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TECHNICAL PAPER

THE ROLE OF FAILURE/PROBLEMS IN ENGINEERING: A COMMENTARY ON FAILURES EXPERIENCED—LESSONS LEARNED

I. INTRODUCTION

"Quality is our job one" is the phrase heard continuously. In a technological age, our lives are influenced strongly by quality or the lack thereof. Our personal lives are affected. Our professional lives are driven by its focus. We all are concerned with who our customer is and how we meet his or her requirements to build a better product. How do we meet the goals of total quality management (TQM)? is our pressing question. Many tools are in place undergirded with a management theory and a companion set of principles. Many other tools are being developed. However, if the goals are to be achieved, we must have knowledge and understanding. One way of achieving understanding and insight is through studying problems and failures. The study of problems, in the presence of appropriate theory, produces sets of principles important to achieving quality, first of all, and second, helps us focus our technology and better understand our expertise and the physics of the problem. This report deals with the principles derived and lessons learned from years of space flight engineering. A separate report, to be published later, is a compilation of synopses of the problems experienced.

These reports are based on three perspectives: (1) 51-L space shuttle *Challenger* accident investigation, (2) safe return of the shuttle to flight activities and the continuing flights, and (3) 35 years of engineering experience. The general finding upon which the report is based is that "failure, problems, in general, were not due to undiscovered or missing theory; but to the neglect or oversight of basic principles" (fig. 1). These oversights are in management, criteria, procedures, philosophy, test, analysis, communication/documentation and project management areas of a program.

This is not meant to down play technology—technology is foundational to our business and must be vigorously pursued. We get excited about technology, selling it well, and do an outstanding job in its development while other key ingredients appear to be mundane in comparison and therefore take the back seat. This should not be the case.

The study and importance of failure in design evolution is well documented.[1–3] Understanding prior failures provides the basis for technology development, better solutions, systems operation points near margins, and safety. All designs by definition are designed for failure. As the design evolves and changes, it forces changes in the requirements, thus, the performance changes. Reference 1 discusses these compromises of design.

> "The requirements for design conflict and cannot be reconciled. All designs for devices are in some degree failures, either because they flout one or another of the requirements or because they are compromises, and compromise implies a degree of failure.
>
> "Failure is inherent in all useful design not only because all requirements of economy derive from insatiable wishes, but more immediately because certain quite specific conflicts are inevitable once requirements for economy are admitted; and conflicts even among the requirements of use are not unknown.

> "It follows that all designs for use are arbitrary. The designer or his client has to choose to what degree and where there shall be failure. Thus the shape of all designed things is the product of arbitrary choice. If you vary the terms of your compromise—say more speed, more heat, less safety, more discomfort, lower first cost—then you vary the shape of the thing designed. It is quite impossible for any design to be 'the logical outcome of the requirements' simply because the requirements, being in conflict, their logical outcome is an impossibility."

This being the case, it is imperative that failures, as well as the problems experienced, be understood. As the Greeks say about the Phoenix bird, that out of the ashes of destruction rises newness. Problems and our reaction to them determine character and through this effort comes the greatest learning and achievement. As man has pushed technology to achieve the successes of space exploration, many problems have occurred, some resulting in major failures, even national disasters. Disasters bring one to the ashes, both personally and collectively, both technically and economically. Out of these ashes must rise again the new Phoenix. There is a story that goes something like this:

> "A farmer and his wife had experienced a very good couple of years' harvests. They were comfortable, with money in the bank. They discussed the situation, noticing their cattle and the rickety old barn. They decided to build a new modern barn, replacing the old one before winter. The barn was built with comfortable stalls, heat, and lighting. The barn was completed and the old barn demolished. They decided to go to town and celebrate. As they were returning home that night, the first winter storm came blowing in. They commented what great shape the cattle would be in. Arriving home, the farmer decided to go out and see how the cattle were doing in the new barn. Turning on the lights, not one of the cattle was to be seen. He panicked. Someone had stolen his cattle! He ran outside to look for evidence and noticed the cattle standing in the foundation marks of their old stalls."

As we at NASA dealt with the *Challenger* (SL-51) accident and the myriad problems that have occurred in the return to safe flight and ensuing flight program, the goal has been to birth a new Phoenix bird, to build a new barn that does not disregard the old foundation, but moves into the new. It is hoped that this report will help in that process by documenting a set of principles and a synopsis of problems and how they were solved. Interwoven with each is a personal testimonial and its resurrection which is probably the real story; however, that is left to others. As stated previously, this report documents a seminar given to several aerospace companies and three NASA Centers. It also augments two previous reports, TP2508 and TP2893, which contain some of the same information. In general this report serves as a general overview with supporting summary data to the other documents. It deals with problems covering all major applied mechanics disciplines and also contains a short discussion of the *Challenger* accident.

In dealing with problems, one can get the idea that one is negative and pointing fingers or placing blame. That is not the case. All have performed exceptionally well, producing unprecedented machines. The purpose in enumerating problems is to learn lessons and produce better machines in the future.

May this report add a small flicker of light on the path to the future of space.

II. BASIC PRINCIPLES

As stated in the introduction, the study of problems has led to the conclusion that the violation of basic principles, not missing technology, is the culprit. The solution of this problem, of violation of basic principles, determines success. The *Challenger* accident, its results, and the attendant return to flight activities were the driving force behind a lessons-learned report published in January 1989.[4] This report was written as the result of numerous inquiries as to "What have you learned?" This paper expands the concepts to include the influence of constraints, schedules, etc., on the design. Saturn, Apollo, Hubble space telescope (HST), and the space shuttle are used to illustrate the concepts and the derived principles. In general, these observations deal with design and verification principles which, if practiced, should greatly reduce problem occurrence, the thrust of this paper as delineated in figures 1 through 4. Two pivotal concepts are the keys to quality: (1) system focus is one of the foundations of high quality, and (2) the correlation of hardware sensitivity to the performance requirements. Twelve principles support these pivotal concepts.

A. System Focus

1. General

What is meant by system focus? is one of the hardest questions to answer in engineering. Most look at some part of systems and call that the system focus; integration, etc. First and foremost, it is an attitude, as it is the foundation of TQM. Second, it is the tying together of large hardware, software, vehicle, facilities, and operational systems into a cohesive bond integrating all disciplines, hardware, software, etc. from determining requirements and performance to verified operational hardware. Third, it implies teamwork and open communications, which says that all involved must have some knowledge of each system outside one's own specialty and be willing to communicate and share (fig. 3). It also implies incorporating manned rating, when applicable, up front in the design as well as failure mode and effects analysis (FMEA)/critical items lists (CIL's) to identify and design out failures (fig. 6). What is neglected in design due to a lack of system focus must be accounted for by good system optimization during operations. It is a pay me now or pay me later condition. This is a fundamental lesson learned from studying the system focus.

Engineering is a process based on principles of technical disciplines, management, etc. Its application involves risks. Reduction of risks requires both knowledge of the process and the inherent subprocesses, the technical disciplines, and the ability to judge merits of each. The system focus is fundamental to lowering these risks through decision making involving the system from front to end, concept to operations, and considering total cost. Total cost is, in all probability, the hardest item to define, certainly it is the hardest to calculate. The great challenge is how one balances total cost with risks to arrive at an acceptable answer.

Figures 7 and 8 are an attempt to show two approaches to the system focus. The first is the idea where one iterates using total cost as the criteria to determine drivers (sensitivity analysis), conducts concept testing, and arrives at robustness criteria that produces a basis for an optimized system. This must be accomplished in conjunction with the customer and his needs. When one talks about total cost, it is all inclusive, including vehicle, facilities, operations, software, hardware, manpower, transportation, manufacturing, design, and maintenance. Robustness says that the design is insensitive to variations, environments, manufacturing, and other effecting parameters. Also that the design controls them and the margins. All are part of the optimization. To produce this optimized configuration, several iterations are required through the total loop (dotted line).

Use of techniques of TQM to transfer the customer's requirements into quality systems enhances this process. A more detailed look at this process is shown on figure 9. The first shows it for the major elements of design while the latter shows still more details. The resulting configuration that is selected and verified then has low operational cost, flexibility safety, and performance. As was stated in the introduction, however, design is a compromise which implies some degree of failure. Figure 8 attempts to capture this situation by changing the contents in the various blocks of the process. Notice that cost is constrained up front as is size, weight, etc., in an attempt to meet goals from outside, such as those imposed by Congress. This changes the other blocks limiting sensitivity analysis and concept testing.

