for structural design and verification must be comprehensive, consistent, and focused. Therefore, it is necessary that common philosophies, requirements, criteria, environment data base, models, analysis approaches, verification requirements, configurations, and missions be employed by all disciplines, vehicle systems, and system elements to ensure a compatible risk assessment, design maturity, and design margins. This implies that the total process must be planned, implemented, and managed, starting with the configuration, requirements, and criteria, moving through the mission analysis, environments determination, performance and trajectory analysis, control analysis, loads, and structural analysis and completing with verification. This process then sets many of the operational procedures and constraints. Figure 1 outlines this total process.

Figure 2 attempts to tie together all the different areas for the discipline of environments, analysis, testing, design verification, and operations. Figure 3 shows the makeup of a typical set of environments.

Up front, the basic problem facing design and verification should be clearly stated. The problem: all analyses are limited simulations that attempt to predict trends and approximate physical reality. In other words, models are models, not exact representations of physical law, but are mathematical assumptions of these laws. The number and kind of assumptions determine the degree of replication. Hardware testing in general does not duplicate flight experience, because it is usually a ground test of partial systems and assumed environments. Test constraints, etc., place the limitations as assumptions do in analysis. How we put these pieces together determines the validity of the design (fig. 4). This problem is apparent for all the different pieces of the process.

A. Statistical Implications

One important piece to the puzzle present in all parts of the process to be discussed is the statistical significance of the data. Uncertainties in the definition of loads and environments, materials properties, geometric variables, manufacturing processes, engineering models, analysis tools, and so on, and all types of testing including development, verification, and certification lead to uncertainties in space vehicle and structural design, and ultimately safety. Clearly, quantifying and understanding "problem uncertainties" and their influence of design variables develops a better engineered, designed, and safer system. Two formats are available for characterizing design uncertainties: (1) deterministic and (2) probabilistic/reliability. In actual practice, some combination of the two approaches is used. The classical deterministic analysis approach accounts for design uncertainties in "lump sum" fashion by multiplying the maximum expected applied stress (load, environment, etc.) as a single value, by a factor of safety. Often design verification is achieved by applying worst-case loading (e.g., a 3-sigma load condition multiplied by the safety factor) to the structure and testing to failure. In areas other than structures, the same approach can be used. In contrast, the probabilistic format attempts to map each individual parameter uncertainty into a probability density function. A test-constructed data base gives the best characterization. If test data are not available,

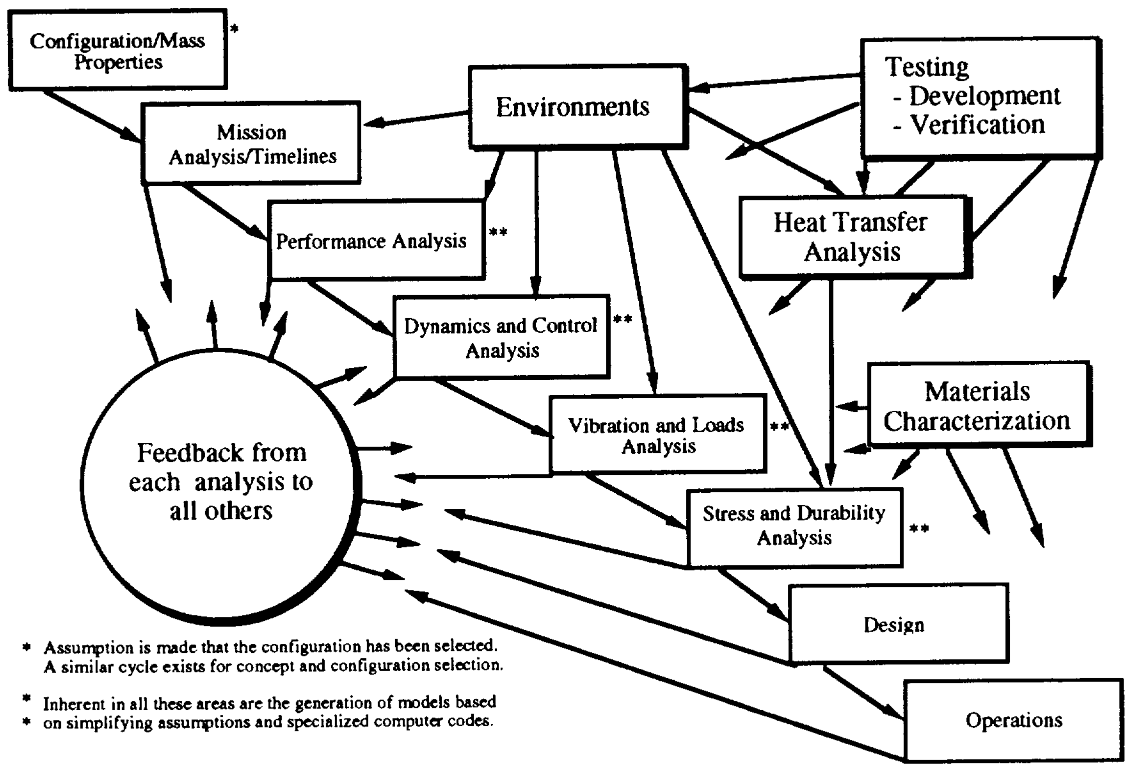


Figure 1. Loads cycle.

Environments

A. Natural
- -Temperature
- -Density
- -Winds
- -Solar Pressure
- -Gravitation

B. Induced
- -Aerodynamic
- -Acoustics
- -Vibration
- -Heating/Thermal
- -Pressures
- -Fluid Flow
- -Control Forces
- -Propulsive Forces
- -Shock
- -Acceleration/Inertial
- -Noise
- -Dynamics

Analysis

A. Performance
B. Control
C. Loads
D. Heat Transfer
E. Stress
F. Fatigue
G. Fracture Control
H. Stability
I. Modeling
- -Str. Dynamics
- -Str. Static
- -Heat Transfer

J. Environments
- -CFD
- -Basic Theory
- -Propulsive

Development Testing

A. Aerodynamics
B. Fluid Flow
C. Propulsive
- -Components
- -All up

D. Structural
- -Vibration
- -Dynamic
- -Static

E. Components
- -Vibration
- -Acoustics
- -Thermal Vacuum
- -Shock

F. Material Properties
- -Basic Characteristics
- -Fracture
- -Fatigue

Design

A. Avionics
- -Software
- -Hardware
  - •Computers
  - •Sensors
  - •Actuators
  - •Power

B. Structures
- -Tanks
- -Interstages
- -Shrouds
- -Thrust Frames
- -Meteoroid Protection
- -GSE
- -Packaging
- -Facilities
  - •Manufacturing
  - •Assembly/ processing

C. Pyro
- -System
- -Devices
- -Logic

D. Control
- -Logic
- -Sensors
- -Actuators

E. Aero/Fluid
- -Geometry
- -Stability

F. Life Support
G. Propulsion
H. Materials
I. Manufacturing
J. Facilities
K. GSE

Verification

A. Environments
B. Structural
- -Dynamic
- -Static
- -Vibration
- -Strength
- -Stability

C. Avionics
- -Software
- -Hardware

D. Thermal/JPS
- -Passive
- -Active

E. Control
- -Margins
- -Software
- -Functional

F. Life Support
- -Mechanism
- -Functional

G. Pyro
H. Propulsion
I. Materials

Operations

A. Procedures
B. Constraints
C. Flow
D. Facilities
E. Communications
F. Computer
- -Software
- -Equipment

Figure 2. Structural design process parameters.

Environment / Life Phase	Atmospheric Properties	Wind and Gusts	Rain	Hail	Sand and Dust	Salt Air	Humidity	Fungus	Atmos-pheric Contaminants	Atmos-pheric Electricity	Solar Thermal Radiation	Albedo	Electro Radiation	Meteoroids	Noise	Runway and Taxiway Roughness
Manufacturing	X				X		X		X							
Storage	X	X	X	X	X	X	X	X	X	X						
Transportation and Ground Handling	X	X	X	X	X	X	X		X	X						X
Prelaunch	X	X	X		X	X	X		X	X	X					
Launch	X	X	X				X			X	X				X	
Ascent	X	X	X		X					X					X	
Space											X	X	X	X	X	
Entry (Winged)	X	X	X							X					X	
Atmospheric Flight	X	X	X	X	X	X	X		X	X					X	
Landing and Horizontal Takeoff	X	X	X	X		X	X		X	X					X	X
Entry (Non-Winged)	X	X							X							
Recovery/Towback		X	X			X	X									

Figure 3. Structural life environments.

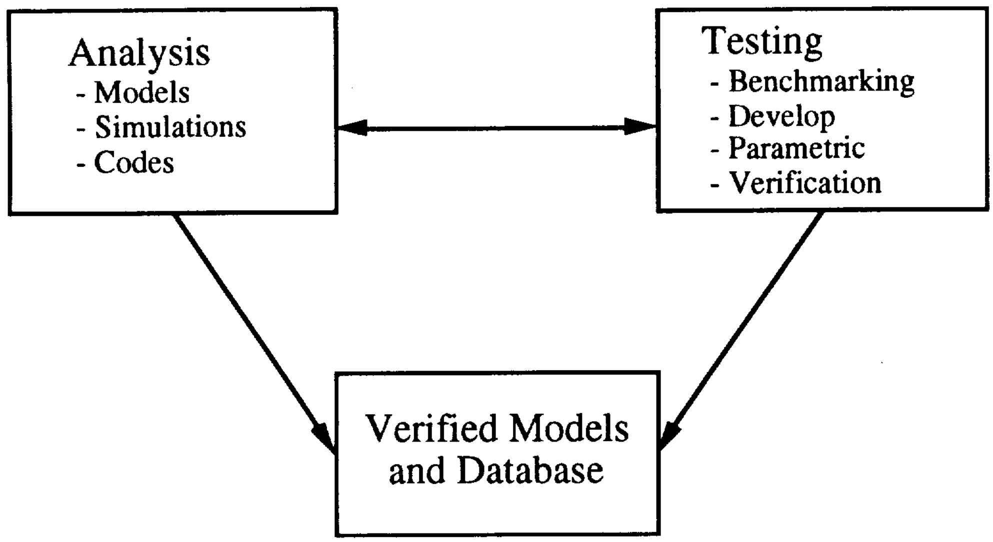


Figure 4. Process.

the engineer must make assumptions concerning the parameter distributions. Once the distributions are defined, transformation equations are used to combine the density functions into a cumulative distribution function of the design variable; for example, applied stress. In this case, the design parameter has an uncertainty that is quantified in terms of risk.

In the case of the design of aerospace structures, it is possible in the near future to develop a NASA structural design code based solely on the probabilistic format without compromising the historical structural safety of hardware design (work at Lewis Research Center and other NASA Centers). This statement is especially true with respect to the currently available probabilistic engineering analysis tools and test verification programs. In general, the analytical tools that have been developed are difficult to understand and implement into design procedure. More importantly, the methods have not been test-verified or universally accepted by the engineering community. Before a probabilistic-based design code or program can be successful, design engineers must develop an experience and education base in the field, plus accumulate adequate failure data bases. Today most engineering schools do not offer probabilistic-based design courses as a part of the curriculum. This does not mean, however, that these approaches do not have merit. They serve as excellent tools for assessing design concepts using sensitivity analysis and trade studies. Other design disciplines such as avionics have substantial data bases and, therefore, are using probabilistic analysis in many ways in the design and verification of their hardware.

True reliability must be demonstrated, not simply estimated, from an engineering analysis. Until failure and failure rate data are available from experience, probabilistic methods can best be utilized as a design tool to help identify the sensitivities of problem parameters. Furthermore, "demonstrated structural reliability" is virtually an impossible task due to the expense and small number of structures that NASA builds. This is not true in avionics. However, it may be feasible to develop a more consistent structural design code that uses the probabilistic format in combination with the accepted safety factor approach to design. The civil engineering profession has successfully used a combined format in the development of the load and resistance factor design (LRFD) code as an option for steel structures. Developing this concept for application within NASA offers a natural extension to the current work tasks (long-term objective) and provides a practical source for future research.

1. Components

All aerospace system components are designed, qualified, and accepted using probabilistic approaches. Their design, in general, is driven by shock and vibration environments that have their source in mechanical or acoustical excitations. Shock is also a source of these excitations. Because these high-frequency environments are nearly impossible to analytically formulate, extensive data bases have been developed for both the excitation and the response of basic structural types with different type (and size) of components. Input and output responses are put in probabilistic format to serve as a base for formulating design, qualification, and acceptance criteria. Using this criteria, shock and vibration tests are run on each component. In special cases, all-up acoustical tests are run as a further verification of the system, using the probabilistic acoustical environment as input. The shock and vibration discipline has become very successful using this approach. However, it has been accomplished through a universal effort to establish data bases, special instrumentation, data evaluation, and basing techniques (see later paragraph).

2. Dynamic Engine Data

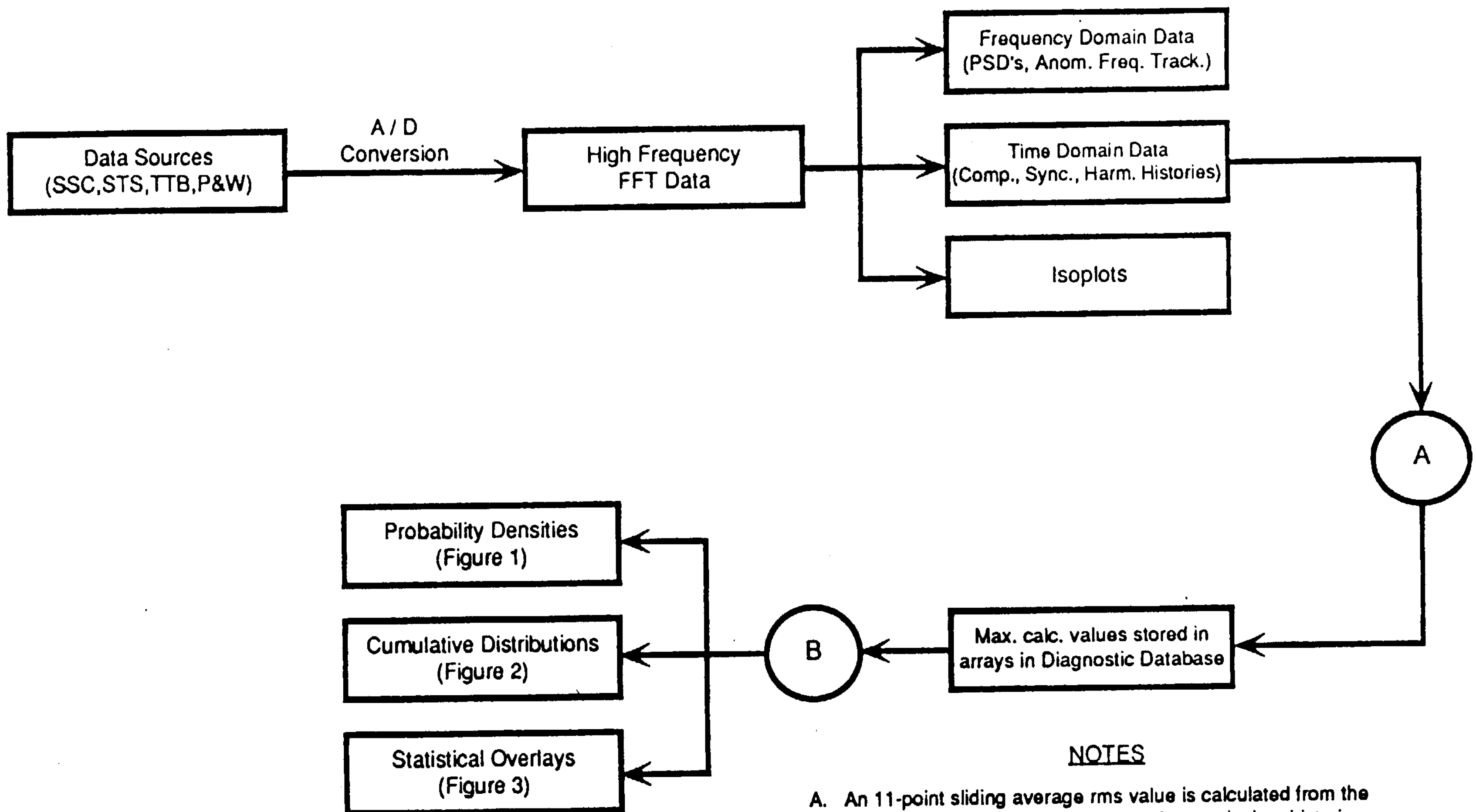
The space shuttle main engine (SSME) has had an extensive program to collect dynamic data (also performance), statisize it, and use it for structural durability, turbomachinery health, and maintenance and refurbishment of hardware. This data base is cataloged by engine number, parts number, test number (or flight), and test stand. Most firings and flights are over 500 s in duration, and the frequency content of interest ranges up to 3,000 Hz. Figure 5 illustrates the basic approach for the statistical processing of the data. Obviously, this creates a very large data base requirement, as well as the need for fast processing schemes and user-friendly access of the data. Figures 6, 7, and 8 are typical plots of data outputs. By combining all test and flight data, including test failures, it is possible to statistically say what constitutes healthful hardware and to determine good hardware during green runs, as well as when to change out parts. In addition, the engine has been mapped into vibration zones and acceleration data acquired for use to determine loads for hardware assessment and redesigns. These data can also be used as a starting point for future engine system design.

3. Dynamic Responses/Loads

Probabilistic approaches have been used extensively in determination of launch vehicle control and dynamic responses and loads. The environments that produce these responses exist as natural and induced environments. The aerospace community has developed a natural environments data base that is very extensive and includes atmospheric density, temperature, winds, solar pressure, etc. This statistical data base serves as one environment distribution into the response analysis. Propulsion system characteristics have had the same rigor applied to their thrust, thrust rise rate, oscillations, and thrust vector misalignments, to serve as inputs for these analyses. The other induced environments, such as aerodynamics, are based on wind tunnel testing and computational fluid dynamics (CFD) to determine their characteristics. The resulting analysis (loads) can be accomplished using deterministic approaches or probabilistic analysis, depending on the needs. Figure 9 is a flow diagram of how this is accomplished for structural analysis. This data base, in conjunction with day-of-launch wind measurements, etc., can be used to ensure a safe launch.

4. Basic Approach

The basic probabilistic approach can be summarized as the quantization of all input data, the plant model (describing equations), and the output in a statistical manner. This requires the use of a



NOTES

A. An 11-point sliding average rms value is calculated from the composite, synchronous, and sync. harmonic time histories for each measurement at each engine power level. The max. average value found at each power level for each measurement is then transferred to the Diagnostic Database.

B. Statistics can be generated for any combination of pumps or engines from this database utilizing these stored values.

Figure 5. SSME high-frequency data statistical processing.

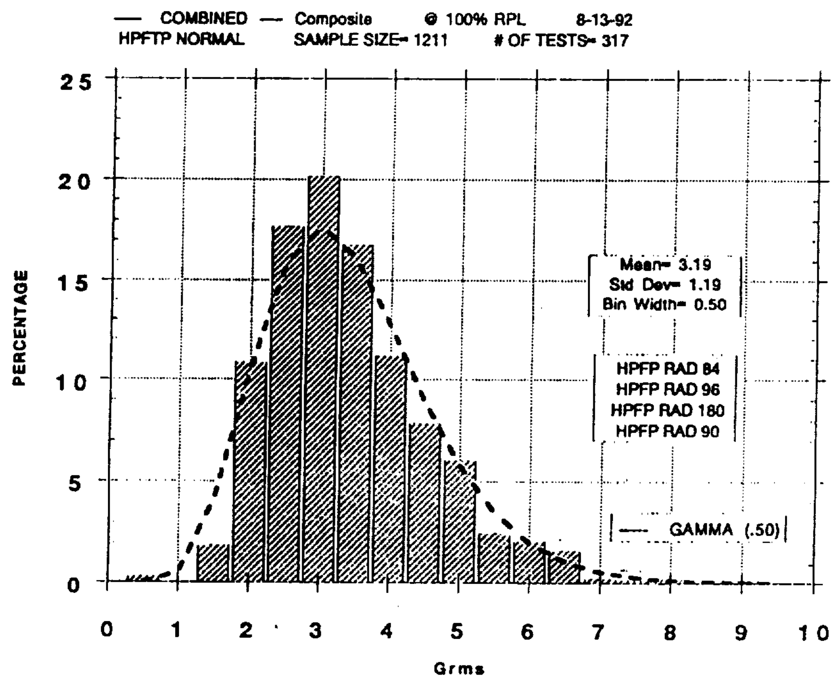


Figure 6. Diversity function distribution.

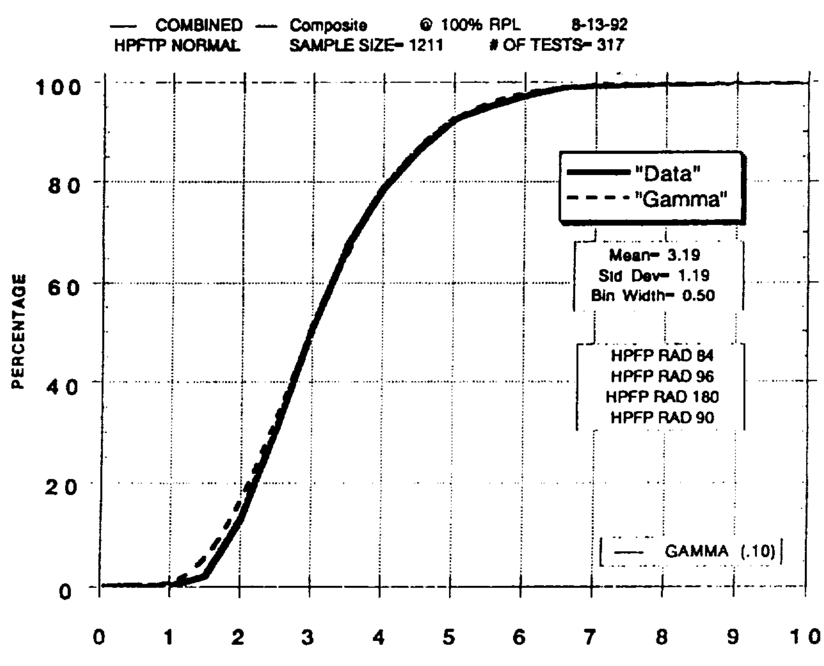


Figure 7. Cumulative distribution function.

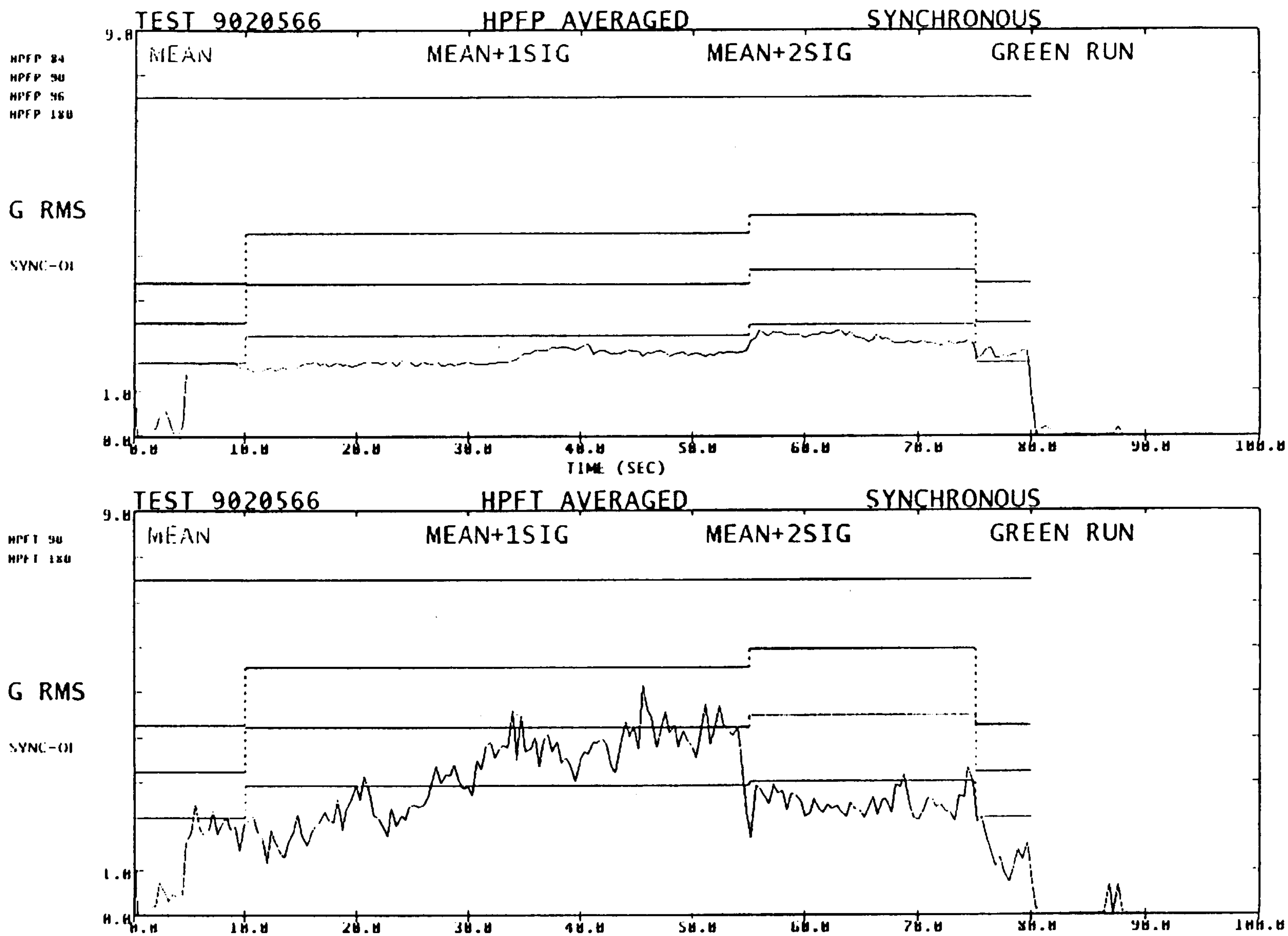


Figure 8. Pump acceleration compared to hot-fire test history.

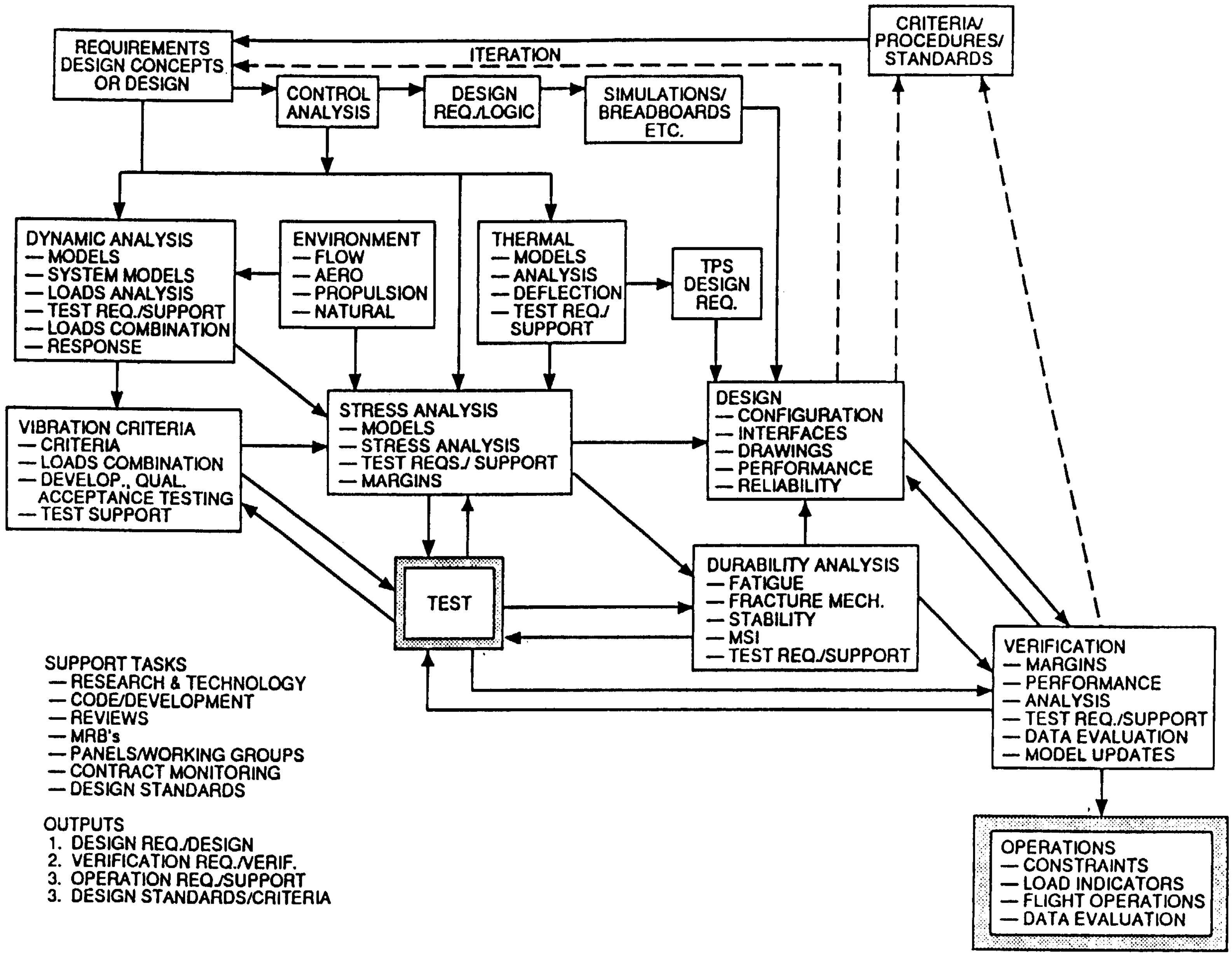


Figure 9. Structural analysis generic flow.

statistical procedure to take the plant model and the input data and produce a statistical/probabilistic output. These techniques range from pure Monte Carlo to integral solutions. Figure 10 illustrates this process for structural assessment. The left-hand side of the figure shows all the input data, indicating some statistical distribution of each. The right-hand side illustrates the various capabilities of the structure, while the center shows the output of the process again in a statistical sense. Nothing is said about how the input or capability data are generated, nor how the plant equations are solved to get the stress or capability distributions. Many techniques exist to accomplish this task. The describing equations can be solved using Monte Carlo approaches by inputting the parameters as statistical distributions then solving the equations for the various combinations selected randomly. The output becomes a probability distribution function or statement. The same equations can be solved using the A-factor approach and the 3-sigma limits of each parameter. The A-factor approach allows the generation of a 3-sigma equivalent time response analysis by root sum squaring the deltas for each parameter variation. This root sum squared value is used with the individual deltas as a ratio to apply to the plant coefficients. The output is a 3-sigma answer. Other techniques exist to deal with this data.[1-8] Regardless, the object is to rate the probability of an event occurring against its capability to deal with that occurrence. This means understanding and predicting the failure modes or capabilities. Given that these can be accomplished, then it is straightforward to know how failures occur. Whether one uses Baysian statistics or many other tools, key statements can be made concerning the reliability of the system when the data or good estimations are available.

This same sequence flow takes place for the deterministic assessment; however, no real probabilistic or reliability statement is usually made concerning the outcome. Ideally the probabilistic statement is highly desirable. In practice, this may not be possible; however, it is prudent to utilize as much statistical information as possible about the characteristics of the system. This means that, in reality, a blend between the deterministic and the probabilistic should be used. How failure modes are dealt with in the design and verification is a key question that results. For example, the design of a launch vehicle dictates that liquid engine failures/shutdowns be considered. The question that arises is: How? Do you combine the total 3-sigma parameter variations with engine failure at anytime during mission sequence or do you combine the probability of engine failure with some level of system dispersions that will produce a 3-sigma total response? The space shuttle dealt with this problem in the latter way. Regardless of how the approach is finalized, it must be dealt with in performance, control, loads, thermal, and so on, as part of the loads cycle and must consider all critical failure modes.

Regardless of the approach taken, it must be consistent across the total load cycle process. Also, its accuracy is driven by both the accuracy/understanding of the input data and the accuracy/understanding of the plant (describing equations, simulations, models, etc.). In the discussion that follows, it is assumed that the statistical implications are understood.

B. Configuration Definition

The configuration must be defined very specifically for the various analysis and development testing that are required to end up with the structural design, verification analysis, and test. The definition starts with the line drawings, defining all dimensions and interfaces, and identifying the various major subsystems and elements. Mass characteristics by elements, subsystems, and systems are first stated as mass, inertia, and center of gravity, followed by mass distributions that are required for certain analyses. Propulsive characteristics must be included along with basic

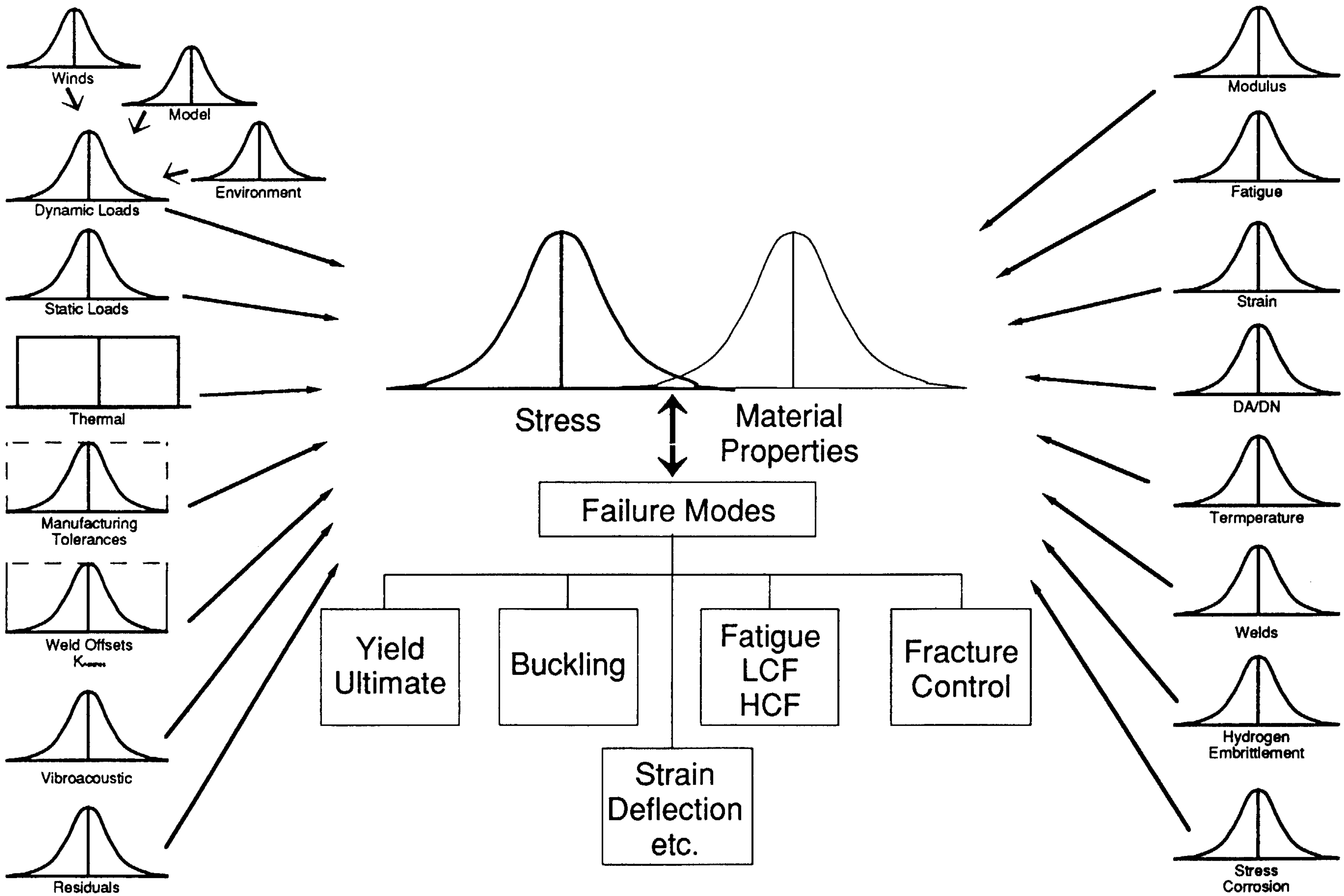


Figure 10. Probabilistic analysis concept.

mission objectives. Concurrent with this configuration definition is the establishment of the general philosophy, guidelines and criteria.[9] It must be emphasized that all these definitions/characteristics be constant across all analyses that feed data to the final structural analysis. This requires that management must set procedures that ensure this consistency.

C. Philosophy, Criteria, Ground Rules, and Guidelines

Key to successful design is the definition of the underlying philosophy, criteria, standards, and guidelines placed on the project. Criteria, standards, and guidelines set the design and verification requirements. They, in general, are legally binding and are, therefore, a fundamental focus of verification. Criteria not met must be waivered, or the product should be redesigned to meet the requirements. Legal requirements must be simple, unambiguous, concise, and direct, providing orders to the engineering process; but not overpowering to where they stifle creativity and remove responsibility.[10] "Optimal performance needs administration for order and consistency (formal) and leadership (informal) so as to mitigate the efforts of administration on initiative and creativity and to build team effort to give these qualities extraordinary encouragement. The result, then, is a tension between order and consistency on the one hand and initiative, creativity, and team effort on the other. The problem is to keep this tension at a healthy level that has an optimizing effect."[11]

Determining the design and operational philosophy is the last guiding decision that has to be made. Many times this is dictated by top management. This is not the best approach. Clearly, philosophy should be made by a team of all areas (disciplines) that are affected by the choice. Many philosophical questions arise such as do you design for redundancy? If yes, in what areas? For example, it is usually not practical to have redundancy in primary structure, while avionic components are generally designed for some level of redundancy. The level of redundancy is a subset of this question.

A trap that is present in using criteria, standards, and philosophy is the dependence on them (the set of requirements) to accomplish a good design while relaxing good engineering practice. In the final analysis, skilled personnel applying good engineering thoughts and practices are the roots of good products. Regardless, development of criteria, standards, guidelines, and philosophy is a part of the loads cycle and successful design.

D. Mission Requirements and Analysis

The first part of mission analysis is to determine the basic requirements. For payloads to orbit, this includes inclination for launch vehicles and launch sites. For a satellite, it includes the orbit, orientation, pointing, and stability. The mission analysis moves from requirements to define mission sequence of events, timeliness, to abort considerations, etc., necessary for the load cycle. Clearly, it can be argued that this precedes the configuration definition; however, in reality, the two move concurrently along with preliminary performance analysis. These are accomplished by iteration cycles. By the time the real load cycle starts (the purpose of this paper), this iteration has been partially accomplished. However, the load results influence the events and must be fed back as a part of the fine-tuning process. Therefore, this part of the process basically determines the sequence of events and timelines. Clearly, the completeness of these definitions is important to the process. In fact, some would put transportation, assembly, etc., as a part of this process area. Regardless, they must be specifically spelled out in order to identify all subsequent analyses required.

E. Environments Definition

Definition and verification of the environments required for all the various analyses and test tasks are very critical to success. Not only must the mean, or expected, value be determined, but also the uncertainties. In general, it is better that this be in some statistical representation. The environments must be established in a consistent data base; however, each analysis task usually requires a different formulation. For example, rigid-body vehicle control analysis for ascent flight only needs total aerodynamic coefficients of normal forces, drag, and moments, while an elastic-body loads analysis must also include aerodynamic distributions along the vehicle body points correlated or consistent with the rigid-body data.

Environments are classified as natural and induced. The natural environments are (see fig. 2 and 3 for more details):

1. Atmospheric winds
2. Temperatures
3. Atmospheric density
4. Solar pressures
5. Magnetic fields
6. Chemical
7. Gravitational.

Induced environments are broader in scope and can be complex nonlinear functions of the system operating conditions and responses. The following list is an example (see fig. 2 and 3 for more details):

1. External flow
   a. Aerodynamics
   b. Aeroacoustics
   c. Propulsion: acoustics, overpressure, thrust, oscillating pressures, drag
   d. Noise
   e. Electromagnetic
   f. Solar pressure
   g. Aeroheating
   h. Plume heating

2. Internal flow
   a. Acoustics
   b. Pressures
   c. Turbulence
   d. Temperature

3. Pyroshock

4. Control forces

5. Propulsive forces
   a. Steady state
   b. Oscillating
   c. Acoustics

6. Vibration.

To the degree that these environments can be understood and quantified is, to a large measure, the degree that structural integrity can be determined. This means that the best in human skills, analysis and computation, and developmental testing must be employed. With the complex shapes and high performance requirement of the modern space system, the problem of accurately determining these values must be balanced with the best tools as well as testing techniques. This means well-formulated theories applied using computation fluid and mechanics tools and statistical tools in conjunction with the test. Deming[12] emphasizes the importance of theory in data interpretation. The approach generally is to anchor all analysis tools through benchmarking against special test and known data (fig. 4).

F. Flight Mechanics/Performance

Outputs of the flight mechanics/performance analysis are one of the keys to accurate structural design and verification. This occurs in several trajectory sets that are generated to create a 3-sigma condition for each unique discipline design. For example, a 3-sigma trajectory for a launch vehicle for thermal environments is different from a 3-sigma trajectory set for loads. This analysis task then has two basic functions; the first of which is to determine the 3-sigma performance characteristics, and the performance reserves and residuals which sizes the tankage and sets certain parts of the mission sequence. The second function generates the specialized 3-sigma reference trajectories required for all the design and verification tasks, including but not limited to:

1. Loads
2. Thermal
3. Control
4. Aborts
5. Maneuvers
6. Aeroelastic
7. Run and docking
8. Orbit transfer
9. Reentry and landing.

Between the mission analysis and the flight or orbital mechanics, the baseline trajectory, timelines, sequence of events, etc., are determined. This provides the framework for all design and verification analyses (figs. 11 and 12).

As a part of this process, the analysis areas that use and follow performance analysis must feed the various constraints that influence performance optimization back to the performance discipline. The space shuttle performance/trajectory has several constraints that greatly influence the optimization. The trajectory constraints are as follows, and the aerodynamic heating limiting is shown in figure 13.

- q-flutter and loads—650 nondispersed, 820 dispersed
- $q\alpha$, $q\beta$ or α, β-orbiter wing and tail
- SRB separation conditions
- SSME minimum throttle at 65 percent
- 3-g max acceleration
- Thermal
- Aborts

For example, to meet the q constraint, two options are available, SSME throttling and trajectory lofting. SSME throttling is more optimum in that there is only a 25-lb payload loss for each 1-lb/ft^2 reduction in q, whereas lofting has the penalty of a 150- to 200-lb payload loss per 1-lb/ft^2 q reduction. The $q\alpha$ and $q\beta$ constraints can be met by:

- α and β shaping
- Wind biasing
- Load relief
- Operational day of launch constraints.

All of the above constraints cost the system. For example, load relief costs performance and introduces a high thermal load when the path error caused by this load relief is corrected (fig. 5). In all cases, it is a balancing act, a tuning between conflicting requirements. This means that all areas must have open communication and continuous feedback in order to achieve the best system. Obviously cost, reliability, and schedule greatly influence these decisions.

It is, therefore, mandatory that good understanding and communication exist between this group and all the design and analysis groups to ensure completeness and compatibility. This is true whether one is dealing with a launch vehicle, a satellite, space station, etc. The trades are different, the analyses are different, but the process is basically the same.

G. Control and Dynamics Analysis

Control and dynamics analysis is fundamental to the loads cycle. In general, it sets the boundaries for the induced environments. In fact, the control forces themselves are part and parcel of these induced environments. There are two fundamental ways that these effects can be determined first. The control discipline in the natural design process determines the control design, including the control system logic and all its parameter variations which satisfy both stability and response

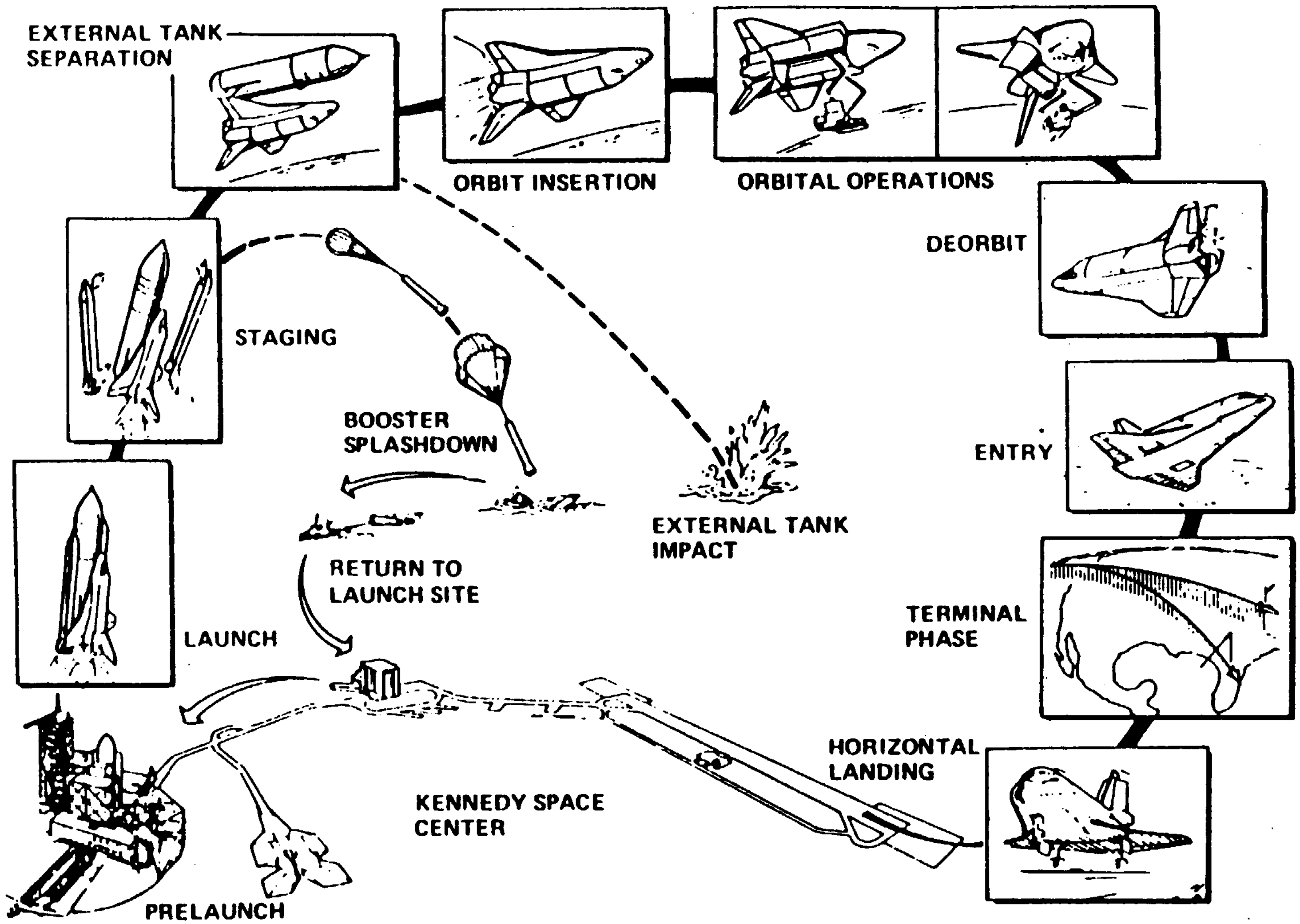


Figure 11. Typical mission profile.

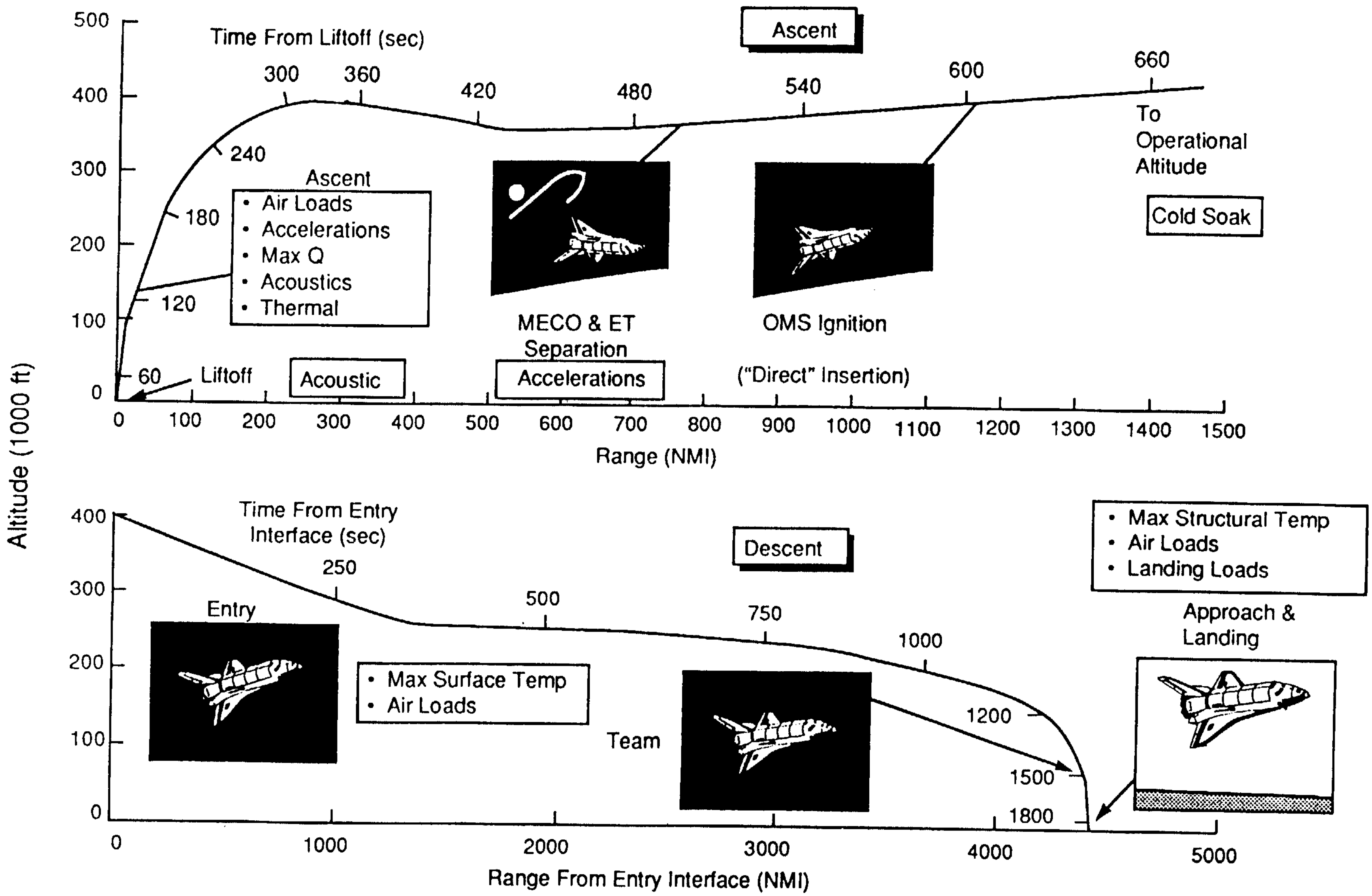


Figure 12. Typical ascent and descent trajectory profiles.