These are not new debates or ideas. References 5, 6, and 7 deal with discussions and debates centering around what has happened in various projects throughout space history, particularly starting with Apollo. Fundamental to this loop is the correct setting of requirements, particularly the derived requirements, which now must be set in terms of constraints; these constraints being in conflict with requirements, objectives, etc. This forces a compromise in the configuration, as is indicated on figure 8. The design is now a suboptimized configuration instead of an optimized one with robustness. Once given this constrained system, one must work within it to produce the best system from requirements to product using the best tools and skills. This interactive flow between the customer's desires, design, manufacturing constraints, cost functions, maintenance, and operations, etc., determines the design and performance. As illustrated in figure 8, the suboptimal approach produces a system that in the end does not totally meet the performance goals, is more costly to operate, and does not have flexibility. In later sections, several space systems will be evaluated in terms of this principle.

In fact, what was not made robust must be covered in operations by system constraints, stringent operational procedures to insure safety. The resulting problems and failures take many forms, and the consequences are determined by when and how they happen. For example, proof testing is designed to screen defects; therefore, failure in proof can indicate the test has accomplished its objective or it can be a design deficiency. Repeated proof failures indicate either a design or manufacturing deficiency. Failures during development can be corrected, but are costly. Failures alluded to can also result in the excessive maintenance and refurbishment required for safety on limited lifetime parts. All these mean that FMEA/CILS's and hazards must be an up-front part of design to help reduce these impacts, design in redundancy, etc. The following table lists the categories of failures and problems one needs to understand.

Table 1. Classes of problems.

I. Major Failures
   a. Design Deficiencies
   b. Quality Control/Manufacturing

II. Proof Test Failures

III. Localized Failures (Contained)

IV. Hardware Limitations (Design Deficiencies) DAR's
   a. Lifetime
   b. Performance Limits
   c. Redlines
   d. Inspections
   e. Refurbishments
   f. Special Analysis and Tests

V. Hardware Limitations (Manufacturing, etc., Deficiencies) MRD's
   a. Measurements
   b. Inspections
   c. Analysis and Test
   d. DAR's

Comparing the two system approaches means that up front much more analysis, test, etc., must be accomplished to determine drivers and to select optimized configurations. Obviously, this is another way of saying what is shown in many TQM courses with the quality level (fig. 10). Notice the factors on quality payoff versus program phase compared to recognition. Does this not say that if one wants to advance professionally, he waits until production then puts on his thinking cap and solves problems. Somehow this must be turned around. This is said partly in jest, yet our rewards system greatly favors the Production Phase problem solving. A companion chart (fig. 11) shows the cost for the two approaches versus program phases. One can further conclude that most of the requirements become derived requirements because their origins lie in the conceptual, design, and development work as modified by imposed constraints. This is due to a general principle which states "What is done up front in a project—requirements, constraints, etc.—determines, to a large extent, the quality and performance of the design. What is done in production and operations tends to be fine tuning of this predetermined configuration and is very costly if robustness is not present." Figure 6 summarizes this. "Pay me now or pay me later" certainly applies.

Coupled strongly with the system focus is the principle that the higher the performance requirements, the greater the sensitivity of the system, subsystem, or part to variations in any parameter including manufacturing, environments, etc. This and the other ungirding principles to the system focus are discussed in later sections.

2. Project Examples

Three programs of NASA (Saturn, space shuttle, and HST) illustrate how the system focus functions in real life. The following discussion of Saturn, Apollo, space shuttle, and the HST is not meant as criticism or that any other path was possible. In fact, it is very probable that no other option existed at the time; however, when that is the only course, it must be clearly understood from cause and effect on systems so that the best design possible is achieved. With the exception of Saturn, these systems have not always met their initial performance goals and were usually more costly than predicted; however, each has been outstanding performers, indicating excellent engineering and management regardless of the situation imposed by economics, etc.

a. Saturn/Apollo/Skylab

The Saturn, Apollo, and Skylab vehicles were an evolutionary process that began with the development of the Saturn I vehicle built from the manufacturing propulsion technologies of the Redstone and Jupiter systems. Tanks, using Redstone manufacturing, clustered around a center tank using Jupiter diameters and manufacturing were used with a spider beam at the top and a thrust frame at the bottom containing a cluster of eight H-1 engines forming the first stage. The second stage was designated the S-IV. This vehicle, which became the forerunner of the Saturn 1B, evolved through two block changes during 10 successful flights. The block I had no aerodynamic fins on the vehicle, and the second stage was not live. Block II had aerodynamic fins and a live S-IV stage using a cluster of Pratt and Whitney RL-10 engines with uprated H-1 engines on the first stage. The propellant tanks were also lengthened. The instrument unit became a prototype for the Saturn 1B and Saturn V.

The Saturn 1B represented major advancements for the hardware and techniques for the lunar missions and was the vehicle for launching men for the various Skylab missions. The vehicle's first stage had a more efficient, lighter weight structure (performance enhancement) as well as further uprating of the H-1 engine. The S-IV stage was powered by a new, single-stage liquid hydrogen J-2 engine (also used in Saturn V). The vehicle was the workhorse to wring out the Apollo command module and lunar module in the manned mission scheduled to be launched on the 51B 204 vehicle. This mission was delayed 1 year to solve problems associated with the Apollo capsule fire. The Saturn 1B afforded the opportunity to flight-test important elements of Apollo-Saturn flight hardware as well as operational procedures, etc. It also powered the first manned Apollo mission, *Apollo 7*, clearing an important hurdle for Apollo. Figure 12 is a schematic of the Saturn 1B vehicle, while figure 13 gives its basic characteristics and performance requirements. After the successful Apollo program, it became the vehicle for launching astronauts to the orbiting Skylab program, completing four successful missions. This evolutionary development program has much to do with the successes of Apollo followed by Skylab, and illustrates much of the system focus being discussed.

The Saturn V vehicle was used to launch both the Apollo lunar missions and the Skylab mission. Figure 14 shows the Saturn V, while figure 15 compares the Apollo configurations and the Skylab vehicles.

The vehicle was a three-stage, in-line vehicle composed of the S-1C first stage using a cluster of five F-1 engines burning RP1 developing 1.5 M lb thrust each. The second stage, S-II, was composed of a cluster of five J-1 engines burning liquid hydrogen, developing approximately 230,000 lb of thrust each. The third stage, S-IVB, had a single J-2 engine burning liquid hydrogen, developing approximately 200,000 lb thrust. For the Apollo mission, the service module had a single engine for midcourse corrections, lunar orbit escape, etc., and was separated from the command module before Earth atmosphere reentry. Figures 16 and 20 show the basic characteristics by stages. The Skylab version replaced the S-IVB stage with the Skylab space station and eliminated the command and service module being an unmanned vehicle.

Saturn/Apollo is a mixed bag in terms of total optimization. It, in fact, was not a total optimized system. It did however, have robustness from most viewpoints. Several books have been written, covering these design and program evolutions from all aspects—political, manned operations, design, etc.[5–10] Early on, a lot of analysis and testing was accomplished which had strong impacts on the success of the program. The program also had problems late that had to be resolved in a brush fire mode; hydrogen engine combustion instability and the Apollo capsule fire, for example. These are probably typical of what could be expected in a system pushing state-of-the-art technology. Many would argue that at least the capsule fire was preventable, which is always the case if one had the knowledge prior to the accident or problem that is known afterward. Interestingly, the focusing that occurs when solving problems sharpens and marshals the brain, which intensifies efforts leading to insight and concepts that are not there in potential problem analysis modes. The Saturn Apollo was, however, robust in most respects.

Robustness is illustrated in terms of structural capability which allowed the Skylab mission. Figures 21 and 22 show the aerodynamic pressure distribution for Apollo and Skylab configurations. The Skylab had a forward peaked aero distribution which peaked the bending moment in the S-VB stage versus the Apollo version which was more averaged (fig. 21 and 22). This resulted in a more in-depth wind biasing and probabilistic (Monte Carlo) assessment using the measure Jimsphere wind ensembles. Figure 23 and 24 show the bending moment probability for nonwind biasing and wind biasing versus bending moment capability. By using wind biasing, the vehicle could be brought into an acceptable loads response level. This was further insured on the day of launch using conditional probability in conjunction with measured wind data for launch constraints, that precluded launching into an unsafe winds aloft condition.