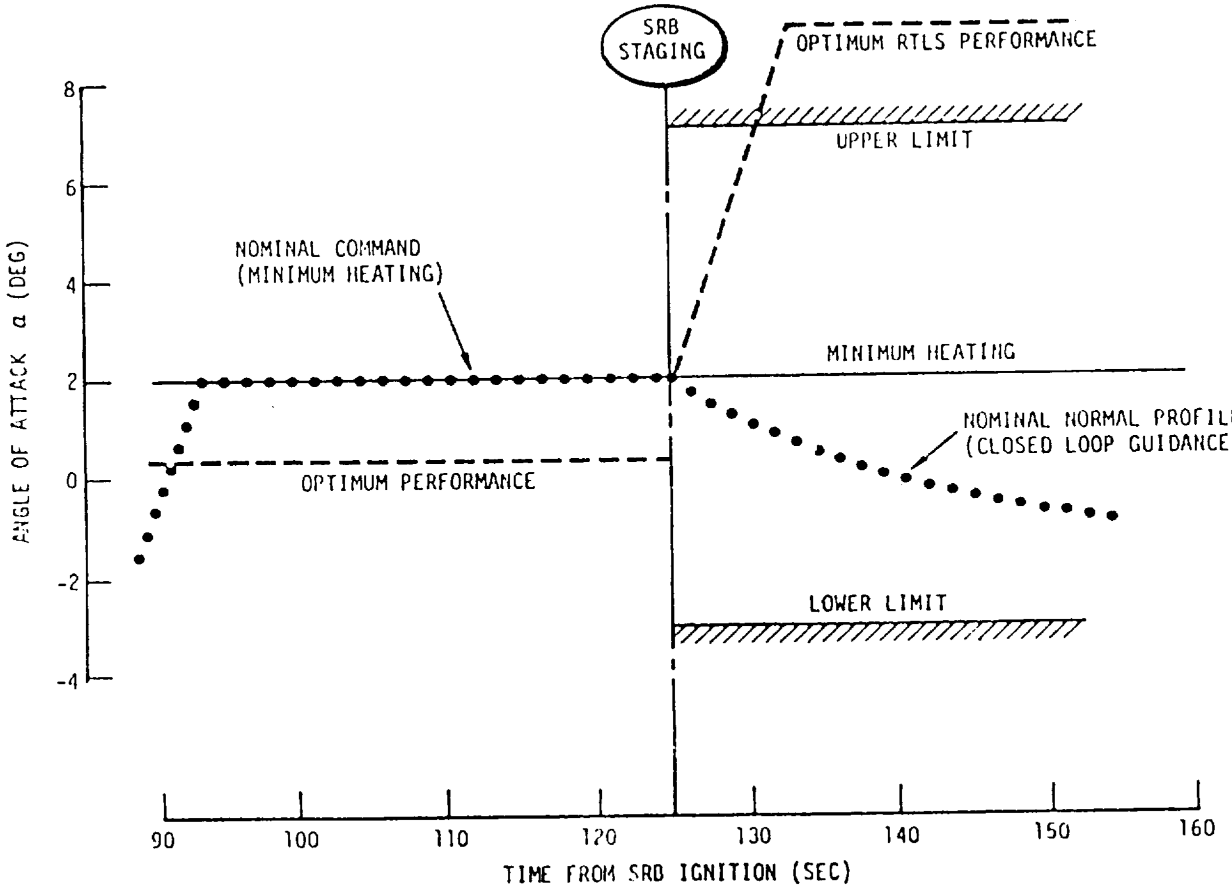


Figure 13. Aerodynamic heating limiting.

considerations. These data logic and parameter variations are given to the loads analyst along with the reference trajectories (fig. 14). He then runs the response and loads analyses. Then, control response analysis can be run in a manner which develops the critical induced environment envelope parameters which are used by the loads analysis teams to generate loads. For example, control response analysis can generate compatible sets of 3-sigma control forces and response parameters such as angle of attach, gimbal angles, rigid body rotation, and translations—including rates, accelerations, and impact forces such as docking. Loads can be computed directly from these data sets (figs. 15 through 18). For the space shuttle, where the key parameter is aerodynamics, $q\alpha$ is plotted versus $q\beta$, providing a simplified set of 3-sigma design conditions (fig. 19). These squatchloids must be generated for each Mach number providing an aerodynamic design envelope as a function of time (fig. 20). Trim gimbal angles (control forces) and lateral and rotational accelerations envelopes must be provided and be compatible with the squatchloids. Both approaches have been used successfully. The choice depends on the project (vehicle, satellite, etc.) and its characteristics. Many times one approach can be used for early design phases, then later design

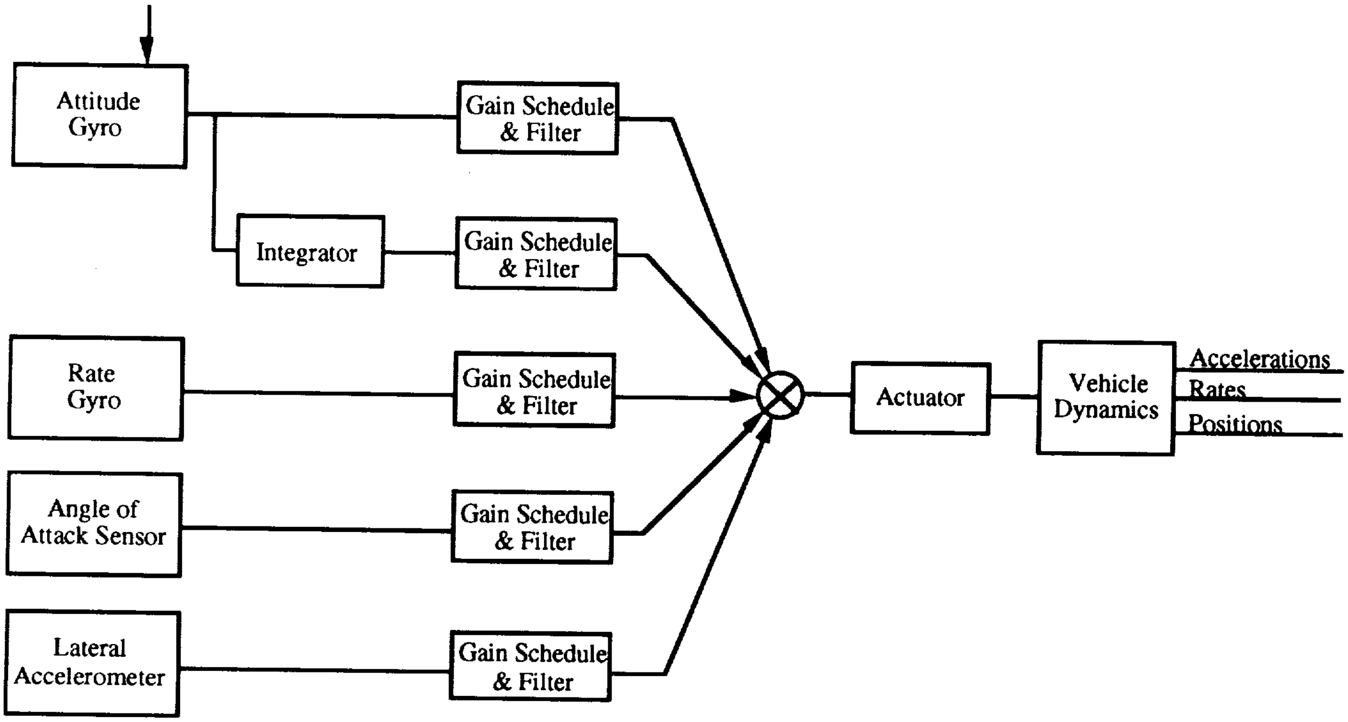


Figure 14. Pitch control block diagram.

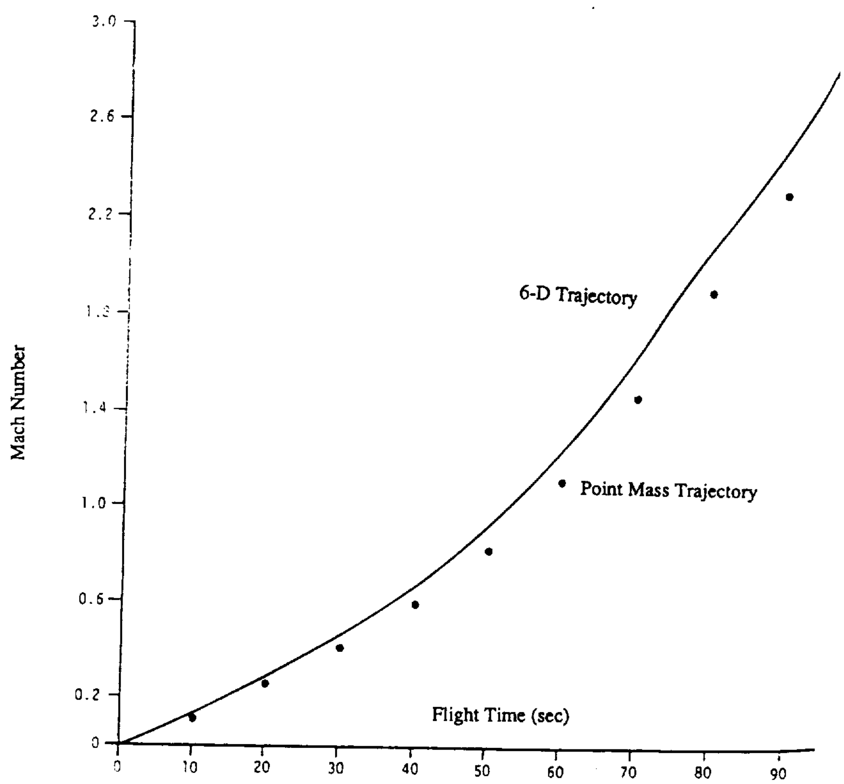


Figure 15. Comparison of Mach number between point mass trajectory and full dynamics trajectory.

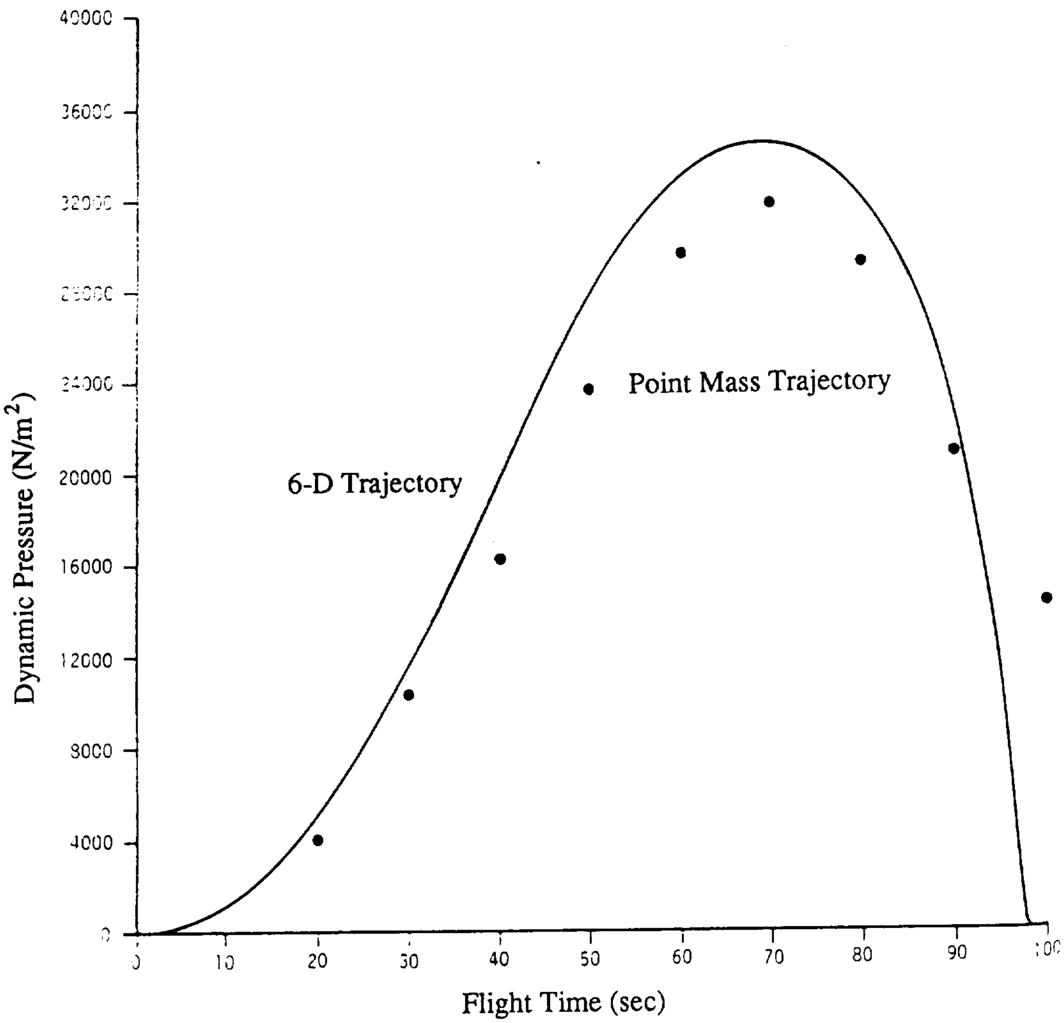


Figure 16. Comparison of dynamic pressure between point mass trajectory and full dynamics trajectory.

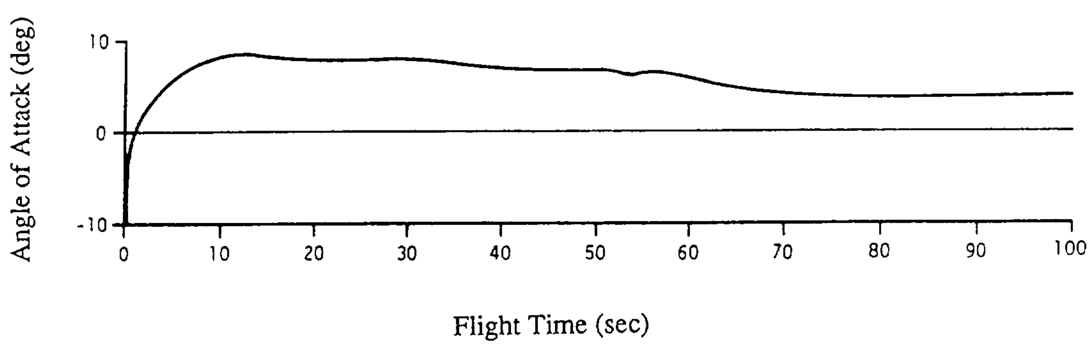


Figure 17. No wind angle of attack.

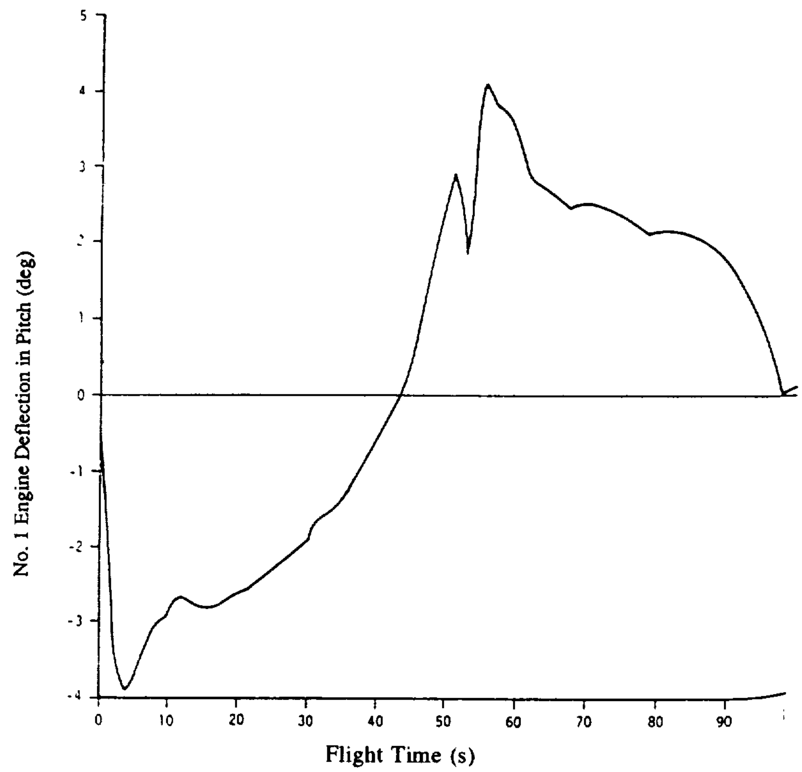


Figure 18. No wind pitch gimbal angle.

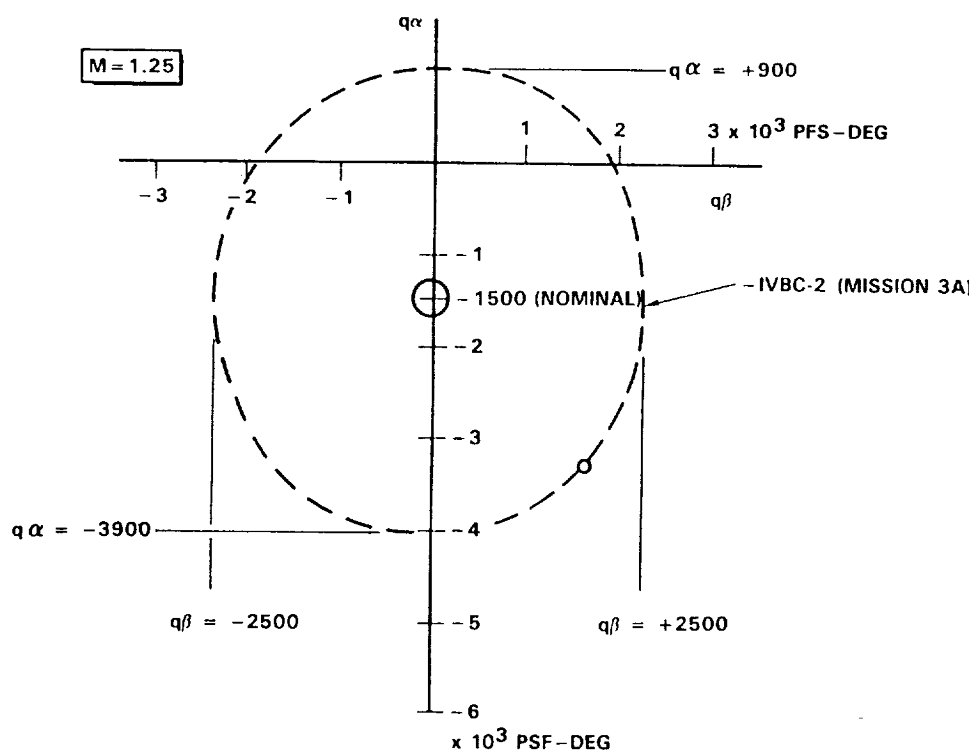


Figure 19. Graphic representation of flight envelope by use of a squatcheloid.

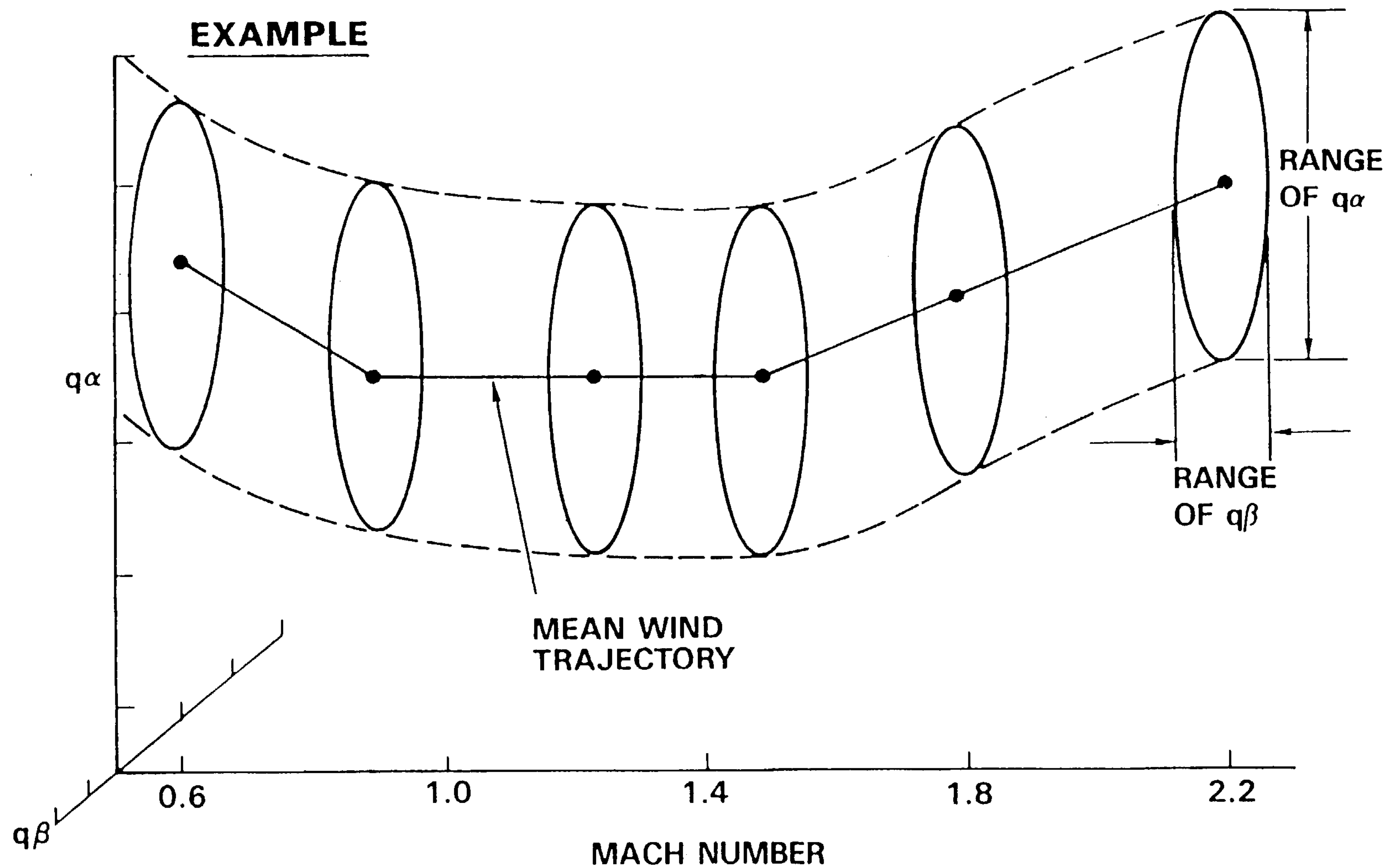


Figure 20. Family of squatcheloids representing flight conditions.

phases would require another. Regardless of the approach chosen, dynamics and control analysis is a key element of the load cycle and must be conducted for all events it interacts with. Some of these events include:

1. Lift-off
2. Max q
3. Separation
4. Rendezvous and docking
5. Pointing
6. Maneuvers.

In addition to all three analyses areas, control functions allow the reduction of responses and loads by passing the requirement of structural redesign to meet margins/verification requirements. In fact, the design can be optimized through the use of control logic such as load relief, modal suppression, auto land, and ride control. This approach, in general, saves weight but always introduces additional failure modes which must be considered as part of the loads cycle.

The rest of the process starts with the loads analysis and heat transfer analysis which become inputs for the stress analysis. The resulting stress analysis determines the inputs for the strength analysis and the durability analysis, determining preliminary margins that are verified in the verification process. All these tasks are treated in detail in later sections of this report. The discussion left for this section is how this process is managed and integrated.

H. Leadership/Management/Integration

A fundamental factor in the design of successful structures is the leadership/management/ integration function. One of the problems experienced on NASA programs has been a breakdown in the systems or integration activities. There has been a tendency towards a linear sequential dump-it-over-the-fence approach that discourages interdisciplinary communication. This results in missed interactions, creating design problems that can result in performance, cost, and schedule impacts. Key to solving the systems and integration issues are leadership and management. The importance of leadership cannot be overemphasized because it sets the mission, the goals, and, therefore, the culture of the groups and the process. Obviously, this has a major impact on the loads cycle success. Just as important is the management approach used. There are many tools as well as approaches that have been successful. Each project has to determine the ones that best fit that project. Some factors are: the project scope and size; the number of elements, subsystems, and components involved; the number of sizes of organizational elements (contractors, government, etc.); and the project complexity (both technology and organization). A few examples are sited for insight; however, regardless of the approaches, some elements are mandatory: (1) critical path schedules that show all the interaction flow, (2) cost control, and (3) technical integrity/recovery.

The space shuttle used a fairly complex organization to ensure integration (fig. 21). This was required due to the vehicle and Government/contractors' organizational complexity. This system has

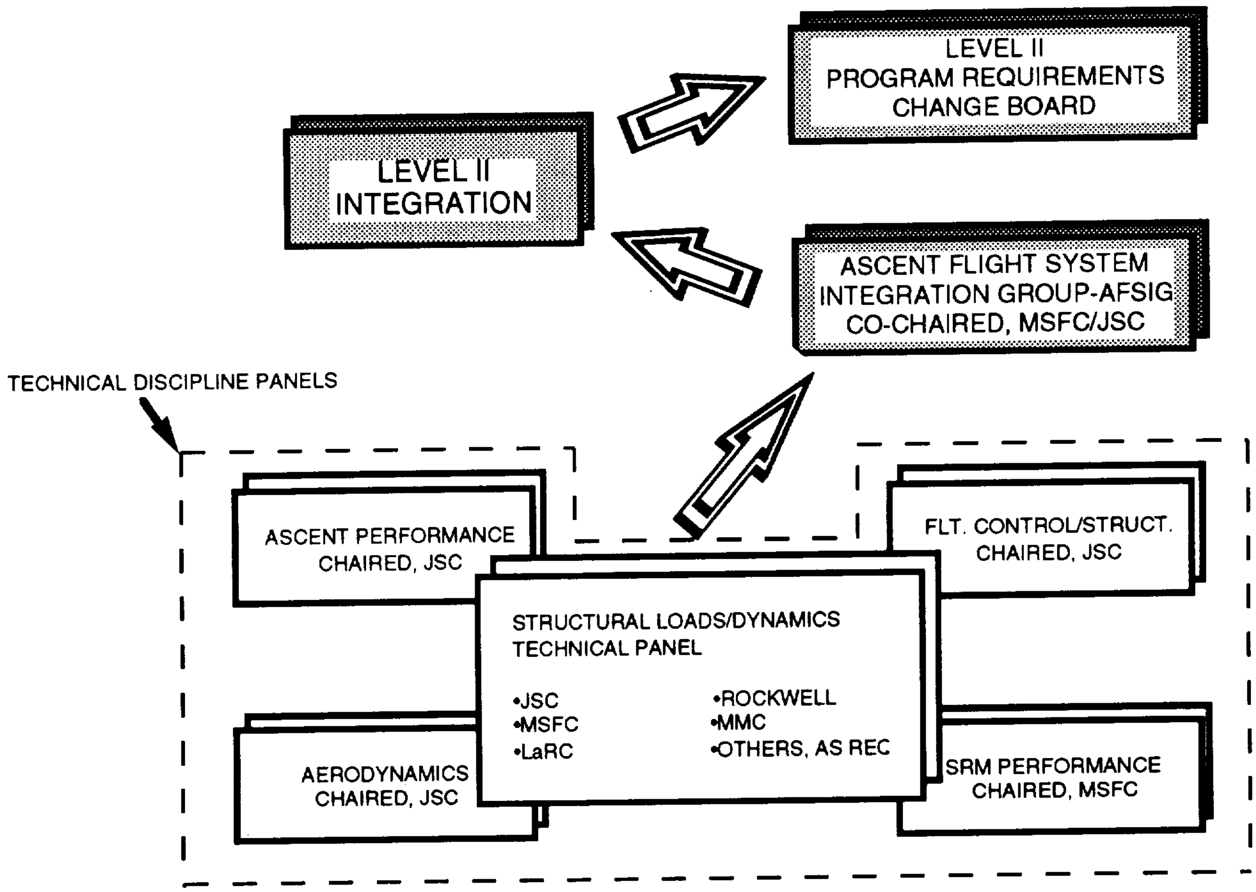


Figure 21. Shuttle level II criteria management flow.

at the top level a program change board that approves all changes that affect cost, schedule, and performance. There is a hierarchy of groups that formulate the recommended changes and carry out the integration function. The over-arching group is the systems integration review (SIR) which has two supporting integration working groups: (1) propulsion (PSIG) and (2) ascent flight (AFSIG). There is a series of technical panels that support these two groups, handling technical issues and trades. The two working groups become a forum for reviews and a mechanism for formulating recommendations to the SIR and finally the Program Requirements Control Board (PRCB). The two working groups also ensure that consistent criteria is used by all areas.

The Hubble space telescope used a series of technical panels that were integrated by the project and chief engineer's offices. Also, during the last 2 years prior to launch, ad hoc Government teams of both project and engineering were located at both the Lockheed and Perkin Elmer plants. The SSME has extensively used ad hoc teams composed of both Government and contractors to solve technical problems and integration management through the chief engineer's and project offices.

As total quality management (TQM) philosophy and tools have evolved, projects are now accomplished using product design teams. In these cases, authority is delegated to the teams for engineering, cost, reliability, and manufacturing. This is proving to be a very successful approach. "Skunk works" have also been used successfully. Management books, courses, and computer software are broad in scope and offer much information and resources. Each project must survey these and decide what is best for them.

The rest of this report focuses on the structural part of the load cycle depicted in figure 22. The end results of the structural part are the design parameters associated with strength, durability, fracture control, stability, and response envelopes, and at verification and operations, the margins associated with these areas. Four fundamental tasks feed the stress/durability/stability/response tasks. These are model development, development and verification testing, heat transfer (thermal) analysis, and loads analysis. The following sections address these tasks.

III. STRUCTURAL TASKS

The basic concept and philosophy of this part of the loads cycle are shown in figure 22. The process starts with each element and its subelements providing the structural models and all pertinent parametric data (example: solid rocket booster (SRB) thrust, thrust rise rate, pressure) to the integration contractor for the system loads analysis. These models must be compatible with all other element models and with the final element stress analysis models.

The system integration approach, parameter variations, statistical criteria, and verification required are worked through the integration groups. Using these criteria, loads analysis for each design condition (parameter combinations with natural environments) are to be conducted and loads outputed. Figure 22 also shows some of the natural and induced environment used to determine the loads. These analyses are made in a statistical manner such that the resulting responses (loads, etc.) are at an approximate 99.7-percent probability level of occurrence when varying all system parameters and environment values within the expected range. Included are all vehicle parameters and natural environments, such as wind speed, wind shears, and wind gust. Individual parameter variations will not necessarily be at the 3-sigma level, but the resulting variations produce a 3-sigma combined statistical response. For example, a 3-sigma response would not have individual 3-sigma wind speed, shear, and gust in combination, but would be a 3-sigma response using the individual probabilities (distribution) of these wind parameters. This response can be accomplished in the response analysis using such techniques as Monte Carlo, or on the environment side, by creating a combined 3-sigma wind environment. The loads are output as bending moments ($M_x(t)$, $M_y(t)$, $M_z(t)$), shears ($S_x(t)$, $S_y(t)$, $S_z(t)$), and interface forces where applicable, $Pi(x, y, z, t)$. Vehicle stations for these outputs are determined by the element needs and integration requirements.

Using the appropriate sets of operational interface and external loads on each element, the structural design parameters and margins are determined. Phase IV starts with a more detailed model (than the one used in system loads analysis) in conjunction with the interface capability plus the interface forces for conducting subelement responses. The subelement response which follows provides more detailed structural capability by using a still higher fidelity model. In addition, this subelement analysis provides the interface forces for a detailed linear and nonlinear analysis of any substructure that requires special considerations or shows low margins. This analysis is to be accomplished using very fine grained models in conjunction with special codes and analysis techniques. The heat transfer and structural models developments are a big part of these structural tasks. The same points made previously in terms of modal or simulation compatibility and consistency apply to these areas also. For example, a test with wrong boundary condition assumptions produces erroneous data. It should be clear from this general approach discussion that models, response data, input data, etc., must be consistent and compatible to ensure proper results. The following sections discuss the details of each of the steps and provide some typical examples.

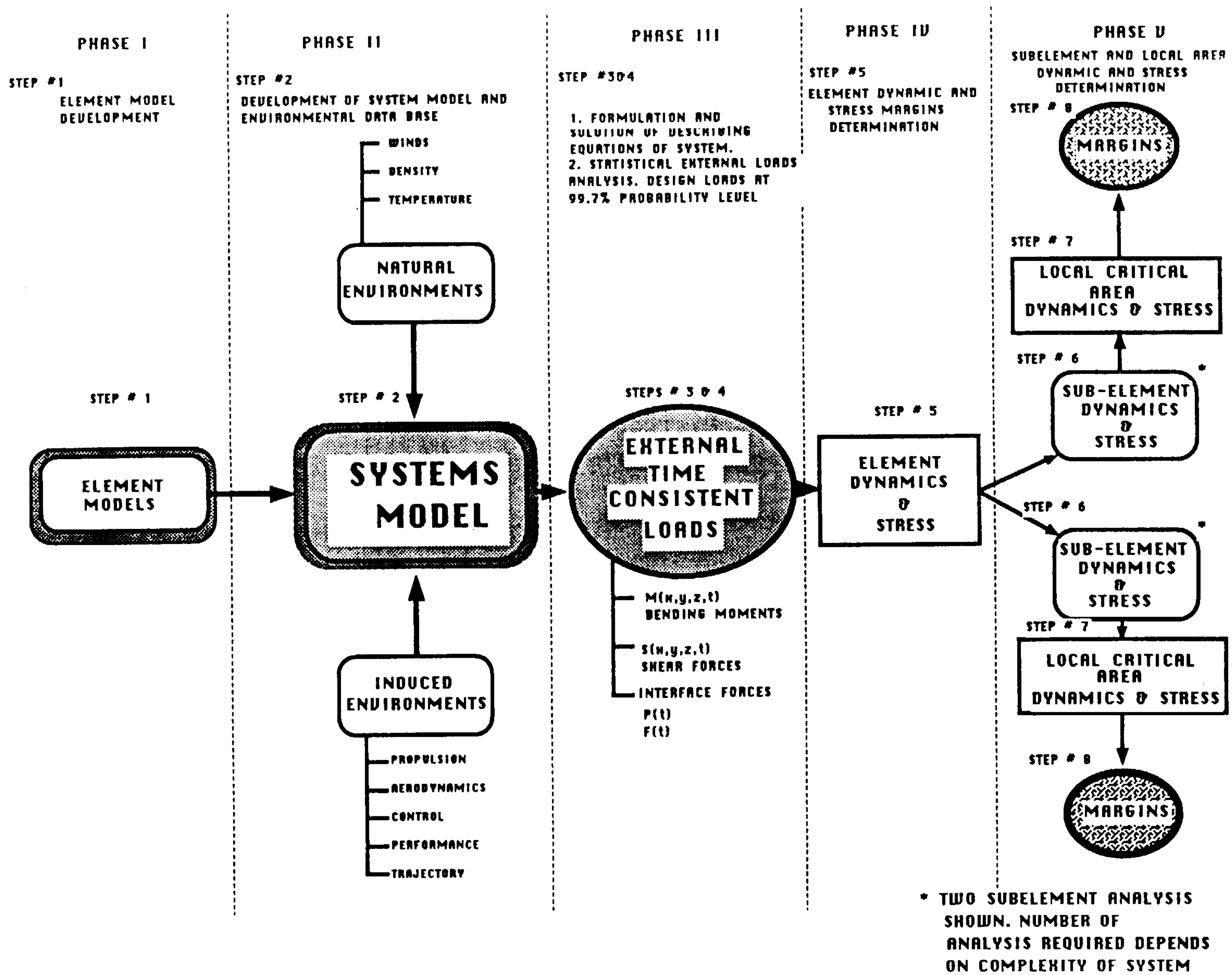


Figure 22. Structural analysis.

It should be pointed out at this time that throughout each of these phases, two major principles or procedures must be adhered to: (1) conduct sensitivity studies to the level that a good understanding exists for all interactions and that key parameters are understood, and (2) conduct simplified hand analyses including free body diagrams, flows, schematics, etc., so that the phenomenon is clearly understood. This insight also serves as a guide to the more comprehensive studies. Computational and testing techniques have become so sophisticated that, without these guides, serious errors will be made. Remember, all computer models, analyses, etc., are models and only as good as the assumptions used.

A. Systems Loads Analysis

Systems external loads analysis approaches are treated extensively in references 1 and 13. This section will highlight the key elements found in these references and in special presentations made over the years. Together these constitute the basic approach to calculating systems loads. The system loads analysis must use models for each element that are of proper detail and characteristics to predict systems interaction and to account for the accurate loads distribution and all element-to-element forces. This means that all element-to-element interface structures and backup structures are correctly accounted for in the system analysis and that these forces are output properly. Figure 23 shows how these interaction studies are conducted. Included in this figure, besides the models, are the additional interactions between environments, performance, loads, and verification. The solid arrows show the interactive analysis portion. The open arrows show the verification. This interaction is depicted for the loads analysis on figure 24 by showing conceptually how the data flow occurs for the different phases of the margins assessment. This chart is a more detailed depiction of the loads and stress portion of figure 22 showing how use is made of interdisciplinary analysis. Notice the strong interactive loops depicted by the double lines. Notice that the major outputs are ultimate and yield margins of safety, fracture mechanics/nondestructive investigation (NDI), fatigue (lifetime), stability, and responses.

1. Approach

The approach used to generate space shuttle loads will now be elaborated on as an example of loads analysis for the lift-off regime in order to make the external loads analysis process clearly understood. The first step (fig. 23) utilizes test-verified dynamic models of each element (SRB, external tank (ET), SSME, orbiter, payload, mobile launch platform (MLP)). These models are coupled together using proper interface models in conjunction with either substructuring or modal controlling techniques. This step produces an overall vehicle dynamic model containing up to 300 modes with frequencies through 50 Hz. Step 2 takes this complicated dynamic model and descriptions of all known forces and formulates a set of describing differential equations which, when integrated time-wise, will describe the dynamic characteristics of any point on the shuttle structure. Various methods can be used to develop this set of equations; however, the Lagrange equations are usually used by selecting sets of generalized coordinates. This allows writing the kinetic and potential energy functions, dissipation functions, and, through virtual work, the generalized forces. Integration of the resulting equations, using either digital or hybrid computers, produces the responses and external loads (step 3). Because generalized forces are not precisely known (i.e., only known to a test-verified statistical level), a discrete loads case will not describe the design loads. Step 4 consists of running many cases of loads determined by taking different combinations of the possible variations in generalized forces. Because different parts of the structure will show

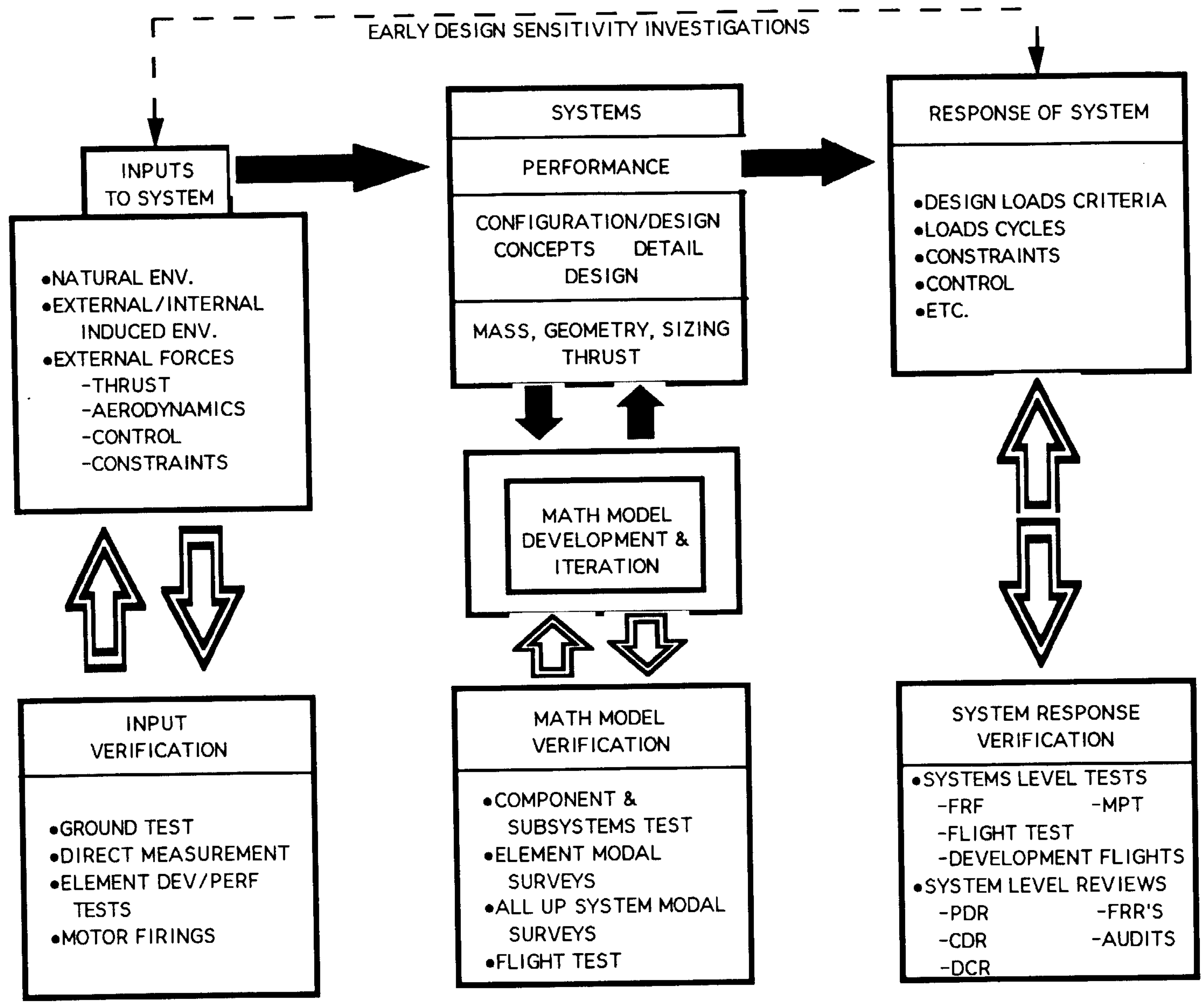


Figure 23. Loads analysis flow.

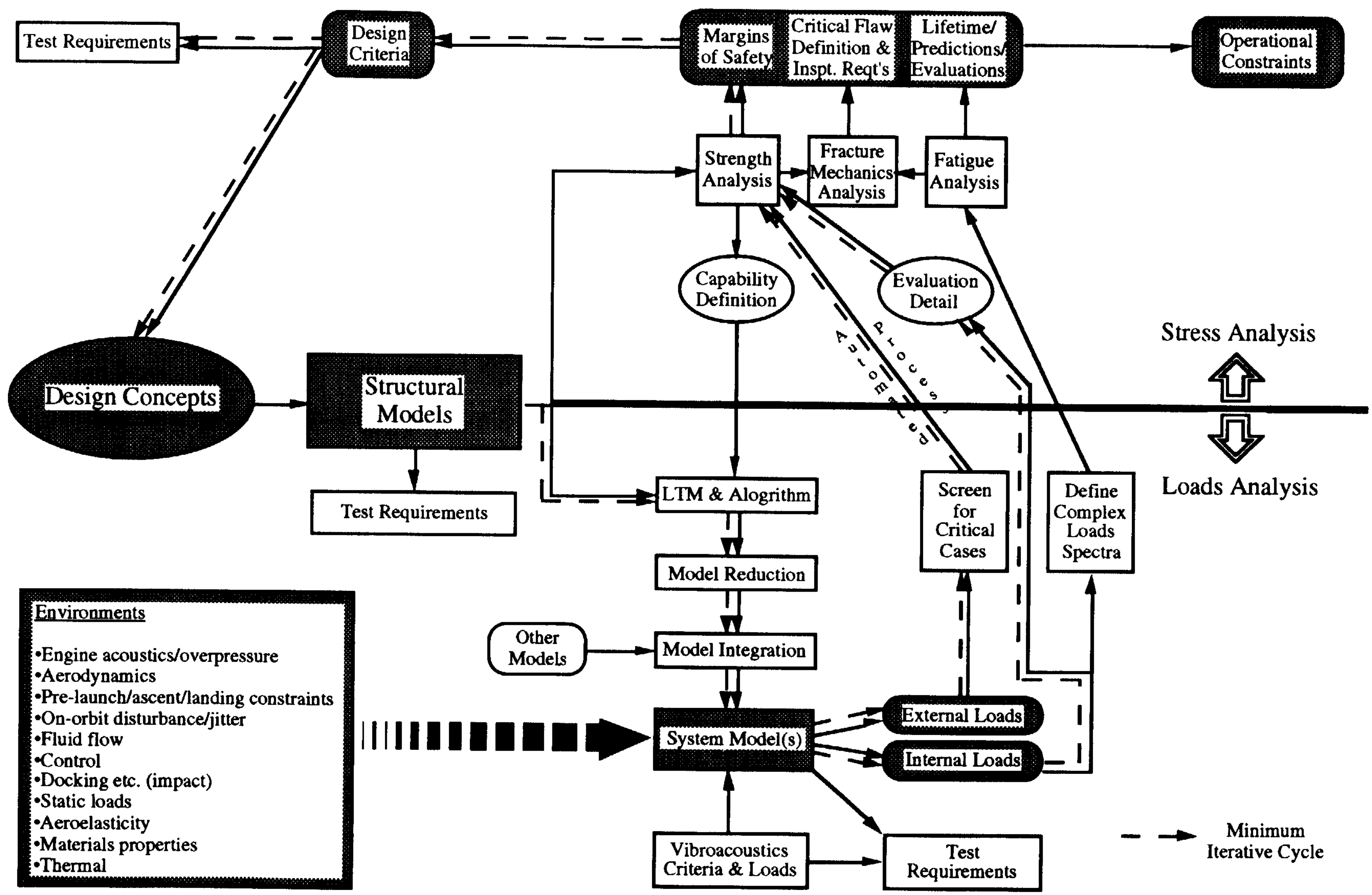


Figure 24. Structural analysis flow.

higher loads for different parameter combinations, enough cases must be run to maximize loads for all critical structures. Figures 25 through 27 show the parameter set varied (generalized forces/parameters) for developing lift-off loads. Presently, it takes 27 cases to develop loads for all pertinent shuttle structures. Therefore, the loads analysis progresses through this process by varying the vehicle and environmental parameters to obtain these 27 sets of 3-sigma loads response. As discussed in the overall section III, 3-sigma loads response is a vehicle structural load that has a 3-sigma probability of occurrence under all possible natural and induced environment combinations, not worse-on-worse combinations of 3-sigma levels of each parameter. One discrete loads case is not possible because different wind directions and other parameters maximize the load for different parts of the vehicle structure. In order to facilitate determination of these different cases, load and stress indicators of critical structural areas are utilized. Load indicators are algorithms that relate external loads to structural capability. Load and stress indicators should be developed early in a program and updated as required in order to simplify analysis and outputs. Two typical indicators are shown on figures 28 and 29. These loads and stress indicators and/or transformation can be analytically determined as part of determining dynamic and stress models or by curve fitting stress analysis results as a function of key parameters (see later section). Using these indicators and other design criteria, design loads cases are run for each of the shuttle operational flight events as was discussed for lift-off. These shuttle operational events include:

1. Transportation
2. Assembly
3. On-pad (including vertical assembly building-to-pad move)
4. Lift-off (SSME ignition through lift-off transient)
5. Max Q
6. High g
7. Reentry (SRB and orbiter)
8. Water impact (SRB)
9. Towing (SRB)
10. Landing (orbiter and payloads)
11. SRB separation
12. ET separation
13. Aborts
14. Pointing
15. Man motion
16. Docking
17. Breaking
18. Planet landing
19. Maneuvers.

	Analysis Tolerance
Vehicle Dynamics	
• First 50 bending modes with 1-percent damping	None
Failure Models	
• None	
Analytical Approach	
• Digital simulation of vehicle flexible body response due to applied forces and release of base constraints	
Combination Method	
• Sequence of events selected or max loads (WOW)	
• RSS similar uncertainties as a group then add groups (± 2s deviations) in worst-on-worst combination	
Documentation of Results	
• SD73-SH-0069-1, -2, -3, and -4 structural design loads data book	

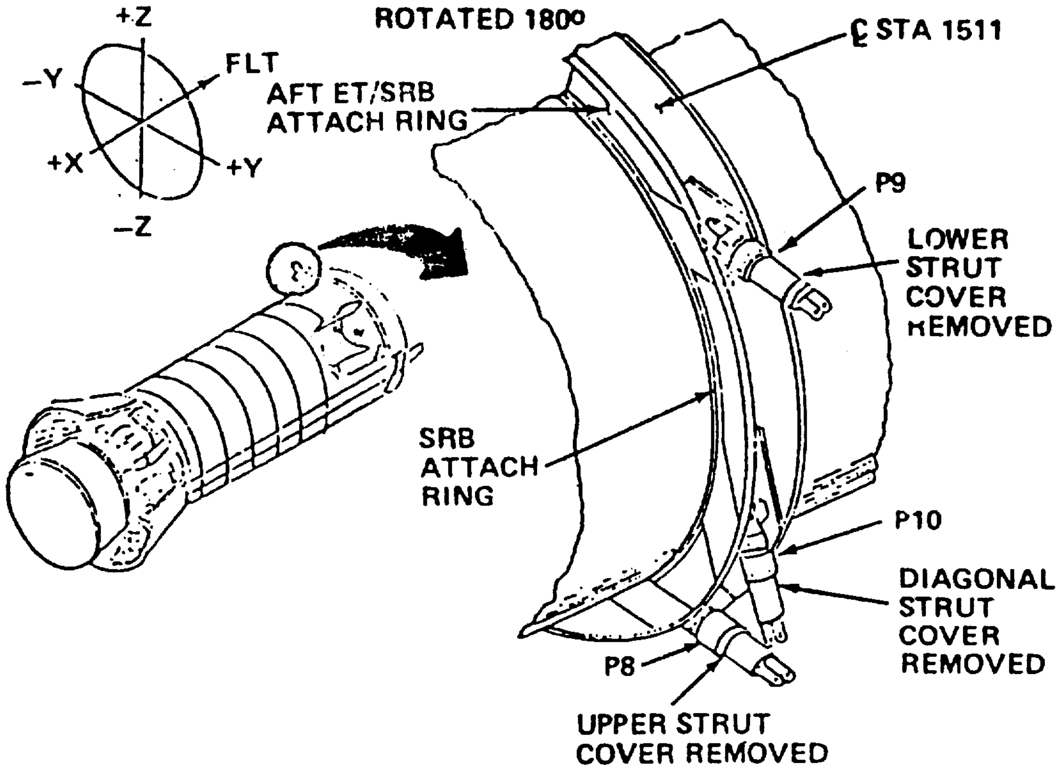
Figure 25. Parameter variations for loads analysis.

	Analysis Tolerance
SRM Propulsion	
• TC227A-75 thrust vs. time curve per se-019-083-2H (SRB systems data book) for max/min grain temperature (TC227H I proposed as update)	90 °F (ETR) 40 °F (WTR)
• Thrust level development uncertainty	± 3 percent
• Steady-state thrust mismatch between SRM's	35,000 lb
• Flight-to-flight thrust level uncertainty	± 5 percent single motor ± 4.percent both motors
• Thrust buildup rate development uncertainty	Ref: SDIL SRM76-037
• Thrust misalignment	± 0.50 percent (both); 0.707° (one)
Aerodynamics	
• Ground wind drag coefficients per SD72-SH-0060-2 (mated vehicle aero design data book) and Rockwell Internal Letter (SAS/AERO/75-430	None
Main Propulsion	
• 3 SSME's at 100 percent thrust (RPL) to 109 percent thrust (RPL)	None

Figure 26. Parameter variations for loads analysis.

	Analysis Tolerance
Mass Properties	
• Minimum payload of 2,500 lb (mission 3B)	None
• Maximum payload of 32,000 lb (mission 3A)	None
• Maximum payload of 65,000 lb (mission 3A)	None
Miscellaneous	
• SRB/MLP holddown bolt preload (750,000 lb)	None
Flight Control and Guidance	
• Rockwell Control No. 7 per SD73-SH-0047-1 (Integrated vehicle flight control system data book)	None
• All nozzles gimbal but SRB nozzle gimbal limited to 2° for first 5 s	± 0.17° (SRB) ± 0.23° (SSME)
• SRB mistrim to 0° until SSV clears the launch pedestal	None
• STB TVC misalignment	2s RSS each SRB in worst condition
External Environment	
• 95-percent wind speed (one hour exposure)	None
• Peak wind speed	24 knots (max)
• Tuned gust (worst case)	None

Figure 27. Parameter variations for loads analysis.



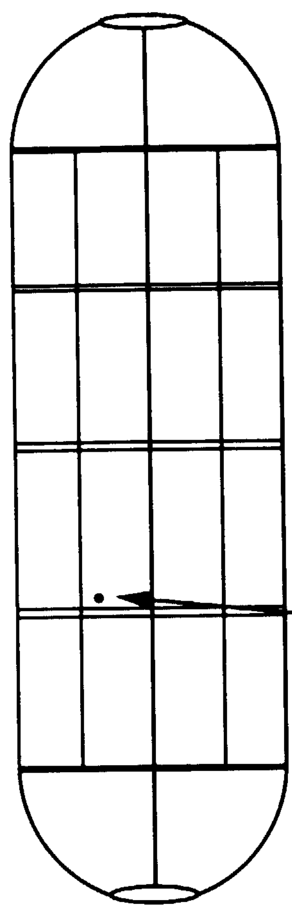
VEHICLE MOMENT (CLOCKWISE) LOOKING AFT ON VEHICLE.

MAX. MOMENT = 28945 X $10^3 \geq -P8\ (57.0) + P9\ (57.0) + P10\ (68.34)$

NOTE: NO MOMENT CAN EXCEED THIS VALUE FOR ANY CONDITION.

CRITICAL AREA	
FAILURE MODE	

Figure 28. SRB load indicator, aft attach.



Load Indicator Equation L3-42

$$22535.3Fx1871 + 8.1452^{M}Y1871 + 108.19^{M}Z1871 - 11821FT07 \leq 10^{7}$$

Effectivity () Design Condition	PL	LO	HQ	BA	PR	(PO)	OA	OE
		X	X					
Critical Area	Barrel Panel 0 = 43° Station 1859							
Failure Mode	Stability		Strength			Other		
	At Ult. Load							
Factor of Safety	Indicator		Analysis			Test Demon.		
	1.53		1.53			1.76		
Indicator Error 0%			Effectivity Cond S.F. = 1.33					

Figure 29. ET load indicator, hydrogen barrel panel.

The more important parameters to be varied in order to provide the sets of 3-sigma loads are:

1. Control (gimbal angle, gimbal rates, vehicle acceleration, vehicle rates, angle of attack, etc.)
2. Propulsion (thrust, thrust rise rate, pressure, etc.)
3. Winds (speed, shear, gusts, and direction)
4. Pyro (thermal)
5. Trajectories (load relief, launch azimuth, orbit, payload)
6. Inertia
7. Mass
8. Configuration (geometric offsets, shapes, etc.)
9. Aerodynamics
10. Payload variations
11. Mission variations.

Satellites are an example of other projects that are even more complex in that they must survive the environments of a launch system such as space shuttle as well as all the phases of the rest of the mission that includes such events as:

1. Docking
2. Rendezvous
3. Retrieval
4. Maneuvers
5. Maintenance
6. Pointing control
7. Orbital plane changes
8. Etc.

All are exposed to a different set of environments such as:

1. Solar heating
2. Solar pressure
3. Gravity gradients
4. Magnetic field.

The process, the concerns, the approaches, etc., are in the same category as those discussed under space shuttle loads. There are various techniques/tools that are available, but not discussed under shuttle loads, such as frequency responses, probabilistic techniques, acceleration factors, Miles relationship, data banks, etc., that have been used very successfully. Modern computers and their high speed have opened the choices even more.[5-8 14 15] All should be considered and weighed in terms of accuracy, efficiency, etc. The final choice depends on the project/system under development.

2. Shock and Vibration/Loads Combination

One aspect of loads analysis that is not usually discussed in general load cycle reports is vibration/loads combinations. All parts of a structure that are elastically mounted (most hardware is elastically mounted) and has a mass under 500 lb have a fundamental part of their loads generated by vibration. They also influence the structure to which they are mounted. In general, the frequency spectrum of the vibration of interest is from 50 to 2,000 Hz. The sources of these vibrations are:

1. Aeroacoustics
2. Mechanical
   –Fans
   –Turbopumps
   –Valves
3. Pyro
4. Propulsion
   –Main propulsion
   –Auxiliary propulsion.

The approaches are straightforward and are based mainly on empirical approaches, although some advances analytically have been made in techniques such as statistical energy methods (figs. 30 to 34). The first step is the determination of an external forcing function if applicable. The second step determines the vibration criteria. This can be accomplished in at least four ways. (1) The first way is through the use of strategically placed accelerometers which map the vibration characteristics. With enough samples, a statistical data base can be developed that serves as the basis to develop the vibration criteria. This approach has been very effective for liquid propulsion engines where extensive ground test development and verification hot-fire programs exists. Also, launch vehicles that have flown many times have provided the same data base. (2) The second approach relies on existing data bases of vibration criteria and their corresponding acoustical environments. By mass scaling between the data base component and the new hardware component, and scaling the forcing function, a new vibration criteria is developed (fig. 31).[16] (3) Another way is to analytically predict vibration using the predicted forcing function. In general, the scaling approach or the direct measurement approach is used. (4) Finally, actual flight or development hardware can be acoustically tested to the expected acoustical spectrum.