The ability to incorporate five engines on S-IC and S-II stages, although not optimum, further illustrates robustness in both the structural and propulsion systems. As a result, performance flexibility made possible the lunar rover mission, and very likely the lunar orbit rendezvous mode option that was made late in the program.[5]

The use of the Saturn I, basically as a development vehicle, and 1B, as not only a workhorse but as a test bed for Saturn V, was clearly a desired evolutionary approach. Funds, etc., preclude this in many cases and, therefore, the development risks must be reduced in other ways.

b. Hubble Space Telescope

The HST is the world's greatest orbiting observatory. Its accuracy and precision are unprecedented. The pointing accuracy is 0.007 arcsec, which is equivalent to focusing on a dime from Washington to Boston. The HST (fig. 25) is composed of the outer protective shell (called the SSM), the momentum wheels that control the vehicle by varying each wheel's speed, and the aperture door for blocking direct sunlight from the instruments allowing more science time. The inner parts are the heart of the optical telescope assembly (OTA) system composed of the metering truss mounting, the primary and secondary mirrors, the focal plane structure, and the aft truss mounting the scientific instrument. To eliminate thermal distortion, the frames are made of composites with near zero C_T (coefficient of thermal expansion). The mirrors must be accurately located relative to each other (fig. 26). The light enters striking the primary mirror, which focuses it on the secondary mirror. The secondary mirror focuses the light back through a hole in the center of the primary mirror onto the scientific instruments. The instruments are: (1) the fine guidance sensor, (2) the faint object spectrograph, (3) the wide field planetary camera, (4) the photometer, (5) the high resolution spectrograph, and (6) the faint object camera. They function to perform the fine pointing and to gather various scientific data from studying the heavens (fig. 27).[11] Power is provided by solar arrays in conjunction with storage batteries. The control system uses six rate gyros and the two fine guidance optical sensors to provide roll, pitch, and yaw information, and is designed to keep the observatory accurately locked to within 0.007 arcsec on a subject for extended periods. This is equivalent to 1.2-cm offset at a distance of 600 mi (1,000 km). Temperatures within the telescope are controlled actively and passively to assure pointing accuracy and structural stability.

Not only is the spacecraft itself very complicated, but so is the management and organization. The scientists gather the data and analyze it while NASA operates the craft. The scientists work through the space institute, NASA/Marshall Space Flight Center (MSFC) was responsible for design and deployment, and NASA/Goddard Space Flight Center (GSFC) was responsible for the scientific instruments and operations. It was a major effort to balance between the scientists' desires and the engineering project constraints during design.

The space telescope was fraught with problems early in the program. Budget constraints, etc., kept changing the requirements and design. Reference 11 is an excellent disclosure of the telescope design, management, and other problems as the project evolved.

Early in the program, as a cost saving, it was decided that the project office would be the integrator and that, due to the proprietary nature of some of the hardware, all data would exist only at two or three co-located rooms. Engineers would have to go to those rooms for information. A tight development cost constraint was also imposed. Military constraints due to their heavy defense involvement at Perkin Elmer early in the program further constrained activities. The end result was a lack of systems focus. Many other earlier decisions and constraints helped shape the HST and influenced adopting the associate contractor approach.[11] As the program progressed major problems resulted, creating large cost overruns. As a result, the project had to retreat and form system teams and panels such as control, dynamics, etc., composed of the members from MSFC, GSFC, Lockheed, Perkin Elmer, etc., to solve the problems. In addition, an MSFC project and engineering team was dedicated to insuring a good system co-located at Lockheed and Perkin Elmer. The team was active for at least 1 year. The end result was a good, verified system, but with a large cost overrun. Some of the problems have been discussed in reference 4, the others appear later in this document, some others were not related to the technical disciplines discussed in this document. Maybe this says that the time to put teams in place at the contractors is early in the program to fully ring out requirements and design issues, eliminating downstream problems instead of waiting until after the problems occur. The problem found in flight of the mirror spherical aberration has been left to the special investigation team; otherwise the HST has performed in an excellent manner for such a complex machine.

c. Space Shuttle

The space shuttle vehicle is composed of an expendable external propulsion tank (liquid oxygen and hydrogen), a reusable orbiter with liquid main propulsion engines (space shuttle main engines—SSME's), the orbiter maneuvering system (OMS), two solid rocket boosters (SRB's) (partially reusable), and the various payloads (fig. 28). The payload maximum size is 15 by 60 ft. The maximum weight depends on the desired orbit. The orbiter has a stay time on-orbit up to 2 weeks with a crew of up to five. The total weight is approximately 4.5×10^6 lb as shown on the schematic in figure 29. MSFC has the responsibility for the development and operation of the external tank (ET), the solid rocket motor (SRM) and booster, and the main engines. Various Centers have responsibility for different payloads. MSFC is responsible for the HST, the Spacelab system, etc. Johnson Space Center (JSC) and Rockwell Space Division are responsible for the orbiter and total vehicle integration.

(1) Characteristics: A typical shuttle mission is shown on figures 30a, b, and c. The mission starts with the vehicle and payload assembly, then moves to the launch pad via the mobile launch platform (MLP). The vehicle sits on the pad unfueled until about 10 h prior to launch, at which time it is fueled. Due to the cryo propellant temperatures, the vehicle shrinks. The aft SRB-to-ET struts are designed to account for this shrinkage. The weight of the propellant further loads the vehicle-to-MLP interfaces and the element-to-element interfaces. This causes the vehicle SRM's to bow laterally and the total vehicle to bend in the pitch plane. The cryo shrinkage moves the struts 7°, putting them perpendicular to the SRB and ET (designed to account for the movement). This causes a punch load toward the tank which is counteracted by the radial shrinkage of the tank. This stores energy in the structure to be released at lift-off (fig. 31 and 32). The SSME's are ignited and must be at 90-percent power level before igniting the SRM's, which store even more energy in the structure.

In order to reduce these lift-off loads, a trade study of performance versus loads was made on delaying the SRB ignition until a minimum stored energy point is reached. The results of this trade came out in favor of the delayed SRM ignition. The dynamics are that the SSME thrust (force) bends the vehicle and lifts it due to engine cants and asymmetries pushing the orbiter and tank between the SRB's in a gear train mode (fig. 32), setting up an oscillation which produces minimum stored energy approximately 6 s after SSME ignition, at which time the SRM's are ignited (fig. 33). The SRB's obtain above 900 psi internal pressure stretching the vehicle in a longitudinal transient mode simultaneously with the release of the stored potential energy. The holddown bolts are blown and the aft skirts released from the pad. Large vehicle dynamic motions result.

Figures 34a and b show a time trace of a strut load during these events. As the vehicle clears the tower, it is rolled up to 180° (mission dependent) to put the orbiter down, which produces a more optimal total thrust angle. At 20-s flight time, the vehicle performance is assessed (velocity). If performance is low, the main engines are not throttled as deeply (adaptive guidance) as planned to make up the performance. If the performance is nominal, preprogrammed throttling occurs. If performance is high, deeper throttling occurs if possible (engines can only throttle to 65 percent). Engines are throttled to keep the dynamic pressure within design limits as the vehicle traverses through the maximum dynamic pressure regime, also, during the time of high winds. Pitch, yaw, and elevon load relief are used to reduce aerodynamic loads at the expense of performance. This also introduces high thermal loads after max q when the vehicle is moving back to its optimum path (large side-slip angles introduced).

The events just discussed represent some of the major trades made during the shuttle design phases. Loads versus performance losses being the key. The option was to beef up the structure to handle loads (performance loss) or deviate time and trajectory path and reduce loads (performance loss and loss of launch probability). The trade, in general, came out to take the deviations and not beef up the structure. In some specific cases structure was beefed up. Meeting requirements is always a trade and never comes for free.

The next event is SRB separation. This is a dynamic event triggered when the SRM thrust drops below a certain level. The event is dynamic with firing of pyrotechnics to separate the interfaces and separation motors to move the SRB's away from the tank/orbiter. Two parallel events follow. The orbiter/ET continues to thrust to gain orbit while the SRB's reenter the atmosphere, opening the parachute in stages to reduce loads, then water impact creating large loads. After being towed back to Kennedy Space Center (KSC), the SRB's are refurbished for reuse. The orbiter/tanks next main event is the tank separation and disposal (breaks up on reentering the atmosphere). The resulting debris footprint is critical and must be controlled. The orbiter then fires its OMS engines to achieve the final desired orbit. After completing its mission, the orbiter reenters by firing the OMS engines, slowing the vehicle, then it reenters the atmosphere and lands. All of these are very fine-tuned and critical events. The reentry drives the thermal protection system design which is very critical to survival. The on-orbit phase is unique for each mission. One additional complication occurs during the ascent phase—abort options (fig. 35). Early in the mission engine failures mean ditching. Next comes return to launch site (RTLS), a very critical maneuver. Later in time the vehicle can abort to alternate launch sites, then comes abort to orbit (once around in a degraded orbit). Then finally, the desired mission orbit is achieved by firing the OMS engines.

A complex launch constraint system is in place to ensure that the vehicle is not launched in unsafe conditions. Part of this program involves taking winds aloft wind samples and calculating structural loads and performance margins. Approximately 2 h prior to launch, a choice is made between several I-loads (trajectory shape to reduce loads and increase performance margins). At 30 min, a decision is made relative to launch whether to launch or not based on this data. In the last part of the sequence prior to launch, all systems are monitored. A launch can be stopped if any system is out of specification. Most of these redline cutoffs are automatic.