Vibration criteria is used for two basic purposes: (1) qualification, acceptance, and development testing of components; and (2) generation of loads to be combined with the quasi-steady loads previously discussed. The subject of load combinations is strongly debated. Low-frequency loads can be easily time phased and combined in that manner; however, the high-frequency loads can have several cycles during the peak of the quasi-static loads, hence, the two peaks must be added. The peak vibration load is calculated using Miles relationship which assumes that the component is in resonance with the criteria. This means one must know the frequency and damping of the component

DIRECTION – LONGITUDINAL
SKIN THICKNESS – .102 cm (.040 in.)
RING SEPARATION – 91.44 cm (36.0 in.)
RING WEIGHT PER FOOT – N/A
STRINGER SEPARATION – 21.92 cm (8.63 in.)
STRINGER WEIGHT – 1.056 kg/m (.71 lb/ft)

FLIGHT OR TEST CONDITION – LIFTOFF
MATERIAL – ALUMINUM
COMPOSITE MEAN – 2.37
COMPOSITE 97.5 – 3.65
VEHICLE DIAMETER – 10.06 m (33 ft)

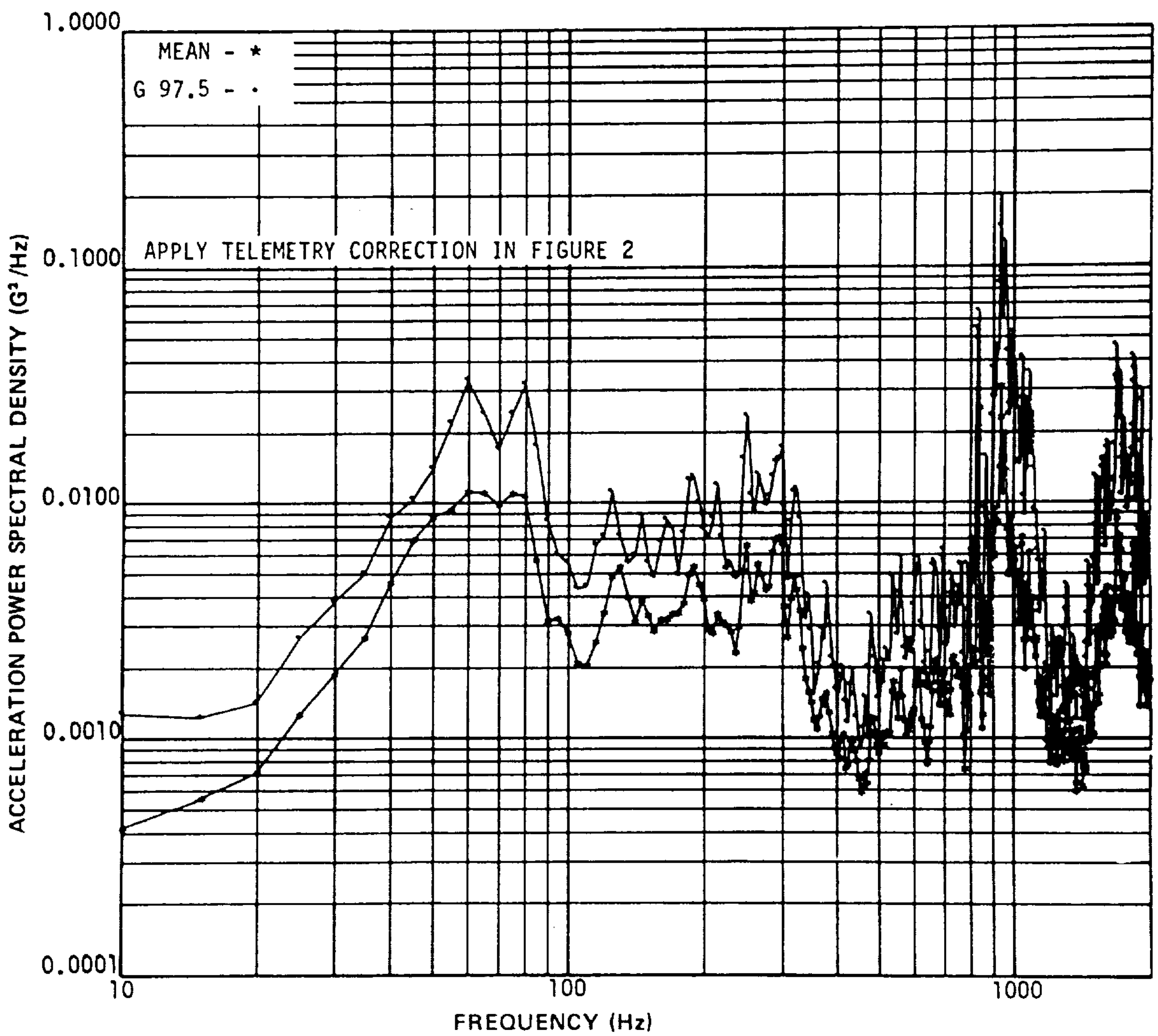


Figure 30. Skin stringer acceleration power spectral density longitudinal, lift-off.

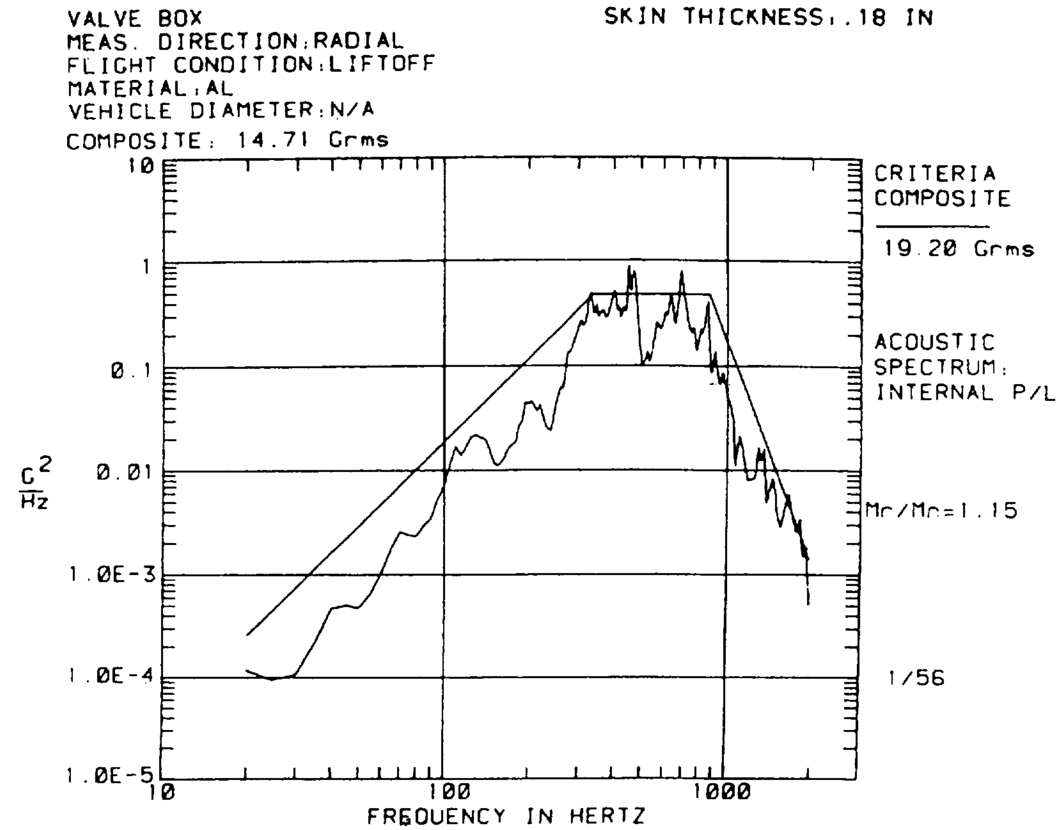


Figure 31. Scaled vibration spectrum with criteria.

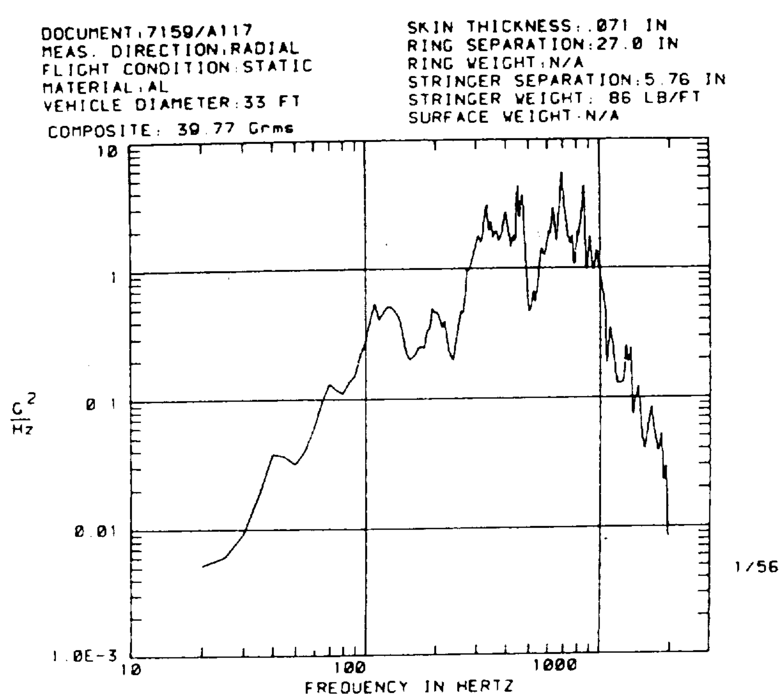


Figure 32. Vibration spectrum.

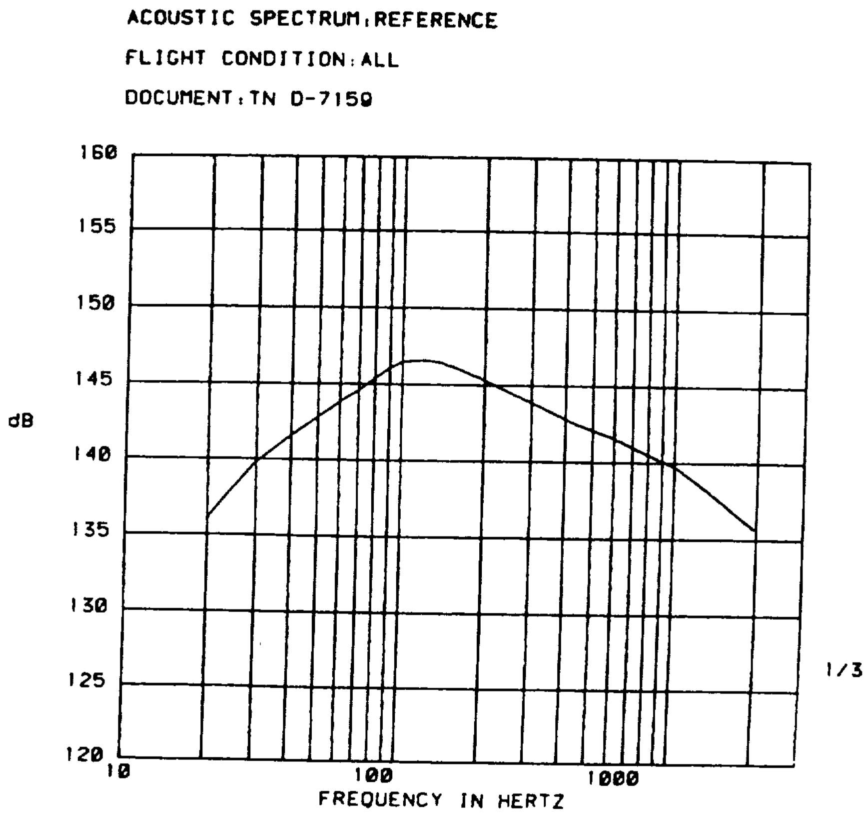


Figure 33. Reference acoustic function.

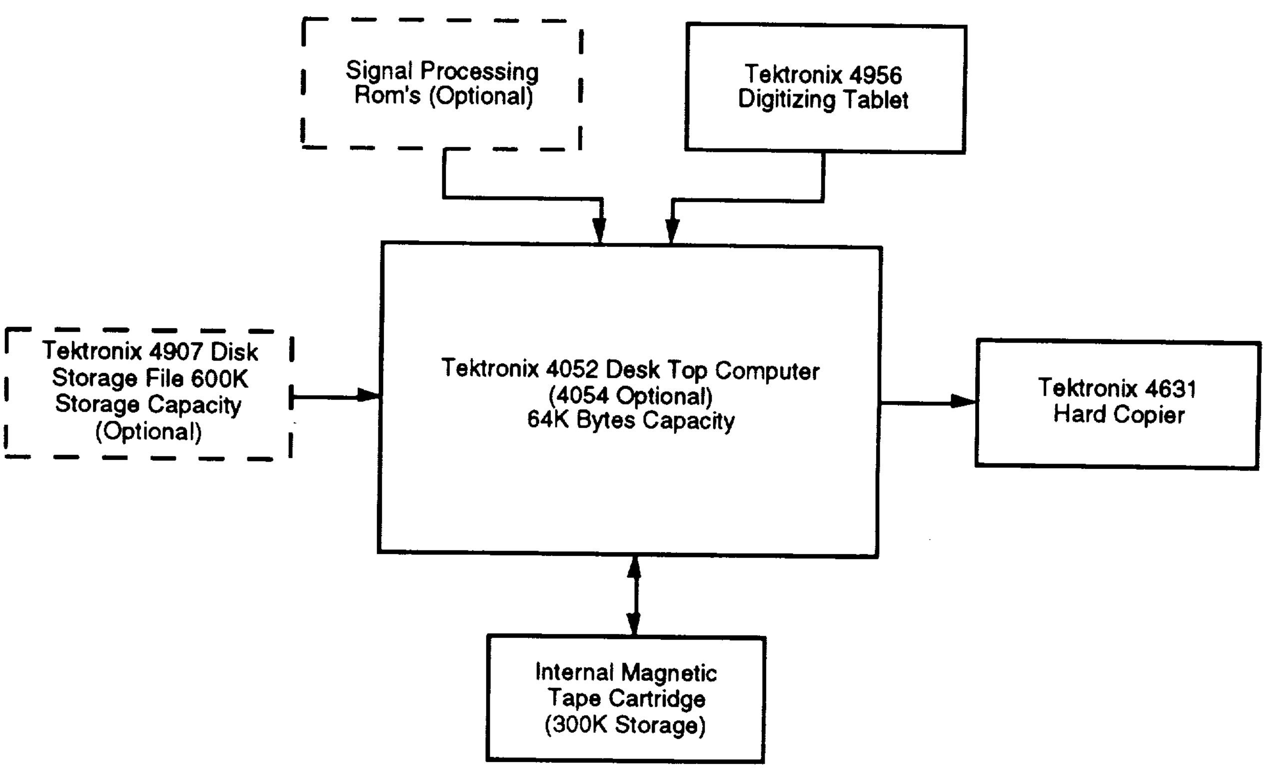


Figure 34. Vibroacoustic data bank schematic.

the vibration is driving. Once this has been determined, one goes directly to that frequency in the vibration criteria, reads the amplitude, and calculates the load. This is basically the "q" (resonance damping gain factor) times the criteria amplitude. Still open is how you combine the various axes of vibration loads with quasi-static loads. No universal agreement exists on how to accomplish this. Regardless of the approaches, determination of the high-frequency loads and their combination with the quasi-static loads are a fundamental part of the loads cycle.

3. Verification

It is mandatory that, for each parameter used, a verified statistical distribution, including the 3-sigma level, be determined and input into the analysis. Any appropriate parameter variation, sensitivity analysis, statistical combination such as Monte Carlo, root sum squaring, etc., can be used to generate the loads data.

The structural models must be verified by dynamic and static tests preferably of full-scale hardware. With proper attention, scale testing is acceptable. All testing must be preceded by a pre-test analysis, guiding the test conditions, instrumentation location, and test approaches. A posttest model update is required, based on the correlation of model and test data, to provide a bias for assessing changes, manufacturing discrepancies, etc., and, particularly, to predict with confidence criteria for operational conditions which were not directly verified by test.

Verification of input parameters is accomplished through tests of various types, such as wind tunnel, propulsion system firing, etc. Pre-test analyses are required for guiding test definition, instrumentation, and the like, with posttest updates providing the final data sets.

The past space shuttle configuration was verified in this manner. Figures 35 through 37 are the summary of some of the key verification tests. Not shown on this list are the thermal testing, component qualification and acceptance testing, etc., that are just as important as those listed. It is not the purpose of this report to provide the overall list, but to show a representative sample area.

All significant design changes are verified and loads analyses reconducted.

The final verification of any system is accomplished through development flights or during operations, highly instrumented at critical areas, for loads and environment correlations to load predictions and design loads. Six of the first seven shuttle flights carried this instrumentation. Typical results are shown in figures 38 and 39 as an example of this verification approach. Figure 40 is a schematic of the ET showing strut or interface force nomenclature for orbiter-to-tank and tank-to-SRB. This is given as reference for the data identification presented in figures 38 and 39. These tables show the measured in-flight load percentage of design load for the interface forces for all flight events for flights STS-1 through -7. Notice that all loads were well within design, except for the bolt loads. It has since been determined that these are not load exceedances but calibration errors. Figure 39 shows SRM forces and moments at several vehicle stations for SSME buildup and lift-off. Compared to design loads for that event, these loads are as expected. The event shown may not be the design event and, hence, the load is low.

The final verification is obtained by correlating actual flight predicted time responses to the measured flight data. Figure 41 is the comparison of strut P10 for STS-5 of predicted versus measured for the lift-off event. Predicted loads are higher than measured, but contain the same

- 1/4-Scale ground vibration testing (QSGVT)

- The individual element modal vibration tests of the empty SRB's, full SRB's, ET, and orbiter (ORB) have been completed. The first mated test with the ET and orbiter started June 15, 1977 and was completed July 31, 1977. The ORB/ET/SRB lift-off condition tests started August 1, 1977 and were completed September 21, 1977. All 1/4-scale modal vibration testing was completed by December 1977. Influence coefficient tests (I/C) were completed on the empty SRB and ET. The I/C tests on the full or lift-off condition SRB was conducted in January and February 1978.

- Mated vertical ground vibration test (MVGVT)

- MVGVT test using the existing Saturn dynamic facility systems and components started in May 1978 and was completed November 1978.

Figure 35. Major integrated ground test.

Test and Location	Configuration	Purpose
• Umbilical systems verifications (LETF) (KSC)	Flight-to-ground umbilicals with associated flight vehicle skin panels and ground systems (i.e., swing arms, tail service masts)	Verify ground-to-flight interfaces in performance and compatibility areas prior to MOF
• Structural test article (ET) (MSFC)	LO_2 tank, LH_2 tank and inter tank	Verify the strength integrity of the primary load carrying structure
• Structural static/fatigue (orbiter) (Palmdale)	Airframe structure including all primary and selected secondary structure, generally no systems	Verify structural integrity for: limit and ultimate loads and 160-mission life X scatter factor of 4
• Static structural test (SRB) (MSFC)	SRB short-stack configuration, structurally flight type vehicle with four center motor segments eliminated	Verify structural integrity for critical design limit and ultimate loads and the normal service life
• FWD RCS status firings (WSTF)	Shall consist of structure and components functionally configured to represent the flight article	Demonstrate the RCS performance

Figure 36. Major integrated ground test.

Test and Location	Configuration	Purpose
• MPTA (NSTL)	Three main engines + flight-weight external tank + flight-weight aft fuselage, interface section and a boilerplate mid/fwd fuselage truss structure	Verify MPS performance and compatibility with interfacing elements and subsystem
• OMS/RCS static firings (WSTF)	Consisted of flight-weight primary and secondary structures, flight-weight qualifiable components functionally configured to represent the flight article	Demonstrate OMS, RCS performance
• ECLSS (JSC)	Boilerplate test article, complete ECLSS, partial avionics, crew equipment, airlock	Verify ECLSS integrated ops and perform man-rating of ECLSS for FVF (8 psi), verify airlock performance
• Flight readiness firing (KSC)	First shuttle vehicle OV-102 Flight external tank Flight SRBs	Perform unmanned SSME firing at completion of the first wet countdown demonstration test, final verification of flight and ground systems prior to FMOF, performed one time only

Figure 37. Major integrated ground test.

Loads Comparison in % of Design

Structure	STS-1 % Event	STS-2 % Event	STS-3 % Event	STS-4 % Event	STS-5 % Event	STS-7 % Event
P_1	52(LO)	44(PO)	45(PO)	43(PO)	44(PR)	44(PR)
P_2	50(LO)	42(PO)	41(PO)	44(PO)	42(PR)	40(PR)
P_3	53(PO)	55(PO)	50(PO)	54(HQ)	58(HQ)	57(PR)
P_4	53(PO)	50(PO)	56(HQ)	56(HQ)	52(PR)	53(PR)
P_5	91(PO)	87(PO)	88(PR)	88(PR)	86(PR)	93(PR)
P_6	88(PO)	85(PO)	88(PR)	85(PR)	88(PR)	91(PR)
P_7	12(HQ)	6(PR)	18(PR)	10(PR)	8(LO)	11(PR)
Crossbeam	88(BA)	88(BA)	90(BA)	91(BA)	93(BA)	92(BA)
LO_2 dome	91(LO)	92(LO)	97(LO)	78(LO)	81(LO)	--
Y ring	95(LO)	96(LO)	97(LO)	81(LO)	85(LO)	--
LH_2 dome	96(LO)	93(LO)	83(LO)	83(LO)	--	--

LO-Liftoff
HQ-Max Q
BA-Max SRB Acceleration
PR-Pre-SRB Staging
PO-Post-SRB Staging

Figure 38. Strut load comparison.

SSME Buildup
SRM Case Loads
Right SRB

Force/ Moment	SRB STA. (in)	Predicted Net Load (kips)	Measured Net Load STS-1 (kips)	STS-2 (kips)	STS-3 (kips)	STS-5 (kips)	STS-6 (kips)	Design Limit Load (kips)
F_x	611	--	260	835	405	237	565	420/1000 (1)
M_y**	611	--	-39	-30	-38	-35	-41	-34/5 (1)
F_x	1251	1070	1490	1085	995	1140	1253	1100/1690 (1)
M_y**	1251	-144	-183	-187	-173	-184	-191	-180/22 (1)
F_x	1758	1490	1697	1687	1498	1747	1593	1540/2130 (1)
M_y**	1758	-242	-291	-260	-272	-283	-309	-300/30 (1)
F_x	1935	1670	1823	1813	1624	1873	1719	1670/2220
M_y**	1935	--	-332*	-287*	-307*	-318	-350	-347/30

* Net measured data--base loads extrapolated from above loads
(1) Designed by events other than SSME thrust buildup
** M_y given in 10^6 in/lbs instead of kips

$M_y(10^6$ in-lbs)

Figure 39. Force and moment SRM interface load comparison.

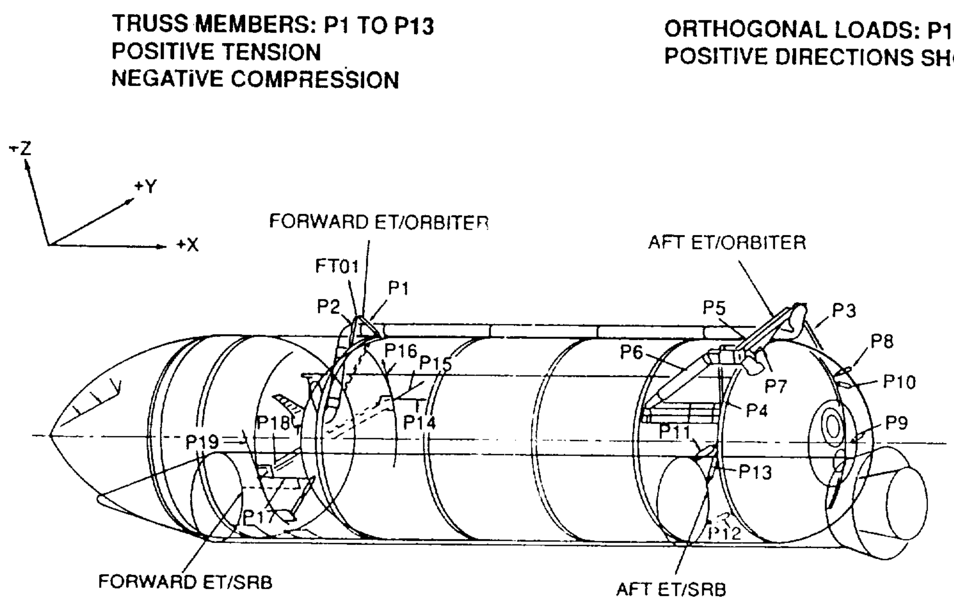


Figure 40. ET schematic with strut forces.

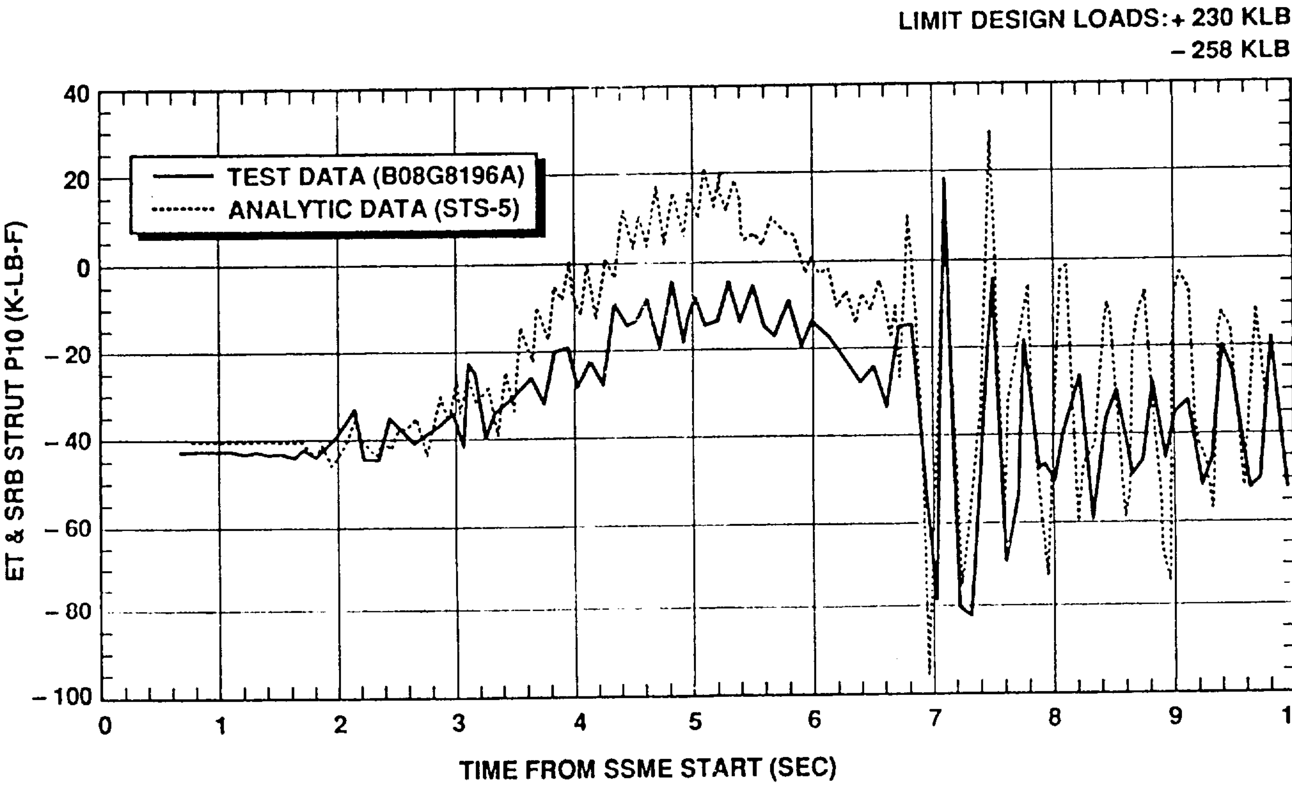


Figure 41. P10 strut load predicted to flight lift-off.