(2) Design Evolution: The questions that must be addressed are how did the shuttle evolve? and what major decisions shaped it into one of the world's most impressive systems? It is very complex, in most respects, being resuable, operating during launch, on orbit, reentry, and landing. Blending all these requirements into one machine was a great challenge. Initially (phases A and B), extensive sensitivity analyses were accomplished in several areas: propulsion systems (high performance engines), reentry heat protection, and applied mechanics. These early trades and sensitivity studies were accomplished to focus requirements and design. The key sensitivities identified have guided not only the design, but the guide flight operations. Figure 36 shows the key system issues identified which includes trajectory (performance), loads, and control coupling, as well as control concepts and control authority issues. Figure 37 illustrates this performance control coupling showing the high

sensitivity of performance to the control concept chosen, as well as the trajectory shaping philosophy. Figure 38 illustrates the increased dynamic complexity over the Saturn V vehicle.

With the advent of the parallel burn solid configuration, the complexity increases further, requiring 200 to 300 modes to represent the vehicle and payload combination at pre-lift-off and lift-off. Figure 39 illustrates the problems associated with lift-off and the unsymmetrical configuration, while figure 40 shows how this unsymmetry couples up the POGO oscillation (longitudinal vehicle oscillation with the analogy of the pogo stick providing the name). As shown in the chart, this coupling was experienced on Saturn Apollo with only a small unsymmetry in the lunar excursion model (LEM) illustrating the power of dynamic coupling.

The evolution of the space shuttle is shown in figures 41a, b, and c. Initially, the shuttle was totally reusable with a flyback booster. The engines were liquid using the same powerhead, but optimized nozzles for the booster and orbiter stages. The cost was estimated to be $14 billion for design, development, test, and engineering (DDT&E), based on estimated weight. The orbiter had ferrying capability and met all cross-range requirements. The payload size was constrained to the Air Force requirements of 15 by 60 ft. Due to national priorities, the funding was cut. An exercise was conducted during phase B to change the configuration to one that had parallel burn between the boosters and the orbiter stage. The booster options were liquids or solids. Finally, the cost (DDT&E) was frozen at the $5.5 billion level and the solid booster configuration was selected. This meant that the engine nozzle could no longer be optimum since it had to start and operate in atmosphere and then operate in vacuum. This led to a requirement for the 470,000-lb vac thrust with an Isp of 453 s. The orbiter self-contained ferrying requirement was eliminated, driving the system to the Boeing 747 ferry mode. the cross-range requirement from the Air Force remained, leading to the modified delta wing. Passive tiles for reentry thermal protection were chosen.

The next step, in conjunction with the dollar constraint, was to place weight constraints on the total system gross lift-off weight (GLOW) and each of the main vehicle elements. This drove volumetric constraints along with the payload volume of 15 by 60 ft. As the vehicle evolved, the orbiter had problems meeting its constraint. The passive tile selection possibly had some weight impact also, the silicon-based tiles are very sensitive to impact damage. This fosters a very elaborate program to eliminate ice and debris that could impact tiles and lead to a safety problem. Damage occurs on every flight but none to a safety concern. Damaged tiles had to be replaced. Each tile is hand fitted and installed. It is a well-known fact that the orbiter brake design was marginal prior to *Challenger*. This was fixed while the program was down during redesign of the SRM's.

Constraints/requirements drove several things. First, the SSME had been configured to throttle from 50 to 109 percent of rated power level (RPL) with all above 100 percent being used for abort purposes. The system changed the engine design requirements to operate at 109 percent to increase performance and throttle to only 65 percent for dynamic pressure and acceleration control. The original SSME design was for a 100-mission lifetime. It was decided that by reducing the requirements to 55 missions, the lifetime of the engine could be met with the same basic design as for the 100 percent. This assumption did not hold up. Second, each element was asked to do a weight reduction program to make up the performance. This task was accomplished by all elements taking out margins. The ET accomplished part of this task by reducing the safety factor on all well-known loads from 1.4 to 1.25 since the tank was now expendable. Third, the performance of the SRM was increased to up performance, and the thrust profile shape was modified to meet q constraints. The dynamic pressure "q" on the orbiter wing and tail during ascent greatly complicates the system. The large aerodynamic surfaces create large structural loads and trajectory deviations (drift). Vehicle control, performance, and loads are further complicated by the unsymmetrical configuration, both dynamically and statically. The maximum coupling (dynamic pressure) occurs at the altitude of peak winds. Figure 42 shows these major events and the phasing required to achieve successful flights in terms of loads, control, thermal, and performance.

The original SRB's had no control capability. Early in the design phase it became clear that the shuttle system was uncontrollable without control authority on the SRB's. As a result, the SRM nozzle flex bearing, composed of layers of metal and elastomer, was designed and baselined. Actuators designed for the orbiter were used as actuation authority. This increased weight, complexity, and cost. In addition, two factors were used very early in phase C to take out conservatism, save weight and cost, and improve performance: (1) monthly mean wind biasing was instituted early in phase C as part of criteria change for generating environments and performance, etc. (past programs had held that as a margin for operation and launch probability increases); and (2) prior programs used the 95-percent wind speed in conjunction with 99 percent wind shear and 99-percent gust as a conditional probability approach. The space shuttle used 95-percent wind speed in combination with one half the shear and gust 99-percent levels, then root sum squaring the other half with the other parameters, again reducing margins. These two conservatisms are not wrong within themselves since it could be shown statistically that these were safe approaches. What it did do was take out margins for flexibility, operations, and missed effects. No one, for example, expected the wing aero distribution to be missed significantly. Due to these constraints the above response and certain anomalies such as the aerodynamic pressure distribution on the orbiter wing, the space shuttle is very costly operationally.

Each mission has to be specially shaped. To fly safely a performance loss near 4,000 lb is incurred. In addition, a very elaborate wind monitoring, day of launch performance, load activity, and day of launch I load update is mandatory to ensure safety. It is very costly. The vehicle, in winter months only, has a 65-percent launch probability. To date three launches have been scrubbed for high winds. The SRB aft skirt has low margins and ground wind constraints. The SSME, although a very high performance machine, is very costly to insure safety through part changeout, limited lifetime, and hardware rejection. It is also restricted to 104-percent power except for abort. As shown on the chart, massive redesign has taken place, orbiter landing gear, SSME two-duct hot gas manifold, weld elimination, pump changes, nozzle steerhorn, redesigned solid rocket motor (RSRM) aft skirt, etc. The advanced solid rocket motor (ASRM) is under consideration or in progress with approximately 12,000 lb performance improvements, alternate high pressure turbopumps, large throat main combustion chamber (MCC), MCC casting, and weld eliminations. Orbiter tile damage and refurbishment are continuing costs. This discussion has shown how the constraints, in conjunction with requirements led to a high performance but costly operational system, which demonstrated the correlation between high performance and cost.

The discussion that follows addresses several of the specific shuttle problems, as well as presents a brief look at the *Challenger* accident cause.

(3) <u>MLP/SRB Aft Skirt/Puck Rotation</u>: Reference 4 addressed very briefly the failure of the SRB aft skirt during filament wound case verification testing and STS-26 reverification

testing. Two failures occurred at the same location. The failure was the result of not understanding the sensitivity of the stress in the forging (holddown post) to skirt skin weld to radial loads. Figure 43 shows this sensitivity which was found in a posttest correlation analysis. The total skirt load, mainly compression on one side and tension on the other, was well understood. This load was critical to the holddown post and was studied extensively both for the eastern and western test ranges (different launch pad designs). What was missed was the radial load sensitivity which is a function of pad stiffness, etc., and was found in designing and analyzing loads for the western test range launch pad. As a result, new loads were generated. Although the total load was basically the same, the radial load changed which resulted in the failure of the filament wound case test skirt. New loads were generated for the eastern test range producing different radial loads. This effect can be seen on figure 44 where the radial load pushes the post outward bending the skirt at the weld, thus producing very large local stresses at the weld outer surface. This is a combined bending/shear load. Figures 45 and 46 show the stress distribution on the surface and through the thickness. Notice the local nature both through the skin and surface wise. A special failure team was formed to investigate the failure cause. Special consultants were used to evaluate the NASA/USBI team. It was found that the problem was very nonlinear. No finite element model, in conjunction with extensive material testing, adequately predicted the failure. Nonlinear, theoretical, and simplified analysis[12] [13] have indicated an explanation. What did all this mean? The skirt failed at a safety factor around 1.3 with a design/operational requirement of 1.4. Flight, therefore, must be on the basis of a waiver, or stop the program and redesign.