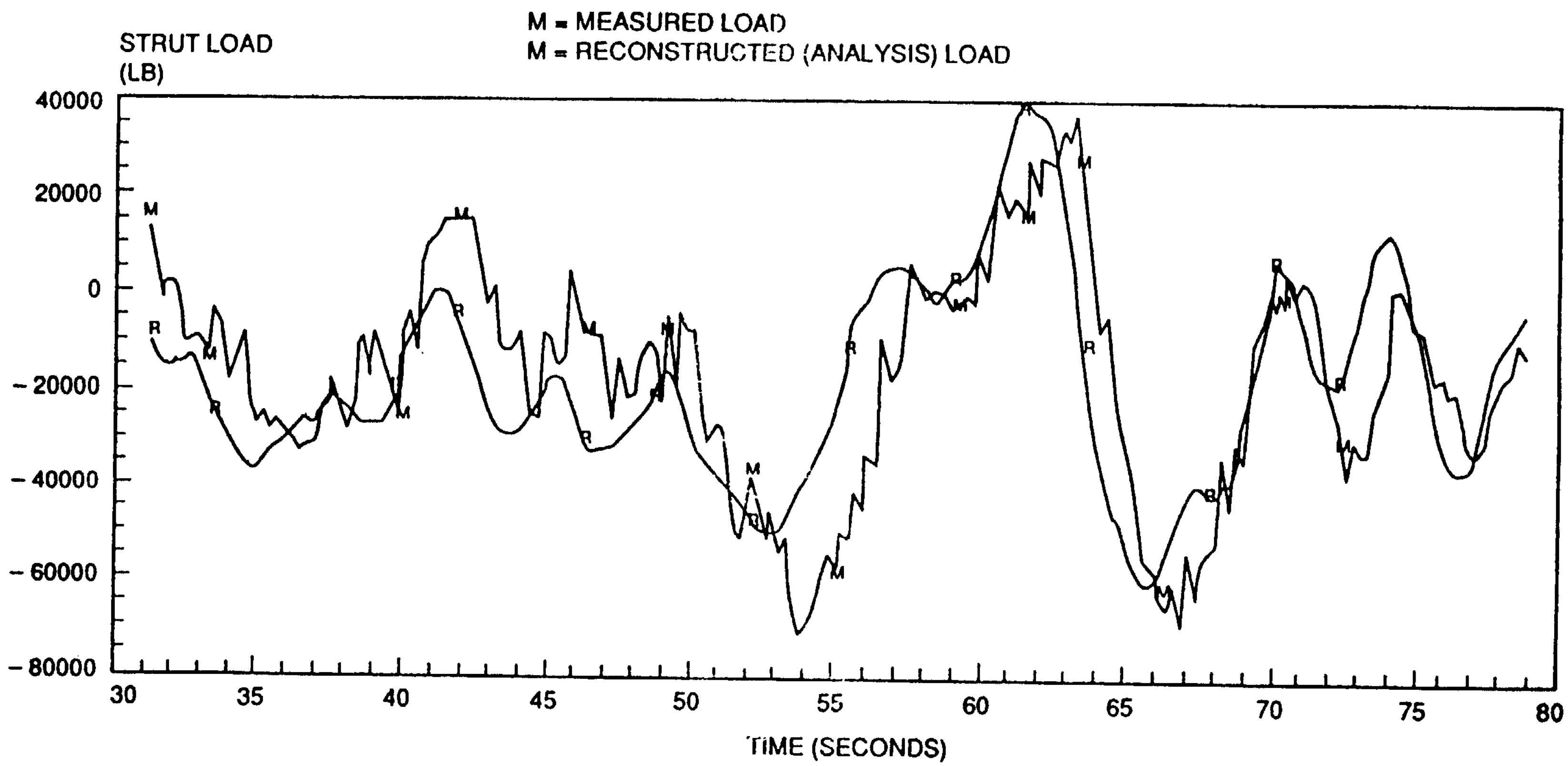
trends and frequency content, indicating good analytical approaches. Figure 42 is a similar comparison for strut P10 for the max-q flight event. Excellent agreement is shown between predicted and measured parameters. Rockwell, Space Division, conducted them and is the source of these analysis comparisons to flight.

4. External Loads Output

The 3-sigma load sets are obtained by the techniques just described, output in format and locations required by the elements for margin assessment. In general, these loads will be output as a time-consistent set of loads at each prescribed station as:

1. Shear forces (x, y, z, t)
2. Moments (x, y, z, t)
3. Interface forces (x, y, z, t).

Figure 43 is a typical example of this type of output for shuttle during SSME buildup through the lift-off transient. Depicted in the center is the shuttle vehicle. On the left is one example of the many input forces used concurrently; other typical forces are listed. On the right are the resulting time responses of the SRB at the ET attach ring station. Included are the three strut forces (interface forces), the three shear forces, and the three moments. Outputs of this form should be available for any vehicle station.



LIMIT DESIGN LOADS: + 230 KLB
− 258 KLB

Figure 42. P10 strut load predicted to flight max q.

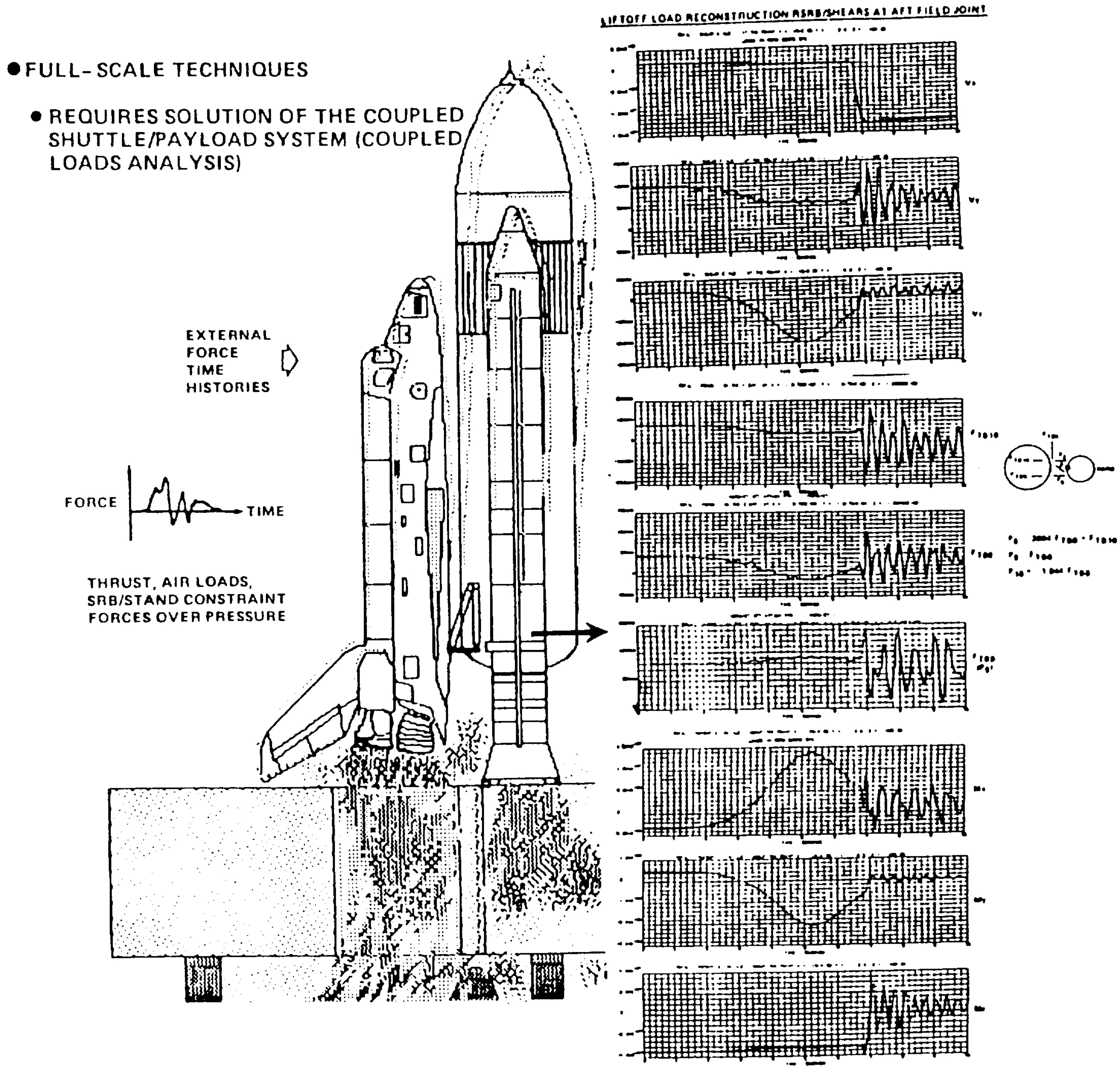


Figure 43. Shuttle lift-off transient loads.

The large capacity of modern computers allows optimization of computer outputs at this point, providing several options. Classically, the time-consistent dynamic loads have been treated as quasi-static loads which are added to the static loads generated in a separate stress analysis. Now these two steps can be treated simultaneously if the dynamic model is compatible with the stress model (compatible node points, etc.). Using stress or loads transformations, the output of one analysis (loads) can drive the transformations, producing time-consistent stresses. This saves modeling time, allows less loads cases to produce 3-sigma conditions, and opens the door to a consistent Monte Carlo stress analysis not possible if the Monte Carlo is done on external loads. The Monte Carlo approach produces a more realistic representation of all parameters than the other approaches used, such as A-factor. As programs mature, load indications can be used in the same manner. The classical approach is still desirable in many cases, therefore, an alternate means of handling this is also available.

The peak values (time consistent sets) for all stations should be combined to provide running load distributions for static analysis. Figure 44 shows typical moment distributions developed for shuttle design. Figure 45 shows a time-consistent applied force and the set of shear and moment diagrams. There must be as many sets of these distributions as there are load sets and flight event analyses. Time consistency must be maintained as a general rule.

The purpose of this document is to delineate procedures and approaches; however, it should be mentioned that as a result of the knowledge of the first 25 shuttle flights, a new loads analysis was conducted. The reanalysis was defined as IVBC-3. The original final verification analysis was defined as IVBC-2. In general, this reanalysis has resulted in lower loads as can be seen on figure 46 for the lift-off and max-q flight regimes.

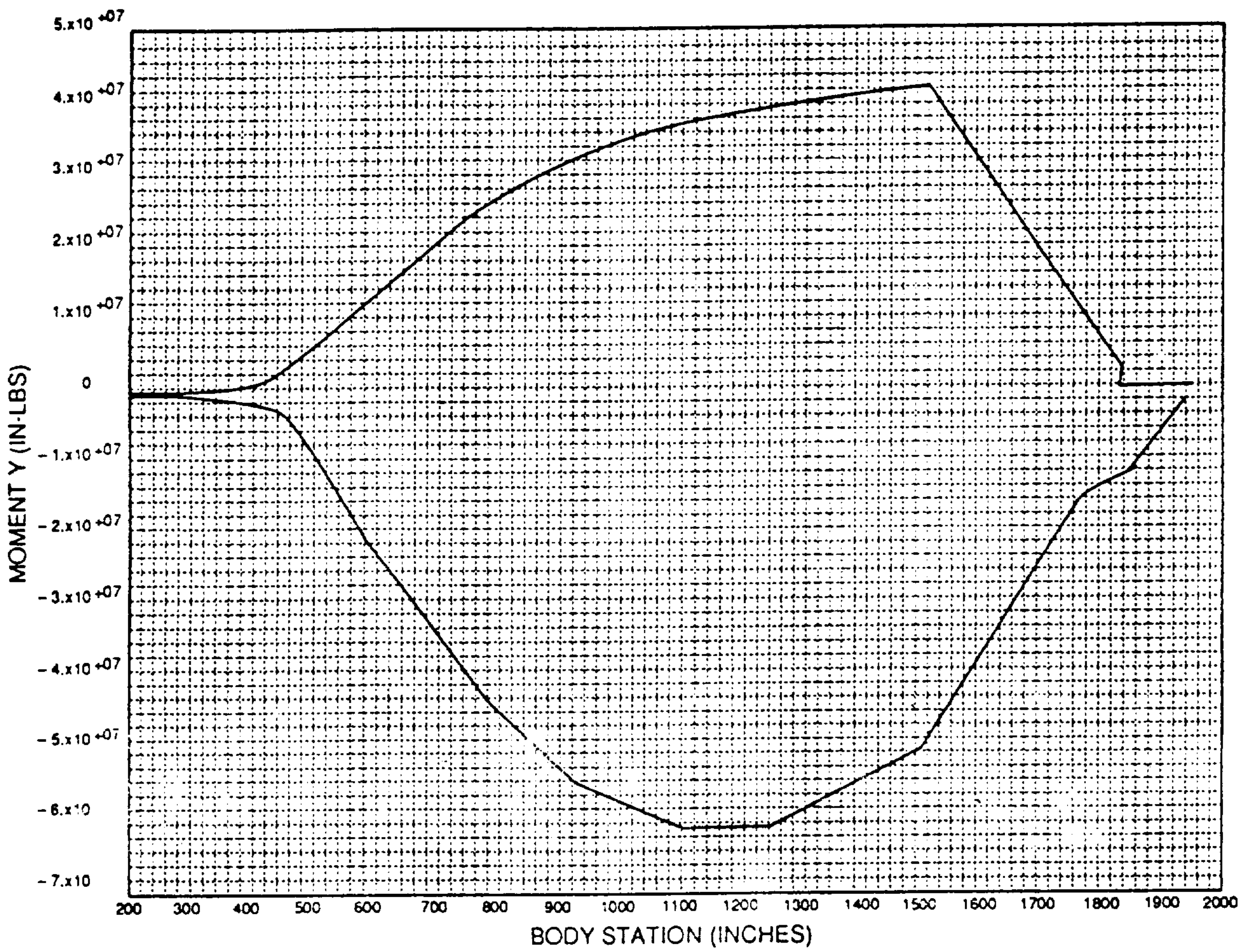
Output of loads, as described in this section, becomes the input for the element dynamics and structural assessment analysis (internal loads) to be discussed in the next section.

The importance of the overall loads analysis cannot be overstated. As can be seen, the final structural margins are a direct result of the characteristics and accuracy of these loads. Early in a program, procedures, approaches, tools, etc., must be established and controlled to ensure this characterization.

B. Heat Transfer

Heat transfer, as well as all the thermal analysis outputs, is important to at least three areas: (1) structural deflections/stress, (2) thermal protection design and verification, and (3) thermal control including life support systems. Structural design and margins are mainly concerned with (1) and (2). Here also, the heat transfer models must be compatible with the stress models. Heat transfer and the resulting deflection are generally performed using codes such as SINDA, PATRAN, and NASTRAN. Other codes exist for special cases such as ablative nozzle analysis. The thermal analysis, the heat transfer, and the thermal protection system (TPS) are all very important in structural design and margins. All the points previously made concerning models, assumptions, etc., are applicable and not repeated.

The thermal analysis (heat transfer) serves several functions. First and foremost, it is a design function that provides the thermal control system or TPS required to maintain structural integrity. Excessive heat lowers the materials properties and, if high enough, erode the material. Second, thermal gradients build in stress, which uses up part of the structural margins. Said another way, it induces part of the design stress field that is combined directly with the stress for loads etc. Third, thermal gradients as well as heating up or cooling down of structures produces unwanted deflections. These deflections can be very detrimental to pointing control systems as well as taking up hardware clearances. For example, the cryogenic propellant affects the ET and the shuttle system significantly and is a major design consideration. Before loading the propellant, the tank is at ambient temperature. When fully loaded, the tank shrinks which introduces radial loads between the two SRB's (held down to the pad with large bolts that are pyro-severed at SRB ignition) and the tank through the struts. The tank also shrinks longitudinally. To handle this, the struts between the



STATION	MAX CONDITION /	MIN CONDITION
275.0	LMKSA063	LMKSA024
447.6	LMKSA063	LMKSA016
492.4	LMKSA060	LMKSA061
592.0	LMKSA030	LMKSA061
931.5	LMKSA030	LMKSA061
1251.0	LMKSA030	LMKSAO61
1448.2	LMKSA030	LMKSA061
1511.0	LMKSA030	LMKSA061
1834.8	LMKSA030	LMKSA051
1935.9	LMKSA030	LMKSA051

STATION	MAX CONDITION /	MIN CONDITION
395.0	LMKSA063	LMKSA016
447.7	LMKSA063	LMKSA016
492.5	LMKSA060	LMKSA061
771.5	LMKSA030	LMK.A061
1107.5	LMKSA030	LMKSA061
1294.5	LMKSA030	LMKSA061
1510.9	LMKSA030	LMKSA061
1758.0	LMKSA030	LMKSA051
1834.8	LMKSA066	LMKSA060
1935.9	LMKSA102	LMKSA051

Figure 44. Moment distribution.

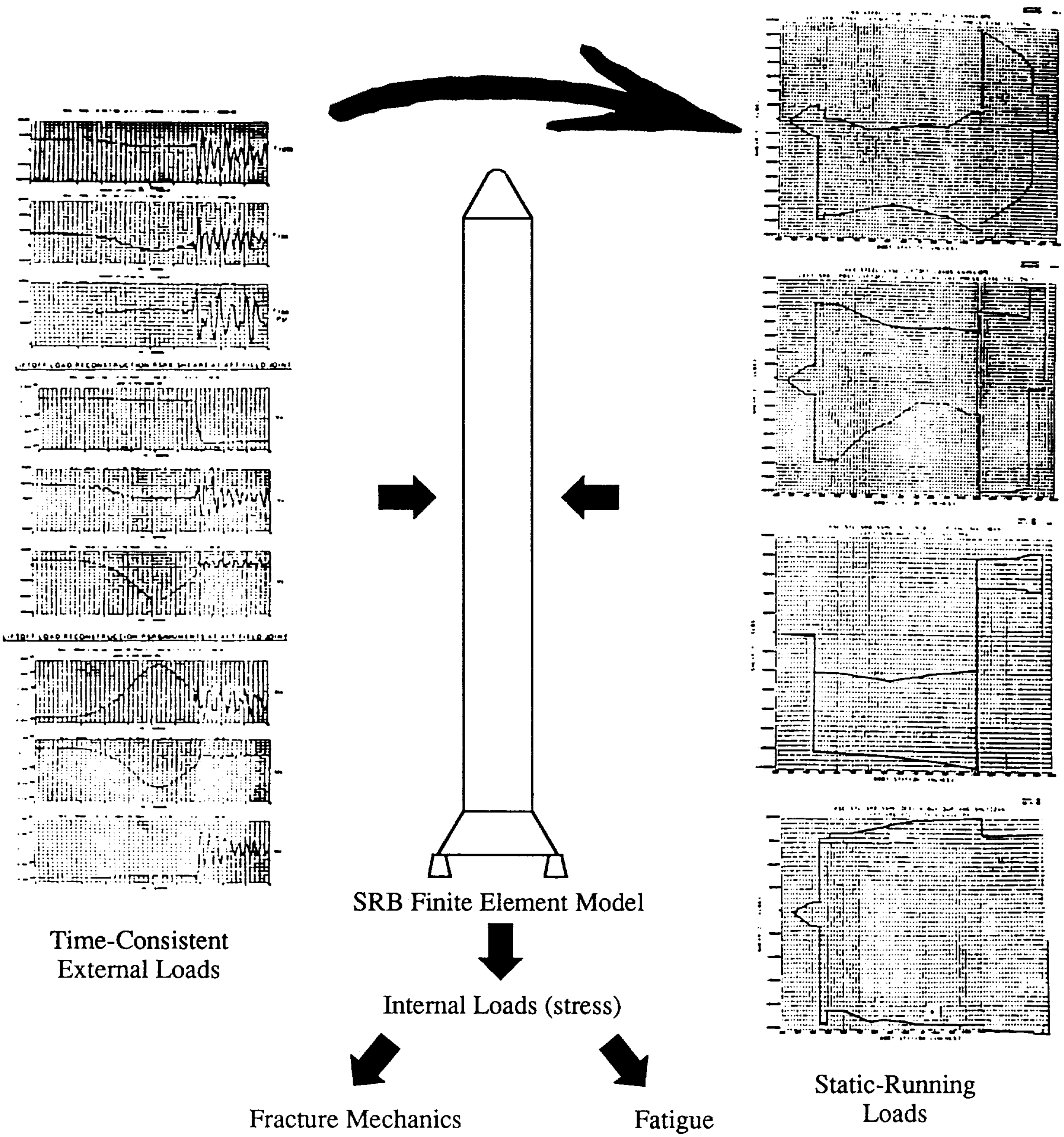


Figure 45. SRB transient and max-min loads.

ITEM	IVBC-2 (OVERALL LOAD)	IVBC-3 (HI Q LOAD)
FTB 1	207/ -206	49/ -69
2	207/ -206	59/ -78
3	182/ -95	88/ 9
4	95/ -182	-8/ -89
5	175/ -1654	-955/-1364
6	175/ -1643	-958/-1358
9	218/ -305	197/ -222
10	306/ -218	214/ -252 *
P 8	265/ -299	166/ -170
9	393/ -291	241/ -117
10	202/ -212	* 203/ -287 *
11	265/ -299	184/ -133
12	393/ -291	195/ -94
13	207/ -193	180/ -250 *

Figure 46. Max-q loads comparison IVBC-2 and IVBC-3.

tank and SRB's at ambient temperature are designed to be 7° of 90° so that at full propellant load they are perpendicular to the SRB/ET. Also, the struts are pretensioned so that with cryo shrinkage the loads are minimized.

Figures 47 and 48 illustrate the basic thermal control and thermal analysis task flows. As was the case with loads, models must be developed and verified; the design concept selected; thermal analysis, thermal design, and thermal use testing; simulations; and materials characterized. Figure 47 depicts the basic TPS design flow. This analysis requires special definitions of the environments and loads that maximize these inputs for thermal protection design and for generation of thermally-induced design stresses. Two types of testing are required: developmental and verification. The developmental testing defines parametric data as ablation rates and thermal responses, and bench marks the thermal model. The verification testing involves combined environments testing, including thermal vac, as well as subsystem and witness panel testing. The output is the operational procedures and constraints as well as margins.

Figure 48 is the flow cycle for thermal control system design and analysis. Many of the steps are the same as for the TPS with the introduction of active control concepts. This brings into play more indepth consideration of failure modes and redundancies as part of the cycle. The end result of this are is the same as for TPS. All are important to structural design and verification.

C. Developmental Testing

Developmental testing covers all aspects of the structural tasks from environmental determination to structural dynamics and statics, thermal etc. The list contains at least:

1. Vibration
2. Thermal/TPS
3. Environments

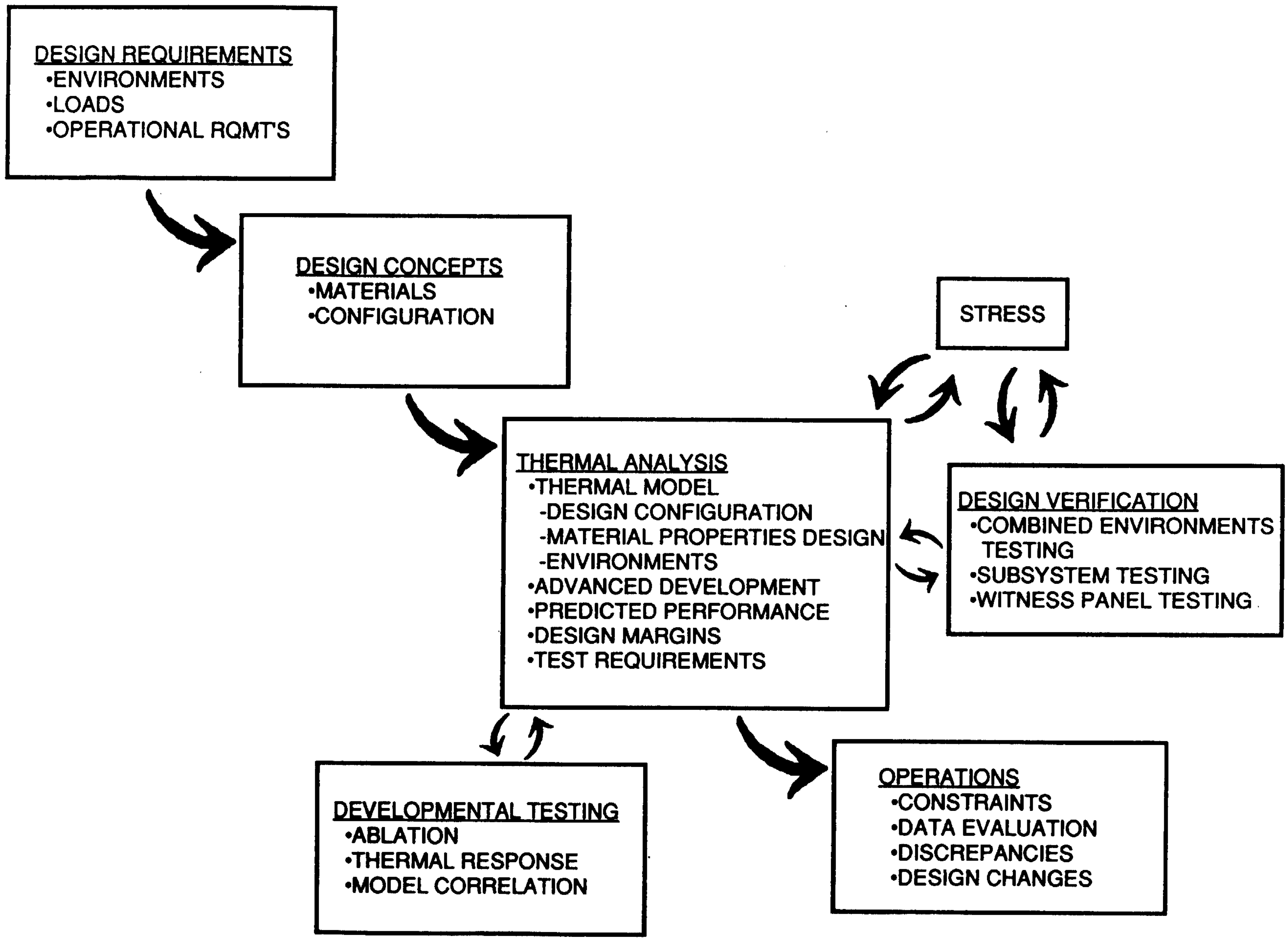


Figure 47. Thermal protection system.

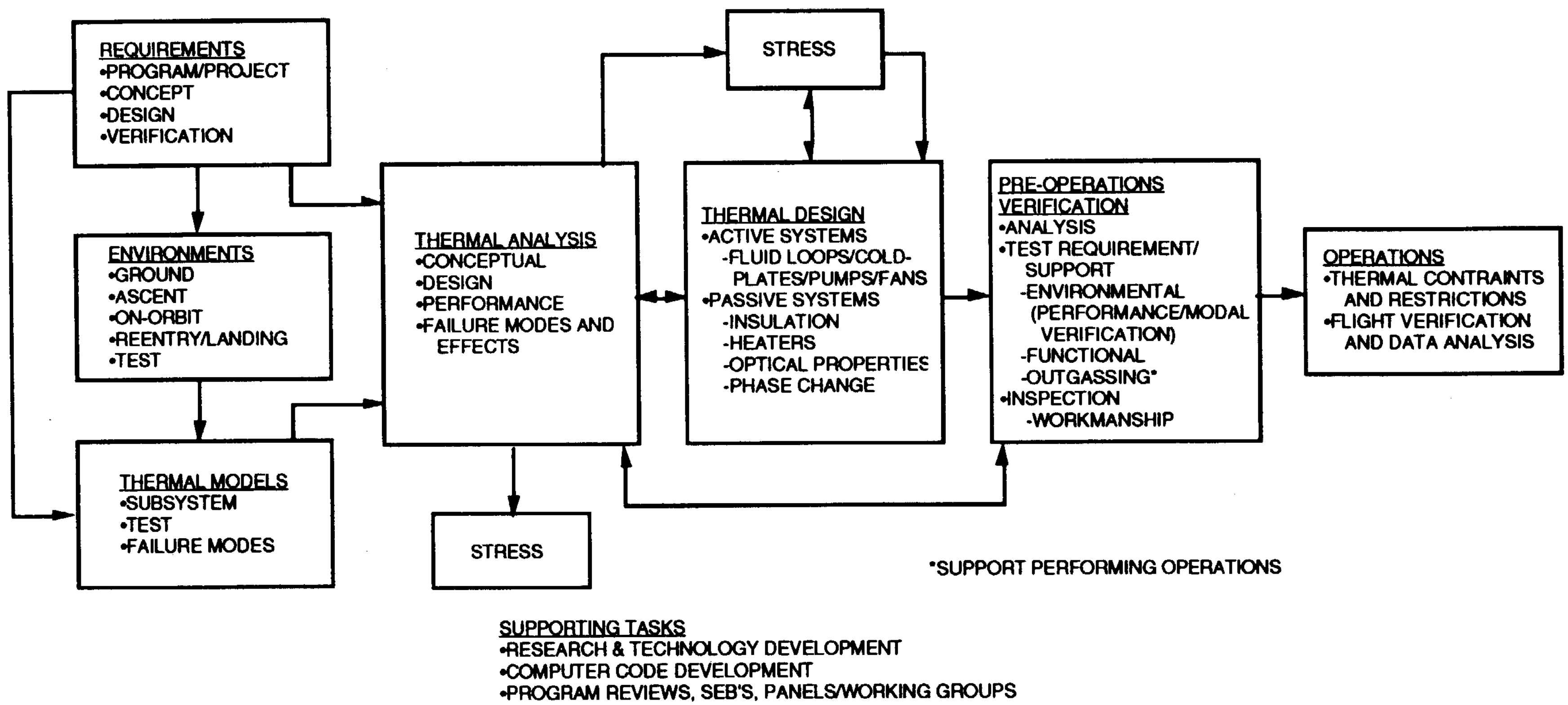


Figure 48. Thermal control branch task flow.

4. Acoustics
5. Propulsion
6. Control.

Full-scale as well as scale-model testing is appropriate. In all cases, the test hardware must accurately depict all features important to the test goal. Test boundary conditions, instrumentation, excitation, data collection, and data banking are fundamental concerns. In addition, during development testing parameter sensitivities must be explored as well as potential nonlinearities so that the system being considered can be understood.

D. Element Structural Analysis

The next phase for determining structural margins is accomplished by the element contractors or Government using the time consistent and running loads generated by the system as discussed in the previous section.

The first step in this phase is the generation of compatible but more detailed dynamic and stress models than the ones derived for the system analysis. The degree and areas for more detail are determined by knowledge of critical areas, such as discontinuities, concentrations, potential nonlinear areas, etc. The same use can be made here of stress and loads transformations. Several choices have to be made in determining the details of these models. These include but are not limited to the following:

1. Element mesh and sizes
2. Element type
3. Symmetrical or not
4. Nodes
5. Degrees of freedom
6. Local geometries
7. Welds
8. Connectors.

Based on these and other considerations, the models are developed and verified using standard check criteria and available test data or by special test.

The next step uses the system analysis outputs, forces, and moment interface time histories, or the running loads, as forcing functions and applies them to this model to determine basic detailed element response. Describing equations, etc., are derived as discussed under systems loads and solved in a comparable manner. Figure 45 illustrates the SRB model and the two types of system force outputs being applied (not concurrently). Output of these analyses are either dynamic responses or stresses. This level of analysis will accomplish several important tasks, as well as provide the forcing functions or interface forces for a more detailed substructure analysis. These tasks are:

1. Definition of critical areas
2. Structural margins for the general structural areas
3. Forcing functions for substructure analysis
4. Correlation with test
5. Identification of flight event design cases.

Figure 49 shows the identification of design events for the SRB. The general margins of safety determined in this manner for the SRM are shown on figure 50. Ultimate margins of safety are determined by multiplying the ultimate safety factor and the limit stress, dividing this product into the material ultimate strength, and from the resulting quotient, subtracting one. Yield margins are defined similarly. Negative margins of safety are unacceptable. All margins of safety must be non-negative. Therefore, the formula is:

$$\text{M.S.} = \frac{F_{TU}}{1.4 \times f_t} - 1 \quad , \quad \text{M.S.} > 0 \ .$$

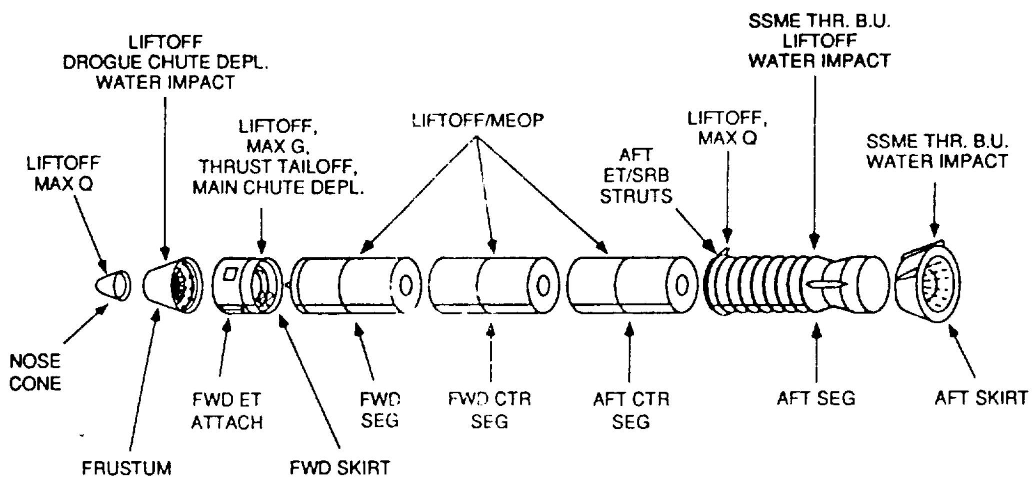


Figure 49. SRB design load events.

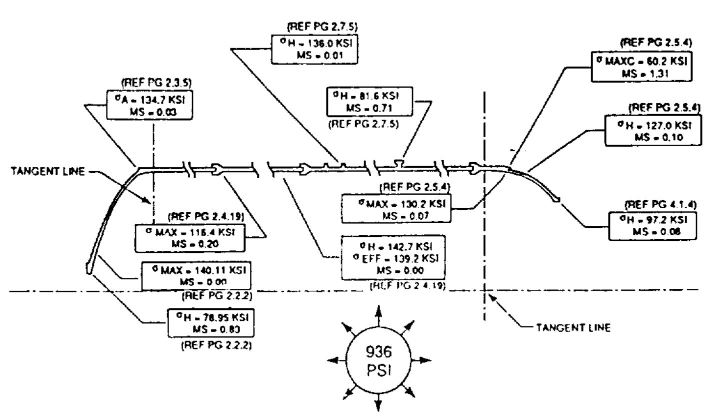


Figure 50. SRM case stress summary.

One final case is shown to illustrate the results of this level of element analysis. During the SSME buildup case at lift-off, the thrust forces introduce a design bending moment into the SRB. This moment is taken out through the four holddown bolts at the base of each SRB aft skirt. Figure 51 shows the resulting stress in the SRB at three vehicle locations. The stress for each station is plotted circumferentially. Notice how the stresses peak near the holddown bolts. This peak load reduces rapidly with distance up the SRB, disappearing near the SRB ET attach ring. In each of these cases, the stress peaks are known as stress discontinuities, and origin and cause are readily recognized by the analyst because of the abrupt change in structural geometry, boundary load, or metallurgical properties. A difficult weld is an example of the latter. ET and SSME examples are not given but can be found in references 30 and 31.

E. Verification

Many aspects of verification have been addressed throughout this report; however, it needs to be tied together. First and foremost, verification is accomplished both by analysis and test. It is impossible to verify everything by test. Many times all that can be done is to verify an analytical model for a certain condition. You then use this benchmarked model to verify the total set of conditions. Second, verification is always against the requirements and criteria and, if not accomplished, requires a program waiver. In general, not only must the structural limits be verified, but so must most environments, models, etc. The process is, therefore, complicated and requires documentation to demonstrate compliance and program tracking (fig. 52). Third, some verification can only be accomplished during operations. For example, the first six space shuttle flights had special instrumentation and data systems to verify many aspects of the system from loads to environments. This means that each discipline, system, subsystem, element, and component must thoroughly understand their requirements, both for instrumentation and data outputs, and must communicate this to the project. This is very basic and fundamental to program success. Without instrumentation, it is unlikely that the shuttle program would have discovered the orbiter wing problem or overpressure at lift-off—possibly resulting in a vehicle failure.

IV. SUBELEMENT AND LOCAL ANALYSIS

This phase of the analysis is very critical. It is at this level where all fracture mechanics, nondestructive evaluation (NDE), nonlinear stress analysis, fastener analysis, stability, and critical margins are determined. This more indepth evaluation requires more detailed models of critical subelements and possible nonlinear analysis techniques. Here the modeling assumptions, code choices, analysis levels, linear versus nonlinear, etc., can produce completely erroneous or very accurate predictions, depending on the engineer's judgments. Again, it starts with the choice of model mesh, elements, and codes as discussed previously. This choice is made based on the hand analyses, etc., discussed up front. Also, the use of load indicators, stress, and loads transformations can be used as a time saver for many of these analyses. Since the analysis is dealing with more localized areas, it is critical that the engineer understands finite element modeling in all respects and not use programs, codes, etc., in a black box manner. Several books and papers exist on this subject. Reference 17 is a typical example. A brief overview of finite elements follows to provide a basis for the other discussions.

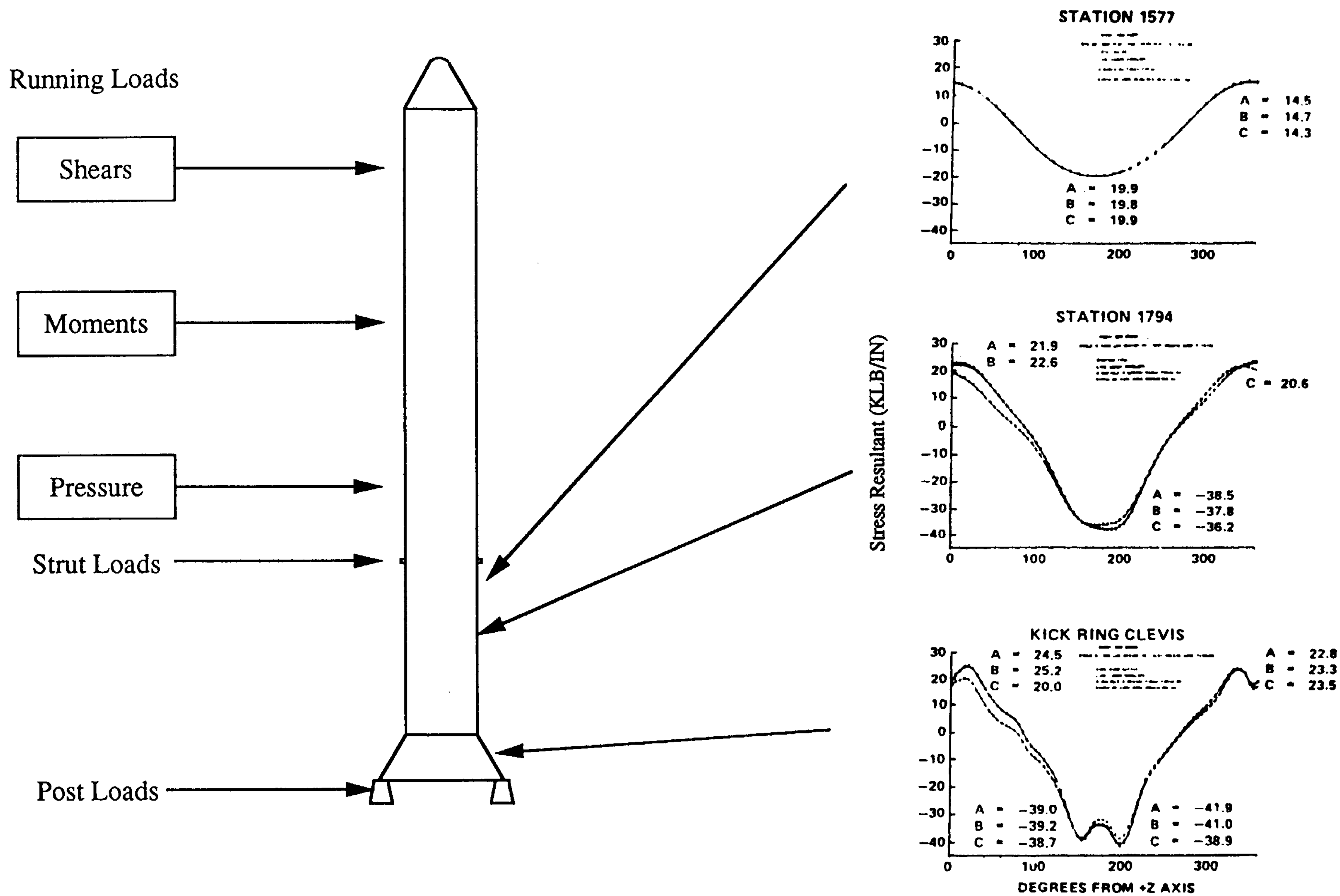


Figure 51. SRB/SRM stress distribution.

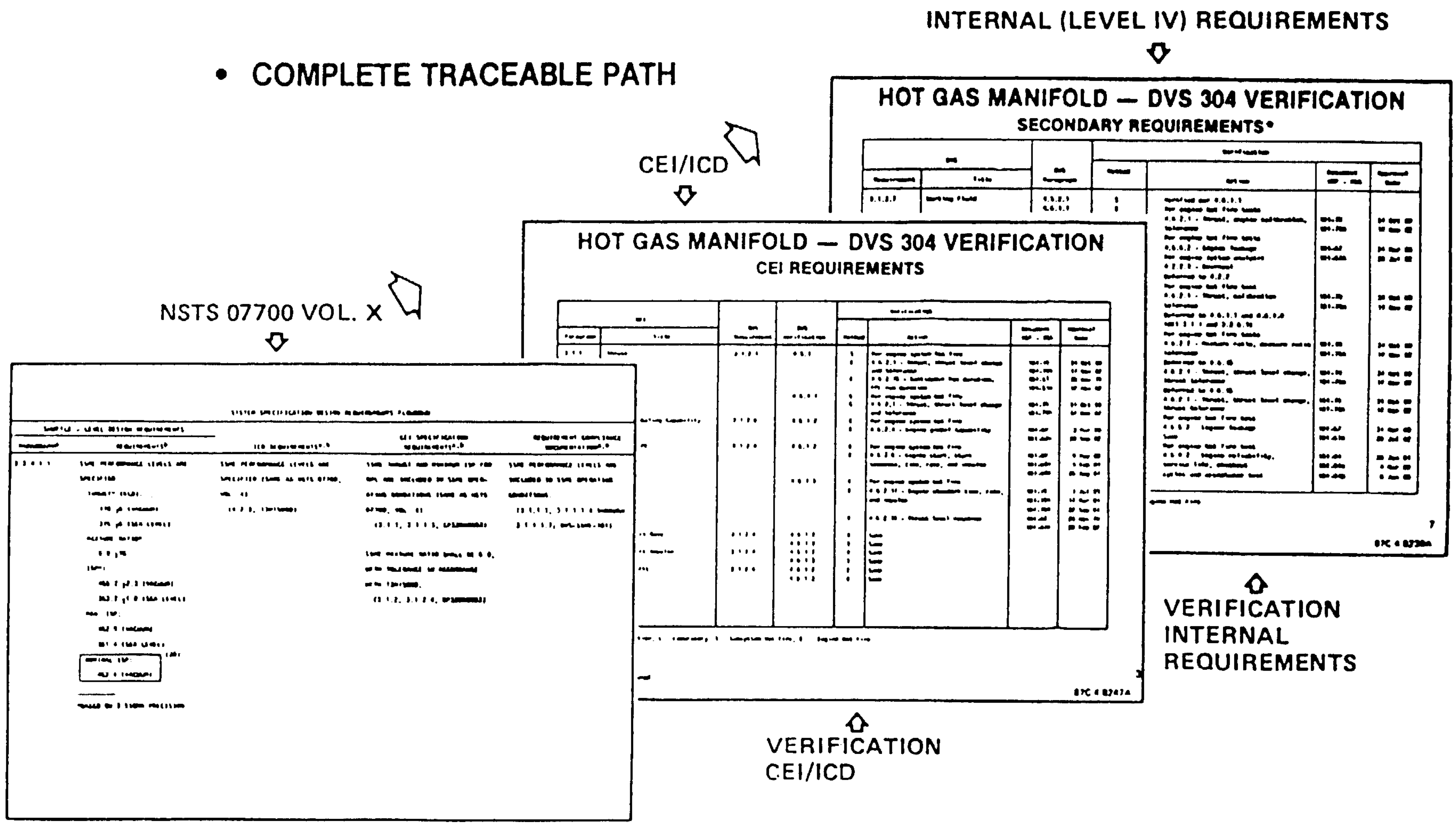


Figure 52. Sample audit trail, DVS program.

The finite element approach is based on the idea that you can take a very complex problem and break it up into many subsets (finite elements) of single problems with simple assumptions yielding approximate solutions, which with proper care in element choices will converge close to the real solution. As the number of elements increase so does the solution convergence. In applying the concept to a structure and solid mechanics, there are three areas of consideration used in the idealization.

1. Design Conditions
   - Geometry
   - Loading
   - Material Properties
   - Boundary Conditions

2. Element Types
   - Simple Frame
   - Plane Stress
   - Solid Elements
   - Axisymmetric Solid
   - Flat Plate Bending
   - Axisymmetric Thin Shell
   - Curved Thin Shell

3. Governing Equations
   - Equilibrium Conditions
   - Compatibility Conditions (relate stress to strain)
   - Kinematic Conditions (relate strain to displacements).

The model is developed by writing an assumed displacement-based function which gives the element displacement as a function of a shape function and node displacements. Then relationships between displacement and strain, strain and stress, and stress and joint forces are written, then combined to give the overall element equation. As the element complexity grows, so do these functions. The general set contains:

1. Shape Functions
2. Displacement–Strain
3. Strain–Stress
4. Stress–Joint Forces
5. Stiffness Equation.

The choice of elements then is determined by the need to properly represent shapes, stress, etc. Key factors are the characteristics of the areas being modeled and whether elastic or plastic (nonlinear) analysis is required. For very complex analysis, many node solid elements are required.

It should be warned, however, in the concern to get details, be sure that basic length, width, and depth ratios do not violate sound principles; e.g., long, thin, and deep elements usually give problems. For very large and complex structures (such as a shuttle element), demand or available finite element solving equipment is exceeded, and the total structure is subdivided according to specific considerations. These subdivisions or components are called substructures or subelements.

Using these basic principles and concepts to varying degrees throughout a subelement, the subelement model is constructed and validated as before. The interface forces that evolved from the system analysis through the element analysis are now used as forcing functions or force distributions on the model. This is a combined static and dynamic analysis using a detailed finite element model with greater details in the special regions. Cautions must be raised in that the subelement model size must be large enough to distribute out the loads and balance the set. Material properties, etc., must match these same details or errors result.

References 1 and 13 contain many examples of this type analysis for various space projects and other shuttle elements.

The final analysis step uses the same approach as this subelement step, using the results from the subelement analysis as forcing functions for a critical area within the subelement. Greater care is required for the very detailed model of this critical area, since both elastic and plastic (nonlinear) analytical techniques must be used. Element choices must be done with great care. Solid elements with good shape functions and additional nodes are required. Material characteristics and variations in critical regions are accomplished. Using this model (critical areas), the dynamic and stress analysis directly provides the margins of safety; however, this is not the end. At least five other analyses are required using detailed data from this critical analysis as input.

1. Fracture mechanics analysis including lifetime, critical flaw size, and NDE requirements
2. Fatigue (lifetime specifications)
3. Stability
4. Nonlinear plastic analysis
5. nonlinear jointed structural analysis.

These analyses[2 9 18–24] require judicious choice of analysis codes, materials data, and test derived parametric data. Bolted joints are a problem, since individual bolt loading and local yielding are not deterministic. Elastic analysis could easily show major problems when no problem exists. In other words, bad assumptions produce totally erroneous analysis. The starting point for fracture analysis is accurate stress at the potential failure locations. Many examples and additional guidelines could be given, but are beyond the scope of this report. The same is true for fatigue. These analysis approaches are not discussed in this report, but are covered in detail in NASA safety factors design documents. These are left to the reader.[2 9 18–25]

V. OPERATIONS

The final loads cycle is not totally complete until the design (vehicle, spacecraft, or space system) capabilities/characteristics are manifested into operational procedures and constraints. This formulation of procedures and criteria ensures that the system operates correctly and within the bounds of its capability of preventing failures. Many examples could be given; however, the space shuttle was chosen because it is currently in the operational mode.

The space shuttle is a highly tuned system that blends basic design options with operational procedures and strength to ensure structural viability. This process, design and operation, was managed by Johnson Space Center with heavy involvement with Marshall Space Flight Center and Kennedy Space Center. The shuttle design calls for monthly mean wind trajectory biasing coupled with pitch, yaw, roll, and elevon load relief. The design ended with marginal structure (particularly the orbiter wing), even with these load reduction schemes, due to the inability to predict prior to flight the aerodynamic distribution on the vehicle.[13 26 27] To protect the vehicle structure and ensure adequate performance, the Launch Systems Evaluation Advisory Team (LSEAT) was formed to develop, implement, and be the focus for systems evaluation during each space shuttle launch.

The procedure starts the shaping of the basic trajectory for each launch. This is accomplished by using the vehicle structural capability as constraints. Figure 53 shows the capability of key orbiter elements. All critical shuttle elements have constraints given in terms of load indicators (figs. 28 and 29). Figure 54 illustrates how this is accomplished for the monthly mean wind for the month of the scheduled launch. Using this monthly mean wind bias trajectory, 3-sigma dispersions are generated for each load indicator (critical structure) for use by LSEAT during operations. Using these dispersions to protect against parameter uncertainties, the operations procedure is set in place. It consists of sending up wind sounding balloons at various intervals prior to launch, then calculating the performance and load response to these winds (fig. 55). The nominal values generated then have the 3-sigma dispersed values added as well as a wind persistence value to account for wind change effect at launch time. If all loads are under their limit values, then the decision is go. If not, then there is an option to bias the trajectory further using the wind profile measured called DOLILU. If the indicators are now within limits, the call is still go; if not, the process is continued until the 2-h wind profile (fig. 55) is measured and responses evaluated, at which time the call is maybe. If the limits are satisfactory, then it is go; if not, the launch recommendation to the management team is no go.

Figure 56 is a typical pitch plane wind profile plotted with the monthly mean and 95- and 99-percent envelope values. Figure 57 is the response of a wind indicator with the monthly mean, the nominal response to the latest wind profile, and a 99-percent dispersion value. The limit is plotted as a straight line. Figure 58 is a plot of the top 10 (nearest limit) load indicators for that wind, while figure 59 is a table of several parameters for each wind profile starting 50 h prior to launch and continuing until launch minus 4.25 h (L–4.25).

This is a short synopsis of the procedure. The procedure continues to evolve as more is learned; therefore, the process as stated may not be current, but illustrates how operationally structural reliability can be ensured. Projects must utilize all the best available from concept selection, through design, and during operation to ensure successful missions.

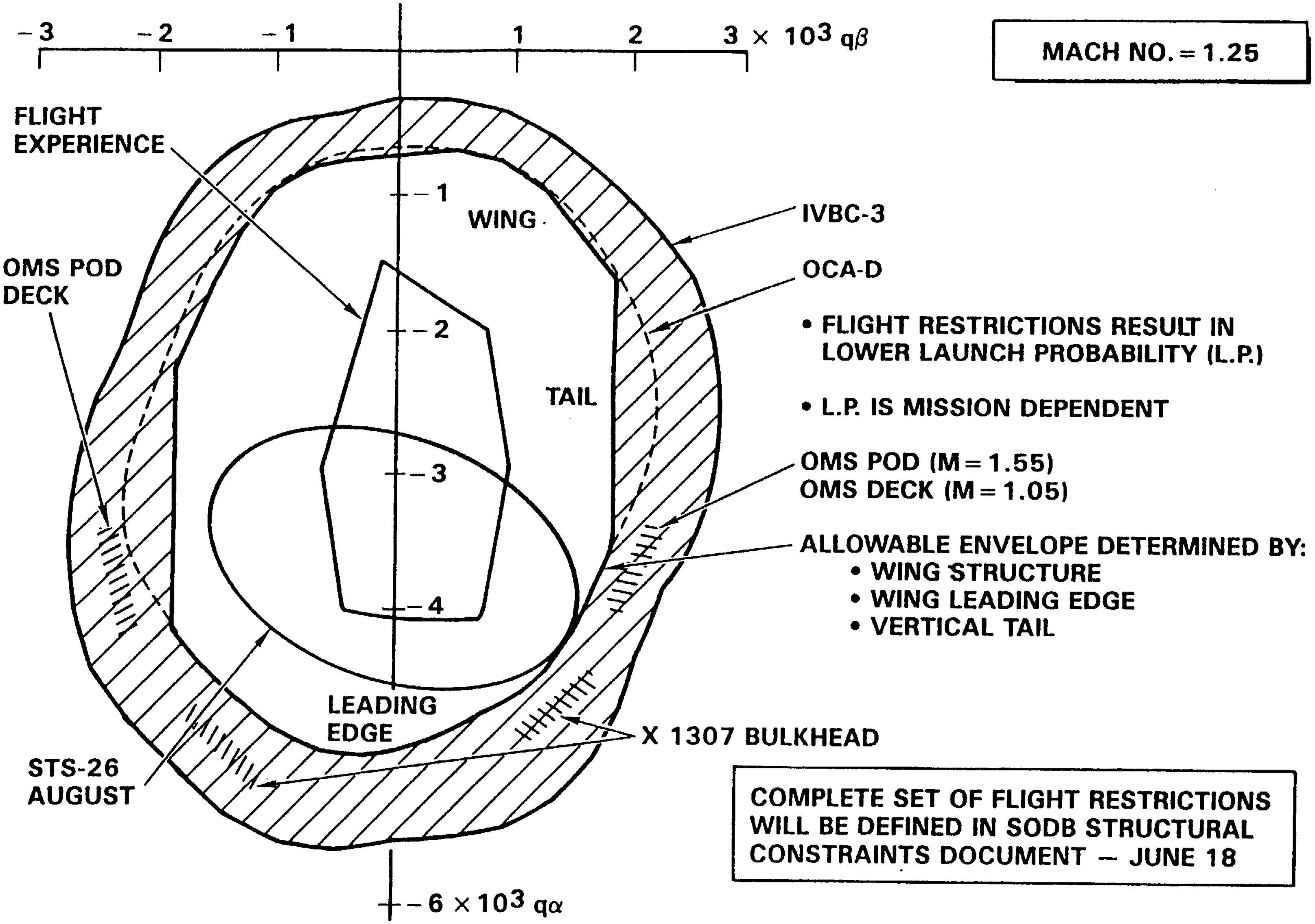


Figure 53. Example of ascent flight restriction derived from orbiter 6.0 analysis results.