Flying with a waiver as chosen in conjunction with several activities:

a. Very extensive testing of the MLP to accurately define a new model for loads calculation.

b. Loads were recalculated using this refined model.

c. Strain gauges are grouped in the failure area to correlate loads predictions—this was used for STS-26 flight readiness firing (FRF) and all subsequent flights—showing the safety factor was not deteriorated with the stack. All flights showed the same general results.

d. These same strain gauges are used to correlate analysis during stacking of the SRB and vehicle. Safety factors are calculated for each flight based on this data, and some improvement in margins has occurred.

e. The puck on the post can be rotated biasing the skirt, producing larger margins; this has been demonstrated and used in flight. Special tests are underway to determine the sensitivity and limits of this biasing. It may be possible to get the safety factor back to 1.4 in this manner.

f. Design analysis and test are progressing to define an alternate configuration which will restore margins, etc.

The message is clear. Sensitivities must be understood and used to define all environments (loads in this case) or costly operational procedures, and analysis must be performed on a flight-by-flight basis.

(4) Debris Damage to Orbiter Heat Protection Tile: The reentry heat protection tiles have suffered damage on each flight. The major damage has occurred both at lift-off or ascent and orbiter landing. The landing damage is only a refurbishment/cost issue while the ascent damage can become a safety issue. Major emphasis has been placed on these events to eliminate debris sources. Some of the potential debris sources are (1) ET insulation, (2) ice buildup on the ET, (3) SRB nose cone insulation, and (4) pad debris blown up by SRB thrust, etc. Extensive effort has been made to insure that insulation does not come loose. Included are bonding changes, insulation changes, pull test and repairs, pad cleanup prior to launch, etc. Prior to each flight, an ice team inspects to see if dangerous ice has been formed by the cryogenic propellants. A team inspects and maps each orbiter after landing to help determine sources. Special cameras are employed on some flights for the same reason. Clearly, the orbiter passive thermal tiles do an outstanding job; however, special care is required through the total system to insure safety of flight. System analysis and requirements must be under constant review with all changes evaluated against these considerations.

(5) 51-L (*Challenger*) Accident: Before discussing the accident itself, it seems prudent to discuss some philosophy and approaches for design and failure investigations. It is a basic philosophy that all systems be modeled, analyzed, and tested to get data, then test verified, plus hot-fire and flight instrumentation for insurance and final verification. The space shuttle followed this philosophy using numerous avionics, dynamic, structure, wind tunnel, etc., tests, including the ALT program (orbit drop test). To verify the system, the first six flights were designated as development flights. Special instrumentation flew on these flights to gather information and verify the system. Several flights after the *Challenger* accident also flew special instrumentation. The design of a vehicle dictates that every event, from transportation through each flight phase, be fully analyzed and sensitivity studies conducted with key design data by event for each element, part, etc., developed. In general, during design and/or failure investigations, all events are analyzed to determine the key event for that part. The data that are presented then become the design data for that part, for that design event, and not the total vehicle or for other events. For example: the bending moment and shear for each SRR/SRM station is for the worse case event for that element and that station or part. The *Challenger* investigation followed that procedure in that most of the data are for the failed SRB, its failed joint, and its corresponding ET to SRB struts loads, although all the data for all events were analyzed.

The *Challenger* accident was the major disaster of the space shuttle program. Lives were lost, a vehicle was lost, and the space program was shut down for several years, greatly hampering military operations as well as science and engineering research. The discussion that follows could be under SRM; however, the final result was a total system failure. No attempt is made to alter the Presidential Commission report, which is the basic reference document, but rather to provide a synopsis on the effort and the technical results. It is a part of this report due to its importance and impact to the space program.

The primary failure was the SRM o-ring leaking the internal hot combustion gas to the outside through the first field joint in the direction of the SRB/ET attach point on the ET. All subsequent events and failures, including loss of the vehicle, were the result of this leak. Many other theories were advanced to explain the leak and/or the vehicle failure other than that concluded by the Commission; however, all were studied and ruled out by the Commission. These potential causes included (1) extremely high lift-off loads, (2) excessive winds aloft, (3) inappropriate assembly, etc. The breakdown in the system, whether NASA management, Congress, etc., that led to a faulty o-ring system is not discussed, only the technical cause and effect of the design on the failure. First, the o-ring field joint characteristics, including failure, are addressed followed by a discussion of why the other causes could, with high probability, be ruled out.

The field joint o-ring configuration is basic in concept but complex in characteristics. Figure 47 shows the field joint o-ring as part of the two aft SRM segments and as a cross section of the two mating areas, the tongue and clevis. At ignition, the SRM becomes a pressure vessel due to the expanding burning propellants, reaching over 900 psi in around 600 ms. This large pressure has two effects: (1) the SRB case expands longitudinally, and (2) the case expands radially from the large pressure induced hoop stress. Due to the tang clevis configuration and the fasteners (pins) which lock the two segments together, these two effects cause a rotation between the tang and clevis at the o-ring location opening up the joint o-ring area.

Initially, this phenomenon is transient in nature with the gap opening going from neutral to near maximum in 600 ms as the pressure rises. The gap opening then basically tracks the SRM internal pressure. Primarily the o-ring resiliency should energize the o-ring (initially compress at the neutral position) and track the opening gap. Secondly, under most conditions, the SRM pressure will further pressure actuate the o-ring providing a seal between the two surfaces. If the seal does not actuate, then hot gas under high pressure escapes to the outside, destroying the seal. Other influences on the gap opening are the structural dynamic case response to vehicle dynamics and SRB-to-ET strut loads. Detailed finite element analyses correlated by test data were conducted in conjunction with lift-off and ascent response and loads analyses to determine the gap opening and the seal ability to track this opening. The lift-off and ascent analyses were a total dynamic shuttle systems simulation using several hundred dynamic modes and 3-sigma combinations of all environments.

Figure 48 shows the resulting total gap opening during the time span of SSME ignition, SSME thrust buildup (first 6 and one-half s), SRM ignition (600 ms), and lift-off dynamics (approximately 3 s). Two extreme conditions are shown: (1) where the tang and clevis are initially metal-to-metal, zero gap time zero, and (2) maximum allowed clearance is present (20 to 25 mils gap, zero time). Notice that at maximum SSME thrust-induced bending moment the gap opening delta is around 2 mils. At SRM ignition, 6.6 s, the gap opening delta diverges very fast. At maximum lift-off dynamics, there is superimposed on the pressure gap opening a dynamic effect from strut loads and bending (around 2 Hz). The split of the gap opening causes are: 85 percent due to pressure, 7 percent due to strut loads, 7 percent due to bending, and 1 percent due to shear. These effects are based on 3-sigma design loads. The o-ring clearly could not track the gap opening with a cold o-ring, as was the case on 51-L, without pressure assist. Scale-model and full-scale tests, in conjunction with detailed instrumentation, have verified these effects on gap opening and o-ring resiliency (ability to track) as a function of temperature. One additional effect can keep the o-ring from tracking. If the clevis tang is near metal-to-metal in conjunction with o-ring and groove tolerances that cause the o-ring to totally fill the groove, then the pressure cannot actuate the seal, but instead will hold it in the groove (figs. 49 and 50). This was a strong potential for the failed joint based on tolerance data stacking data. Scale-model and full-scale test, in conjunction with detailed instrumentation, have verified these effects on gap opening and the o-ring resiliency (ability to track) as a function of temperature.

The above scenario explains the leaks (puffs of smoke) coming out of the aft field joint during lift-off. Why it sealed until max q is not well understood. Scale model tests showed leaks that sealed, probably with residuals from burning propellant, then reopened later. Also, why the joint (leak) reopened cannot be proven. As is shown in figure 51, the joint opens to its maximum early in flight, then closes down to about 80 percent of this maximum during max q due to reduced thrust and internal pressure that was implemented early in design to control maximum dynamic pressure. Around 60 s the SRM pressure and thrust start rising again, opening the gap further. Residuals plugging the hole could have been crushed during this gap closing and become susceptible to dynamic effects (wind gust), combustion noise, or the slowly increasing internal pressure-induced gap opening. Internal SRM pressure, vehicle state (aero changes from leak plume, etc.) movies show the leak reopened at this time, continuously increasing in size until the vehicle failed. The internal pressure loss corresponds to the increasing plume (leak) observed.

The obvious question follows: How can the other proposed causes such as excessive loads, particularly from the strut, be ruled out? To answer the question it is best to split it into two parts: (1) pre-lift-off through the lift-off transient, and (2) post-lift-off transient through maximum dynamic pressure.

(a) Pre-Lift-off Through Lift-off Transient: This event starts with vehicle stacking, transportation to the pad, fueling, start, and lift-off. The vehicle weight by elements is known. The mating is accurately controlled. The SRB's are shimmed to get uniform post loads and alignment. All these data are checked and recorded. Propellant loading is accurately monitored. Much data are recorded from strain gauges on the MLP side of the SRB holddown posts (milk stool), including camera coverage from several angles, showing SSME and SRB thrusts, temperatures, wind speeds, control data including rates, accelerations, actuators, and vehicle (SRB and ET) nose tip excursions, etc. The amount of energy stored in the vehicle from (a) weight, (b) cryo shrinkage, (c) winds, (d) thrust, etc., is well-known. Events timing is accurate. Using these data, loads, etc., can accurately be reconstructed. Figure 52a shows the vehicle on the pad showing peak load and bending moment for one SRB. This bending moment is the peak bending moment, commonly called quasi-static or static equivalent, determined using a detailed dynamic transient simulation (300 dynamic modes). This eliminates the need to calculate a static load, then put the conservative factor at 2 to cover dynamic effects. This later simplified approach is only recommended for simple systems. In complex systems like the shuttle it is a requirement that an all-up transient analysis be accomplished, eliminating the need for the approximate approach. Figure 52b shows a time trace through lift-off of bending moment and axial load. How can we know that? Six out of the first seven flights and all flights since *Challenger* (51-L) have skirt, strut, etc., loads accurately measured with strain gauge and accelerometers. Using the data mentioned above, the load events were reconstructed and correlated to the measure data (figs. 53 through 57). Accuracy has been very good. In addition, the design loads, particularly for the SRB, were generated for SRB ignition with maximum base bending moment instead of the near nominal measured on all flights. It also precluded a pad abort with the loads cycle repeated several times. Also, the dynamic model for loads was verified in a full-scale mated-vehicle test. All stress margins were verified by ultimate load test, element by element, for design loads.

All design lift-off loads have been generated using a 2-sigma worst-on-worst parameter variation approach which indicates that the nominal strut load expected should be around 60 percent of the design load. Reconstruction of 51-L loads showed this to be the case (see Presidential Commission report). Also, remember that the design strut load added only 7 percent to the total gap opening (fig. 58). In other words, for 51-L MLP post loads, SRB and ET tip deflections, propulsion system thrust, etc., were all near nominal. Only the ambient temperature was low. In addition, full-scale SRM segments were tested with and without strut loads in conjunction with numerous o-ring/temperature tests, etc. that fully verified the analytical model. Prior to STS-26, a full-scale hot-firing of the redesigned SRM was conducted with maximum expected strut loads. Special instrumentation was used to measure various effects. This was the final verification of the analytical models and the worthiness of the redesigned motor for flight.

(b) Post-Lift-Off Through Max Q: Actually, for this area more data are available for reconstruction than for lift-off from the dynamics and loads standpoint. Again, six of the first seven flights, plus flights since 51-L, have measured loads data to verify the reconstruction process. The measured data for this flight regime include the vehicle position at all times from radar tracking and from the onboard guidance system (position, velocities, and accelerations). Control data gave the instantaneous vehicle angular and lateral positions, velocities, and accelerations along with the thrust control system responses. Propulsion system data include pressure, thrust, temperature, etc. Wind data are obtained prior to flight and 15 min after flight. The vehicle responds very quickly to all wind shears and gusts and is reflected accurately in the control system/vehicle response data. The process of reconstruction is well established starting with Saturn and other programs. First, the trajectory is reconstructed from the radar tracking and onboard guidance (data best estimated trajectory) (BET). This reference trajectory (BET) becomes the base for all other reconstruction. The next step takes all propulsion system, mass (weight), etc., data and reconstructs a trajectory to match the BET. This reconstructed trajectory is the base for control, loads, thermal, etc., reconstruction analysis. Next, the wind speed, shear, and gust profile is estimated from the measured wind data taken prior to and after flight. These data, in conjunction with the propulsion, weight, etc., data from the reconstructed trajectory, are used to perform the control system/vehicle response reconstruction. These data are correlated directly to the telemetered control system data mentioned earlier. Loads such as strut load can be directly calculated from these data.

Figures 59a and 59b are examples of how well loads were correlated on STS flight 6. These same reconstructed data for the 51-L flight showed that although the winds were high, less than 60 percent of the design wind shears and gusts were experienced. Also, because loads are generated using 3-sigma parameter variations, loads were well below design levels; therefore, they would not be a primary cause of the failure. The 51-L failure was caused by the faulty SRM joint/o-ring which, through the impinging leaking gas, caused the vehicle failure. Photographic coverage of the flight clearly showed the leaking gas. The failure of the SRM internal pressure to rise back after max q correlated to the observed leaking plume size. Reconstructed aerodynamic shifts were required for this effect to match the control response. See the Presidential Commission report for details of this reconstruction.

Technically the basic message is that one must read what development and operational hardware is telling you. It has the answers. Also, one must understand clearly all the phenomena and sensitivities of the system. To understand a failure, ruling out potential causes is just as important as finding the real cause. System data are very important in all these cases and are the backbone of design as well as failure investigation.

The next section addresses the resulting loads characteristics of the space shuttle and the system implications.

(6) Loads: References 4 and 14 give examples of shuttle loads for both lift-off and max q. The sensitivity of loads due to the large energy stored and the complex static and dynamic configuration were alluded to. One important item was not discussed, namely design factors, etc. Looking at the system, it is easy to see that 1 lb of ET or orbiter weight savings is equivalent to 1 lb of performance increase. On a vehicle that is performance critical, loads, thermal, and other environments must be very accurately determined. Conversely, a decrease of 10 lb of SRB/SRM weight is equivalent to 1 lb of performance increase. Therefore, it was decided early that the SRB/SRM design environments would be maximum/minimum to build in robustness and eliminate redesign as environments change downstream. The tank and orbiter, however, used 3-sigma time consistent loads to save weight. The tank loads that were well defined had only a 1.25 safety factor applied to the limit load to provide a safety factor versus the 1.4 normally used. As a result, as loads and other environments evolved, the SRB/SRM design did not require change. Design changes had to be made to ET for these same loads. This is a good example of using system analysis and proper cost guides to set the best design. Many other system loads problems, such as aeroelastic effects, both static and dynamic, have been studied and incorporated into the design. No known problems have occurred in these areas.

(7) Loads, Control, Thermal Interaction: It was alluded to earlier that the original shuttle parallel burn configuration had no control authority on the SRB's. In fact, this control was not baselined until early phase C. The shuttle vehicle is aerodynamically stable, hence, it naturally turns into the wind and drifts. Also, the large aerodynamic forces would introduce drift, thus, performance loss. This meant that classical trajectory optimization could not be used, but must include moment balanced (control and aero) simulations. In addition, it was found that although the vehicle was aerodynamically stable, it could not turn into the shears and gusts fast enough to reduce loads, hence, load relief control was required. This derived requirement indicated that more control authority was needed to handle this problem; for example, using the orbiter's elevon and/or a trim system on the SRB's. The problem was compounded by the unsymmetrical configuration which caused the vehicle to roll. Many argued that one should "let it roll" during atmospheric flight; however, adding the effects together produced large performance losses and increasing loads.

During this timeframe, historical data from the then in-use solid programs would only produce a thrust vector nominal alignment within a 1° circle per SRB. Looking at the total configuration with the large moment arms of the SRM thrust, neither the orbiter elevons nor the SSME's gimbaling authority could take out this SRM thrust misalignment effects on the control and trajectory shaping.[15] Figure 60 shows this effect. Obviously, the best place to counteract the thrust misalignment effects was at the source—gimbal the SRM nozzle or go to secondary injection. It was decided to gimbal the SRM nozzles.

An additional driver to the requirement for SRM gimbaling was the SRM thrust tail-off regime. Here the thrust unbalance between the parallel SRM's creates torques that must be controlled out. Neither the SSME nor elevon control could do the job ("q" too low for elevons).

Since performance was becoming a problem, weight reductions were in vogue for all shuttle elements. It was found that some performance could be gained by rolling the vehicle and putting the orbiter underneath the system which allowed the SSME side thrust (introduced cant angle required to track the center of gravity (C.G.)) to counteract gravity. The SRM gimbal capability allowed this option to be taken. At 20 s into flight, the shuttle was rolled to place the orbiter underneath the stack. Now then the vehicle had the authority to control it throughout flight. Load relief could be beefed up. None of this comes without cost. Controlling the vehicle and adding the load relief control options produced large drifts. Once out of the high dynamic pressure regions, the vehicle could be controlled back toward the optimum path. This introduced large angles-of-attack and side-slip which introduced large thermal loads. In the end, the system had to balance between these conflicting requirements. The system flies with pitch and yaw accelerometer load relief gains, rolls the vehicle to minimize loads, and has elevon load relief to reduce orbiter loads.