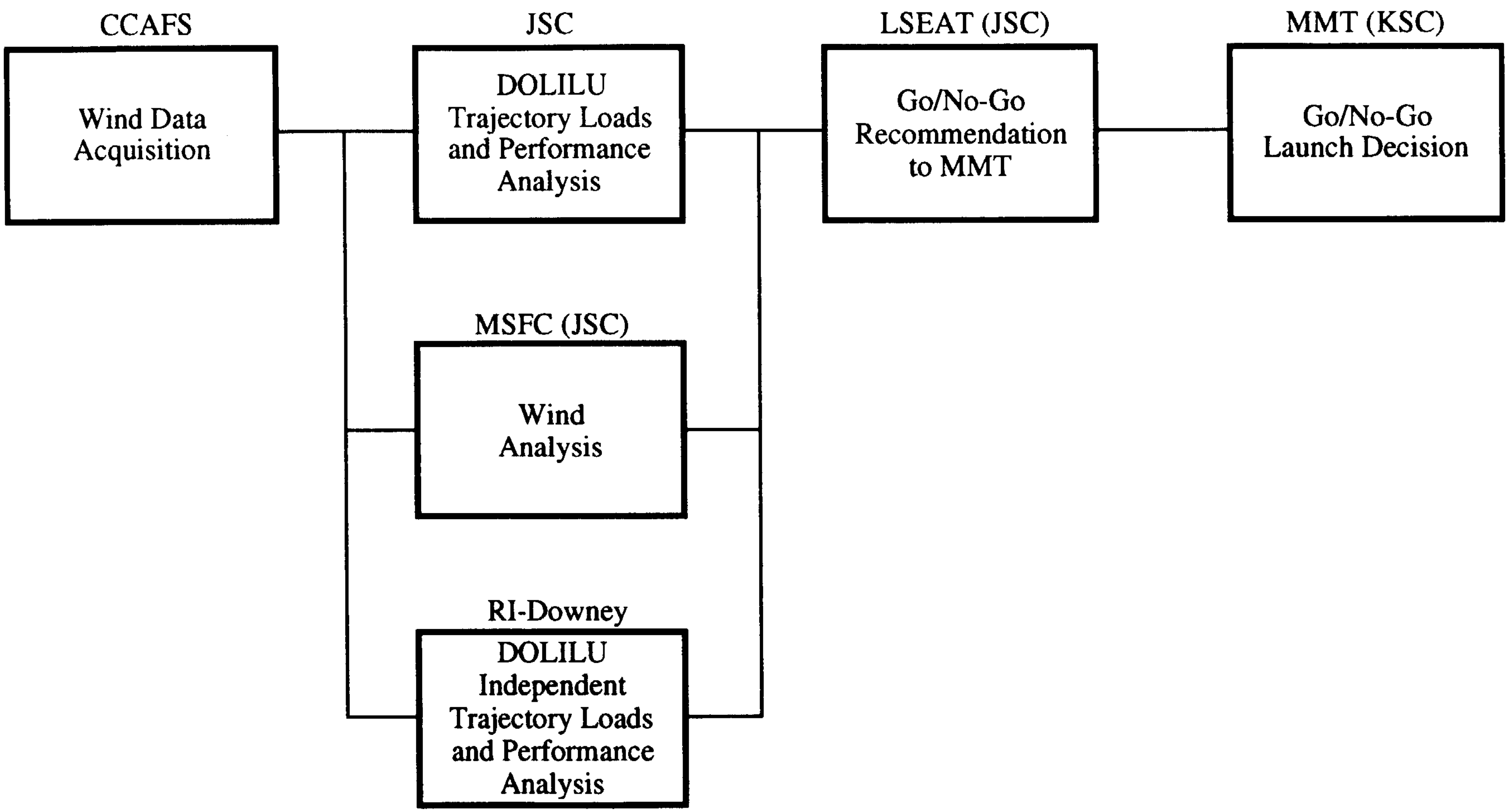


Figure 54. LSEAT overview.

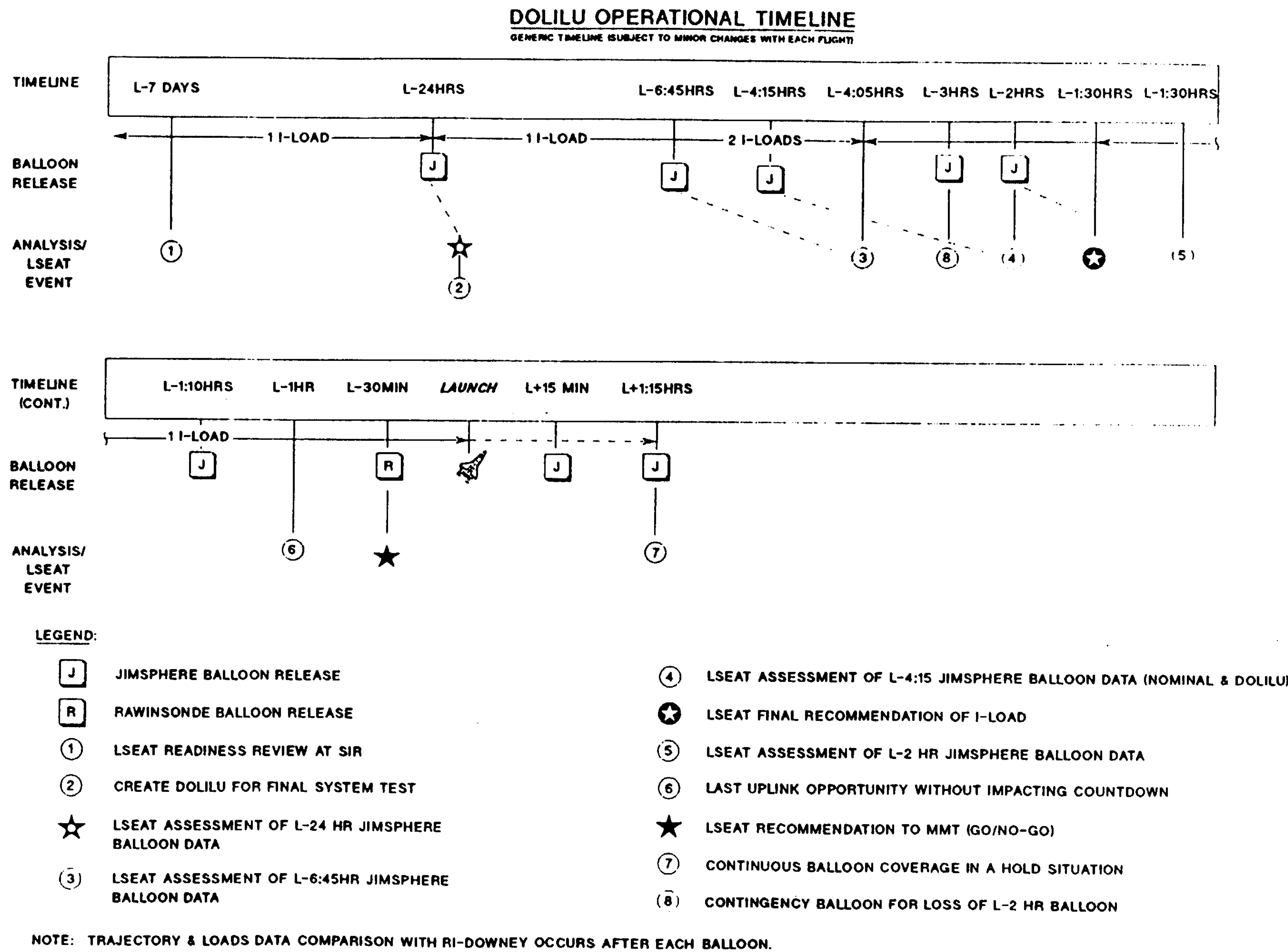


Figure 55. Day-of-launch I-load operational timeline.

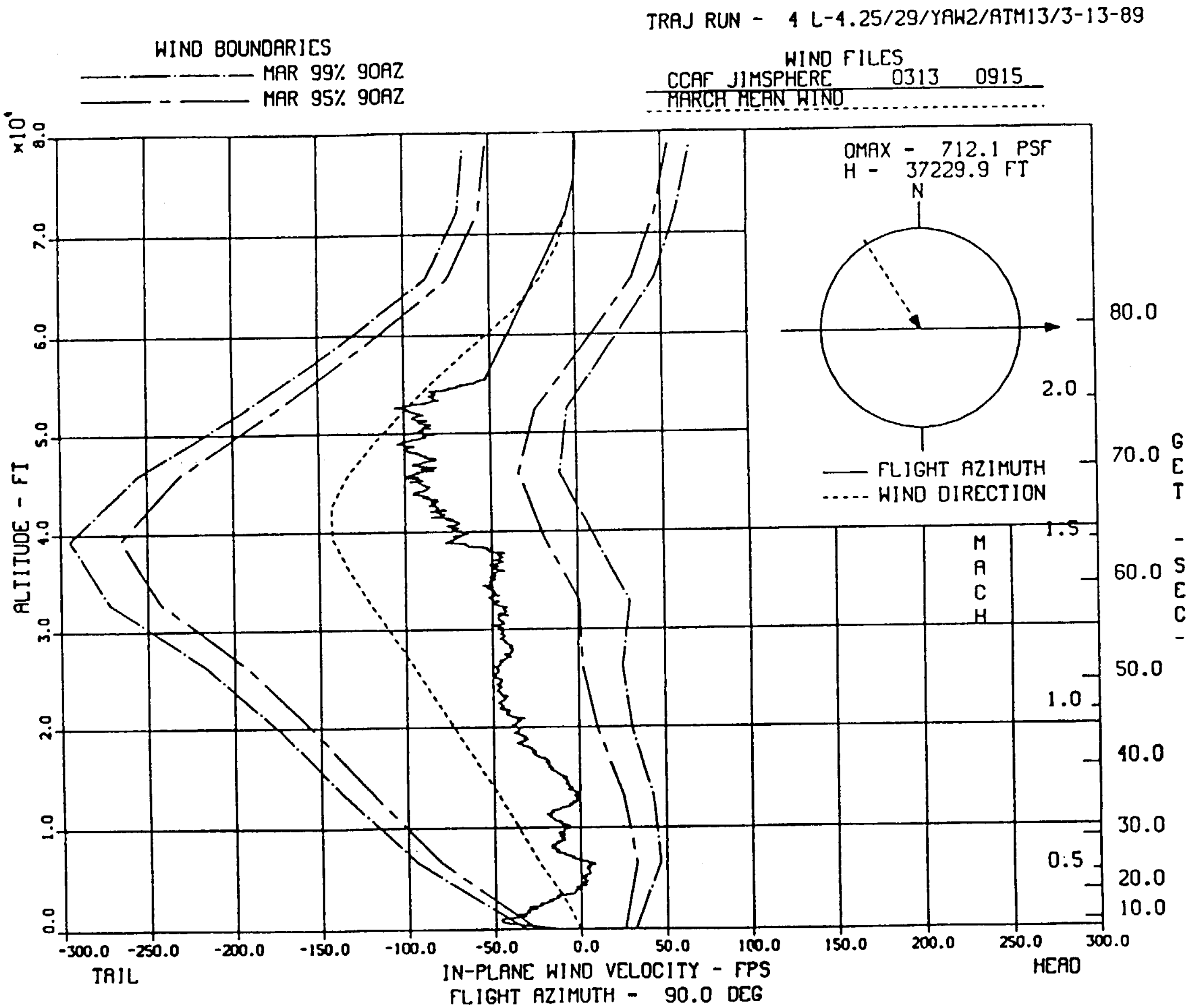


Figure 56. Typical pitch plane wind profile.

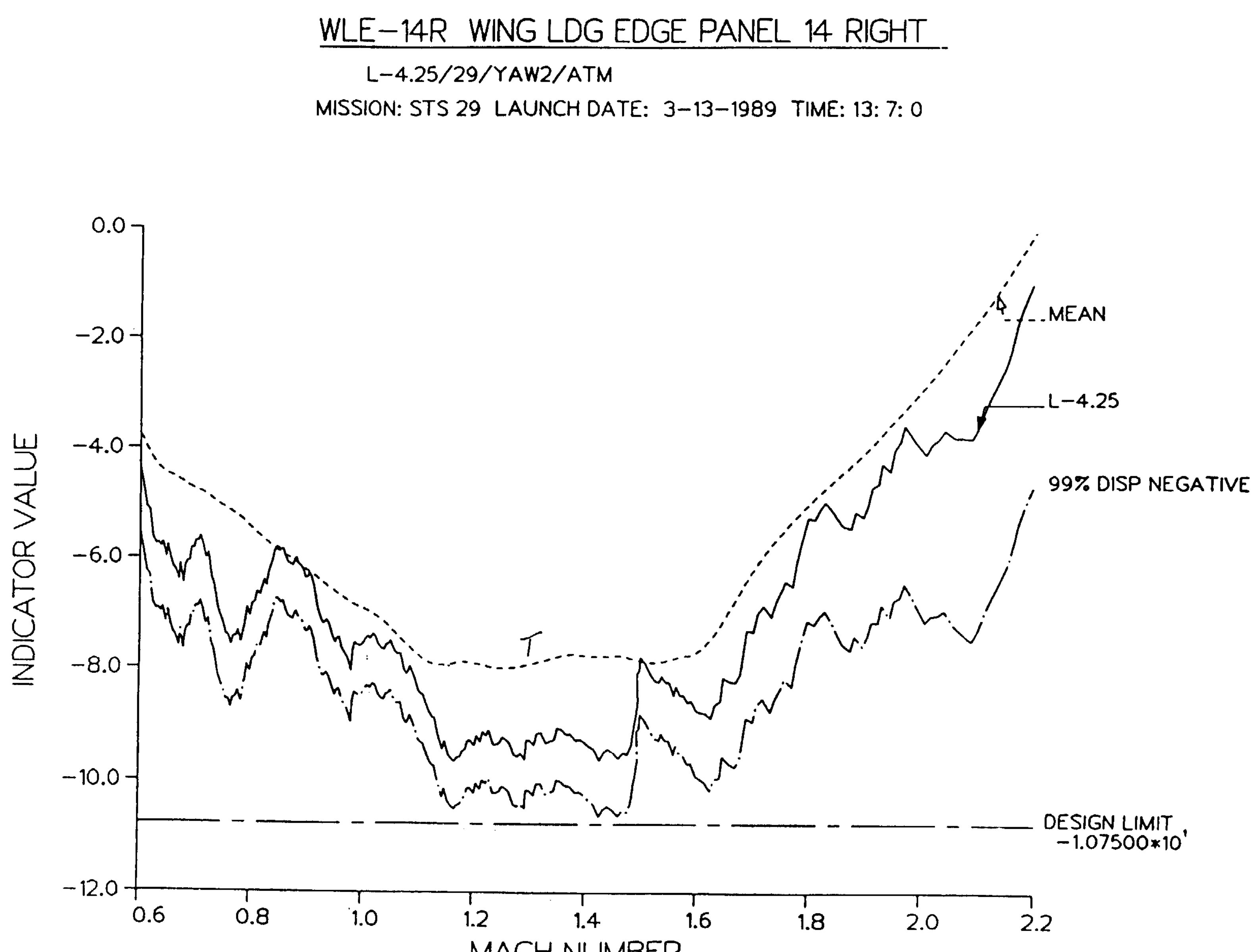


Figure 57. Response of a wind indicator with the monthly mean.

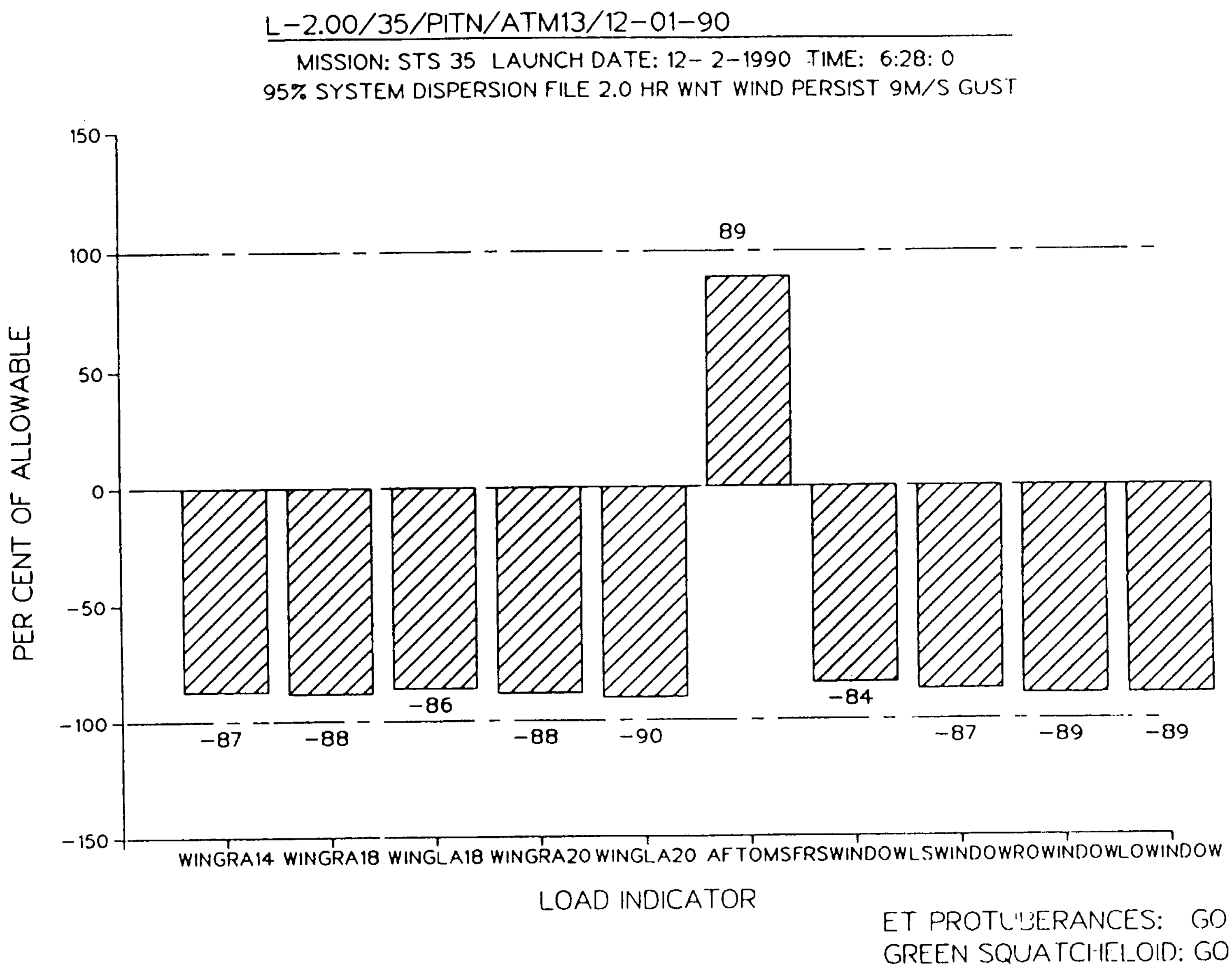


Figure 58. Load indicator top 10 bar chart.

LSEAT TRAJ/LOADS SUMMARY STS 29 (ALT YAW2)
LAST BALLOON: L-4.25/29/YAW2/ATM

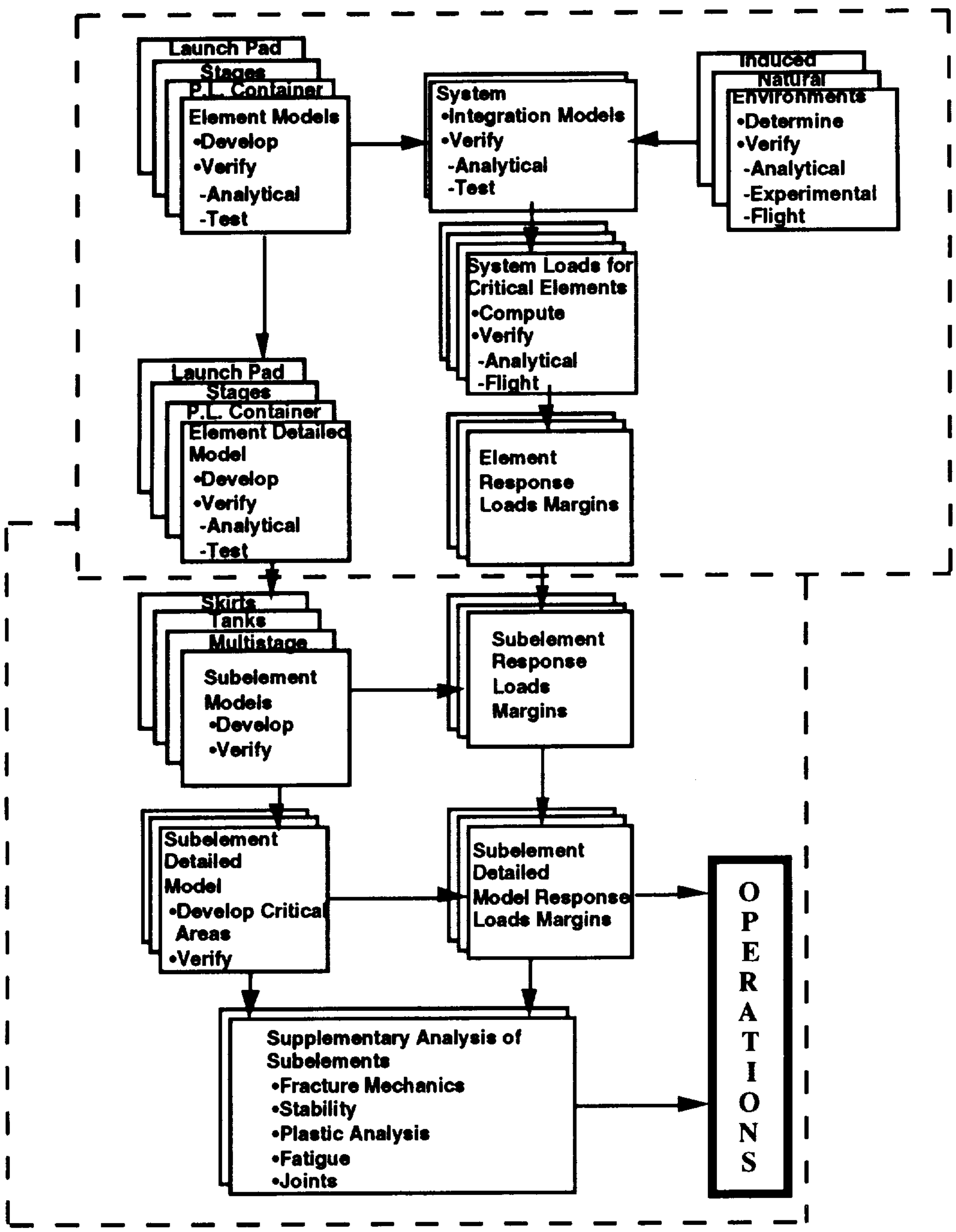
	FLIGHT RULE	BALLOON RELEASE TIME IN HOURS: MARNOM	L-50.0	L-28.0	L-18.0	L-14.0	L-8.25	L-6.25	L-4.25
TRAJECTORY ANALYSIS									
MAX UNDISP QBAR (PSF):	N/A	639.2	739.1	706.7	706.2	699.3	702.2	701.3	712.1
AT MACH NUMBER:		1.39	1.45	1.37	1.38	1.42	1.41	1.38	1.48
MIN DISP QBAR MARGIN (PSF):	>0 PSF	35.4	17.6	20.5	19.3	20.1	20.3	21.8	19.1
AT MACH NUMBER:		.74	1.13	.77	.82	.77	.82	.81	.78
MIN Q-ALPHA (PSF-DEG):	N/A	-3516.	-4982.	-4731.	-4573.	-4292.	-4476.	-4426.	-4388.
AT MACH NUMBER:		1.24	1.37	1.37	1.27	1.40	1.21	1.22	1.17
MAX Q-BETA (PSF-DEG):	N/A	252.	1423.	1419.	1309.	1343.	789.	926.	818.
AT MACH NUMBER:		1.34	.63	.65	.63	.61	1.47	1.48	.76
USABLE MPS AT MECO (LBS):	>4713	8309.	8478.	8545.	8664.	8708.	8723.	8699.	8652.
PERFORMANCE MARGIN (LBS):	>0	3596.	3765.	3832.	3951.	3995.	4010.	3986.	3997.
2-SIGMA DT HOLD (MIN):	N/A	19.7	20.4	20.6	21.1	21.3	21.3	21.2	20.7
LOADS ANALYSIS									
MAXIMUM LOAD INDICATOR:	N/A	AFTOMSF	GRN SQT	GRN SQT	GRN SQT	GRN SQT	GRN SQT	GRN SQT	GRN SQT
PERCENT DESIGN LIMIT:	<100	89.	• 154.	• 137.	• 112.	• 121.	• 106.	• 105.	• 112.
AT MACH NUMBER:		1.04	1.37	1.37	.69	.63	1.36	1.38	.76
ET PROTUBERANCE:	=GO	GO	• NO-GO	• NO-GO	• NO-GO	GO	• NO-GO	• NO-GO	• NO-GO

•-INDICATES CONSTRAINT VIOLATION

Figure 59. LSEAT trajectory/loads summary.

VI. SUMMARY

Design and margin assessments of flight structures are a multidiscipline process initiated by mission analysis and progresses through concept selection, loads, and stress analysis. This complex process is organized through a sequence of discipline models such that solutions evolving from unique models and data bases will comply with the structural system elements, and subsequent performance and margin requirements. Structural performance and margin assessment requires many steps, great skill, computer capability software, test, and flight verification. A summary of basic steps and flow are:



Some steps may be eliminated; however, indepth assessment should be made before any are deleted. Verification of all models and analyses is imperative. Preverification test analysis must be performed to guide the test and to provide proper instrumentation and data evaluation. Posttest analysis, including model/analysis update, must be accomplished so that adequate tools are in hand for design changes, deviation assessment, and operational constraint determination. Using these approaches, a safe, reliable space mission can be accomplished. Deviation in any area can lead to programmatic adversities at best.

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Determining structural design inputs and the structural margins following design completion is one of the major activities in space exploration. The end result is a statement of these margins as stability, safety factors on ultimate and yield stresses, fracture limits (fracture control), fatigue lifetime, reuse criteria, operational criteria and procedures, stability factors, deflections, clearance, handling criteria, etc. The process is normally called a load cycle and is time consuming, very complex, and involves much more than structures. The key to successful structural design is the proper implementation of the process. It depends on many factors: leadership and management of the process, adequate analysis and testing tools, data basing, communications, people skills, and training. This report deals with this process and the various factors involved.

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