(8) Aerodynamic Wing Load/Performance: As mentioned earlier, the prediction of the aerodynamic distribution and vehicle movement for the orbiter wing was missed due to improper SRB and SSME plume simulations for wind tunnel testing. This simulation had to be accomplished by developing equivalent cases which represent the airflow influence of SRB and engine plumes. This was not easily accomplished since accurate prediction tools were not available. This caused the STS-1 vehicle to loft higher than predicted. Measured strain data on several flights, additional wind tunnel testing, and analysis showed the wing loads to be higher than predicted. Since the trajectory (performance), loads, control, launch probability, and dynamic pressure are strongly coupled for this unsymmetrical vehicle with large aerodynamic forces, how to handle this problem was not easy. Figure 61 illustrates this coupling and where the vehicle must fly if the wing was not fixed. Three options were open (1) fix the orbiter wing (structurally beef up), (2) constrain the flights to specific winds (lower launch probability), or (3) fly off-nominal trajectories to reduce the load (performance less). In the end, all three options were used to various degrees. The orbiter wing leading edge was beefed up to allow more negative angle of attack. The trajectory was reshaped at about 5,000-lb performance loss to reduce dynamic pressure and loads. (Dynamic pressure limits are also imposed from flutter and buffet.) The flights are constrained to certain wind conditions using day of launch wind monitoring and day of launch I load updates. Figure 62 illustrates the characteristics of the wing load versus angle of attack and the trades required to fly the more negative angle of attack.

Figure 63 shows the q envelope versus Mach number designed to (solid lines) and one set of limits imposed from the change zero data base. Limits are still evolving as more flight data are obtained. Where a –2° tilt trajectory was optimum, the trajectory is currently changed to fly around –6° creating the approximately 5,000-lb performance loss. Coupled with that is a reduced launch probability to around 70 percent for the windiest month. Operationally, each launch has to have a special trajectory and loads analysis coupled with a detailed day of launch constraint program, procedures, and criteria.

(9) Overpressure: Shuttle overpressure was treated extensively in reference 16. Overpressure is a pressure wave engulfing the vehicle, caused by the very fast SRB thrust build up, compressing the entrapped air in the flame trenches. Figure 64 illustrates this phenomenon. STS-1 experienced large overpressure loads at lift-off, exciting the vehicle structural dynamic modes to near a dangerous level. Fortunately, during shuttle phase A and B studies, a 6.4 percent propulsive model was built to evaluate acoustical characteristics.

This model served as a test bed to understand, design, and verify a fix for the overpressure problem. Figure 65 is a picture of this propulsive model and the launch pad. Through approximately 50 scaled hot fire tests a fix was developed. It consisted of spraying water into the SSME and SRB plumes through modification of the acoustic suppression water flow, plus a series of water troughs installed to block residual waves not suppressed by the ingested water (fig. 66). It is still debatable whether the troughs are required; however, the cost is minimal for the added insurance.

Clearly the problem has been fixed. Figure 67 shows the STS-1 overpressure valves before the fix and the data measured since the fix.

(10) Acoustics: Since the payload (piggyback configuration) is near the noise source (SRB and SSME thrust exit), noise reduction had to be employed to keep payload bay acoustics at an acceptable level. This was the reason for developing the 6.4 percent propulsion and launch pad model. Through numerous tests, a water suppression system was designed and verified to handle the acoustic problem. Figure 68 shows the effect for the SSME-only burning. Figure 69 shows the overall sound pressure level reduction as a function of water injection. Through this extensive program during the technology and design phase, the acoustics were controlled which allows efficient payload designs.

(11) SRB Holddown Bolt Hangup Versus Debris: Early in the shuttle flight program, it was observed (film coverage) that occasionally an SRB holddown bolt would hang up and scar the bolt hole in the aft skirt as the vehicle lifted off the launch pad. The design is such that the holddown bolt secures the vehicle to the pad until launch. At SRB ignition, two pyrotechnics units fire, fracturing the nut that holds the skirt to the pad through the bolt. The bolt is designed and pretensioned so that the bolt moves away (assisted by gravity). There is a cover over the explosive nut to catch debris. Figure 70 shows the original configuration. As a result of the bolt hangup observations, a detailed study was made as to the cause and effect. Lift-off simulations showed that no lift-off problems would occur due to hangup. The cause of the hangup was due to the timing differences between the redundant pyrotechnics. Work was accomplished to reduce this timing difference thus reducing the possibility of hangup.

As the program progressed and orbiter tile damage became a larger problem, a concern was raised that the nut fragments could be coming out the bolt hole causing debris. The system was redesigned to control the debris but induced more bolt hangup, due to the attach linkage of the spring to the holddown bolt. This had to be redesigned to solve this problem, as shown in figure 71 and 72. Those design changes have basically eliminated the debris and the bolt hangup concern.

d. Saturn I

In section VI, the complexity of dynamic characteristics of the Saturn I vehicle and its coupling with the control system are discussed. That discussion will not be repeated here. There are, however, technical messages to be drawn: (1) boundary conditions and the ability to quantify them are key to test verification, and (2) analysis, data, testing, etc., are only valid within the assumptions used. Stretching the limits, in general, leads to errors.

3. System Conclusion

Suboptimization versus system optimization (total cost), in general, is costly. The space shuttle, although an outstanding vehicle, is costly to operate because of these induced problems. Many other examples can be cited for other systems, as well as things as simple as running tests without instrumentation just to make a milestone. The message is always the same regardless of the project, activity, etc. Deal with total cost to make decisions, even if it can only be done by judgment. For example, the decision to conduct the all-up mated shuttle dynamic test was made in this judgmental manner using trend charts. Dynamic characteristics were required for control system design, POGO suppression design, flutter avoidance, and loads. Partial dynamic model verification could be accomplished using scale model and element tests for the final verification with an all-up full scale. Figure 73 shows a relative ranking of what each test would buy in lower risks. This assessment showed that the driver for mated vertical ground vibration test (MVGVT) was the data for control system design. The trade was clear: one could get accurate dynamic data and design a simple robust control system, or one could have less accurate structural dynamic data in conjunction with a complex adaptive control system (fig. 74). Load relief was a part of this trade. The decision was clear, even without precise cost data, that it was better to conduct the dynamic test and use the simple robust control system. Figure 41 was an attempt to show the above described shuttle evolution in requirements and design and the resulting operational system. Although the system is excellent, the cost, etc., is much higher than predicted, basically due to constraints and outside requirements. This means that for future systems, the total cost function must be used in conjunction with up-front analysis and testing to identify key parameters and their sensitivities coupled with constant review of requirements and performance, particularly the derived requirements. It must be understood that many of the requirements for design are derived requirements obtained as analysis and when tests are conducted. The more these can be identified prior to phase C, the less costly the design phase will be.

B. Fourteen Guiding Principles

As mentioned previously, a set of 14 guiding principles has been developed to support the system focus and highlight design practices (Fig. 75). These were discussed in detail in reference 4. A few were selected for discussion in the seminar and are documented here.

1. Performance Requirements

Coupled strongly with the system focus is the principle that the higher the performance requirements, the greater the sensitivity of the system, subsystem, or part to variations in any parameter, including manufacturing, environments, tolerances, etc. Figure 76 is a curve illustrating this principle. The standard SN-curve is in general the inverse of this curve.

The system performance requirements determine the design, technologies, penetrations, etc., necessary to meet the goal of a safe reliable system. Performance requirements are always broad in scope, encompassing not only the response but also all the characteristics from design through operations. The higher the performance, by definition, the greater the sensitivity of the design to uncertainties. Uncertainties exist in all areas of design: materials properties, environments, analysis, testing, manufacturing, etc.

Design in the flat portion of the curve can basically be dealt with in a linear fashion. As the design moves out on the curve into the steeper slopes, nonlinear analysis is implied. In the first case, the design is inherently conservative and easier to predict since super position works and the nonlinearities not used to gain margin are still present and add to the margins. (Nonlinearities in general are conservative.) In the latter case (high performance design), use must be made of the nonlinearities in order to meet design margins and performance criteria. It should be pointed out that nonlinearities are not easily predicted or analyzed and are more sensitive to unknowns and changes. If the performance requirements are such that the design is inherently in this region, then great care and accuracy must be taken to develop data bases, define environments, and perform analyses, etc. Manufacturing, nondestructive investigation (NDI), quality control, and acceptance criteria parameters must be enhanced. If, however, one designs for robustness, the lower portion of the curve depicts the system, providing margin of the performance index. The optimum lies somewhere between the two extremes. The curve can also be shifted to the right and down through data acquisition and increased knowledge, in many cases a desirable approach (technology advancement). At the onset and periodically throughout the program, sensitivity studies must be made to determine where the design rests, what parameters should be made robust, and what the real optimum is, considering all factors.

Another way of looking at this principle is to plot two parameters, robustness and performance, concurrently versus requirements. As the requirements increase, performance level must increase while in general the inverse is true of robustness (fig. 77). The curves are shown in a generic fashion, where in specific terms the requirements, performance, and robustness would shift relative to each other. Ideally, the design should balance best in the large box centered where the two curves cross, producing some balance between performance, robustness, risks, and cost. In the space business, as well as many others, the trend is to apply linear thinking, with performance as the focus, thus ending up with the design in the box at the far right or somewhere in between. This produces the results previously discussed. What is required is that the linear thinking loop must be broken and lateral thinking invoked, which jumps to the side and plays the game differently using reliability (robustness), total cost, and performance in the balancing act. Lateral thinking is also implied if one wants to shift the relative merits of the two curves. Clearly this shift requires some creative jump to do things differently than the standard practice. Once the lateral thinking jump has been made, the linear thinking approach takes over and serves well. In fact engineering basically is so founded.

Two examples from the space shuttle program will be given to illustrate the reality of the performance sensitivity principles: (1) The 4,000-Hz SSME buzz, and (2) shuttle lift-off loads. The SSME is a very high performance system that, on the lox flow side, has a very high dynamic pressure environment. As a result, various coupled structures are very sensitive to flow and acoustic/structural interaction problems. The main injector lox inlet has a two-blade splitter in order to create a more uniform flow distribution into the lox dome (fig. 78a and 78b). Vane protrusion into this high-flow environment is susceptible to flow-induced oscillations and, thus, fatigue failure. This occurred on the inlet splitter. Three engine units have had cracked splitters. These fatigue cracks are believed, based on analyses and tests, to be caused by vortex shedding off the vane trailing edge, occurring at the vane natural frequency of 4,000 Hz. In addition to the three splitters with cracks, several other units have shown the 4,000-Hz phenomenon, but at a lower level, without cracks. The amplitude determines the alternating stresses, hence life. Figure 79 shows a spectrum of an engine response with and without the 4,000-Hz buzz. The without is the same engine with the splitter modified to eliminate the buzz. Notice the narrow band sharpness of the tuning. The interesting part is that 20 percent of the engines buzz, the others did not at any time in their test history. The buzz cause has to be due to small manufacturing differences in the bluntness of the vane trailing edge and possibly small vane angle/offset differences or slight modal shifts. To understand and solve this problem, extensive scale-model and full-scale flow testing, static testing, dynamic testing, hot fire testing with special instrumentation, and analysis was required over a 3-year period. The solution was to sharpen the vane trailing edge and put a curve wider gap between the leading edge of the two vanes. No buzz has occurred since the fix was implemented.

The space shuttle lift-off phase falls into this same category. There are several problems or sensitivities associated with the shuttle lift-off (fig. 80). Most of these, SRB aft skirt, debris, overpressure, and acoustics, have been discussed in earlier sections. The pad and tower clearance has not been a problem but required detailed dynamics and control simulations to define drift envelopes, operational requirements, and control system settings. Simulations have been verified using control data (vehicle state) and camera coverage.

The lift-off loads have been one of the vehicle and its elements key design drivers and are very sensitive to parameter uncertainties. Design loads must be generated for each time slice of the mission profile peculiar to the part it designs. Not only must the loads data be generated for nominal operating conditions with parameter variations, but for aborts and contingencies also. The lift-off sequence as well as its dynamics were discussed in a previous section. The aft skirt is designed by the weight and the stored moment introduced by the SSME thrust and by the abort case which produces not only the peak moment but several oscillations for LCF concern. Lift-off loads occur after SRB release and are a very dynamic situation resulting from the released stored energy and dynamic tuning between the five elements connected by interfaces (spring) (fig. 32 and 33). Two SRB's, ET, orbiter, and payloads produce these dynamic elements. The vehicle loads of this event are very sensitive to small changes in the elements or the input parameters. Payloads, the element interface hardware, and other hardware are designed by these lift-off loads.

Major efforts have been expended to first develop and verify structural dynamic models using finite element analysis, scale model, and full-scale testing. Constructing a systems model, including the dynamics of the launch platform, was a major challenge. The definition of the parametric inputs with the statistics definition of variations for things such as thrust, thrust vector offset, thrust misalignments, masses, winds, etc., in addition to dynamics, pushed available technology. The final big hurdle was the development of a technique that could handle time delays, nonlinearities in the development of a statistically quantified time consistent sets of loads. A 2-sigma worse-on-worse parameter time consistent combination was first used requiring approximately 30 different design load sets. Monte Carlo time varying analysis has been used to further quantify these loads.

With the baselining of these procedures and criteria and the various loads analyses, sensitivities became clear. Model refinements of the vehicle and pad were necessary. In addition, the number of structural modes required for accuracy of loads predictions increased first to 200 then to 300 modes below 30 Hz. Figure 81 shows the difference in the HST loads for the different design load cycles, compared to the original design values. A factor of 2 increases on the secondary mirror occurred as did smaller increases of other components.

Changes of this magnitude can be expected for multibody low-damped structural systems with elements whose frequencies tune. It is aggravated by the unsymmetrical configuration increasing the coupling.

As stated previously, for these high sensitivity regimes, extreme care must be exercised in determining characteristics and operational criteria. As a result of these high tech requirements, the reliability of the system requires greatly increased technology for testing, analysis, manufacturing, quality, etc. Operations also, in general, become more costly with tighter constraints and loss of flexibility. Does this mean that high tech design is not pursued? In no way; however, increases in knowledge (technology) are required with tighter acceptance controls. This means that judging a design's accuracy requires understanding the operation point on the sensitivity curve.

2. Analysis and Test Are Limited

All simulations, models, symbols, patterns, etc., whether dealing with analysis, test, management, etc., are just that, models which are not complete (limited) and are not exact representations of reality but are mathematical or physical representations or symbols with various assumptions of these facts.[4]

The principle must be fully understood so that everything is constantly challenged for applicability. The major problem we deal with is how this less-than-reality information is meshed together to get verified, reliable systems. Obviously, this can only be done in some probabilistic sense. In addition to the use of robust statistical approaches, how the limitations of models, tests, etc., are dealt with determines the design outcome. There are many ways of approaching the question; however, the fundamental approach appears to be a building block approach using a combination of analysis and test. Fundamental to this approach are the following steps: (1) formulate model, (2) perform pretest analysis and sensitivity studies to guide test, etc., (3) perform test with proper instrumentation, (4) correlate predictions and test, and (5) update model to produce verified model.

The space shuttle SRB aft skirt failure illustrates this limitation. Early shuttle loads analyses conducted using simplified models of the launch pad and the SRB skirt produced a set of loads thought to be accurate for the prelaunch SSME thrust buildup phase of launch. It was understood that major skirt load would arise from vehicle weight combined with the SSME thrust force. At full thrust, the four holddown posts away from the orbiter are loaded in compression, not only from weight but also from the vehicle bending due to the SSME thrust. What was not understood was the sensitivity of the local weld stress near the holddown post to the pad stiffness (fig. 44) as discussed previously.

Part of the loads sensitivity of the aft skirt is due to the holddown mechanism which is composed of the spherical bearing, bushing and aft skirt shoe (fig. 82). As shown on figure 83, the bushing is offset so that the mating of the SRB to the pad could be enhanced. Since the aft skirt load is a function of the radial displacement of the skirt of the post, this symmetry can be used to prebias the skirts post inward, reducing the effect of the applied load and thus increasing the structural margins (fig. 84). This approach is being used currently on shuttle flights to increase the margins.

3. Configuration Complexity Determines Penetration

Just as important is understanding the configuration complexity. It should be pointed out that in many cases the attempt to solve one problem, even though simple, can create problems in another area. Two areas will be discussed: (a) dynamics and (b) static load paths.

a. Dynamics

Dynamic systems are fairly predictable if they are basically a single body without extreme geometric ratios. If the configuration is composed of several separate bodies connected by the links, etc., the characteristics are those of a redundant structure and become more unpredictable and sensitive. The bodies can dynamically tune, greatly amplifying the response and reducing prediction accuracy. Reference 17 addresses the history and classes of problems that have had their roots in complex dynamic configurations.

b. Static Load Paths

Static load paths are in the same category. The simpler the load path, the greater the predictability; the more complex the load path, the less predictable. Unsymmetries worsen the situation by loading both in bending and shear, coupling everything together. These complexities produce stress concentrations, quality control problems, and nonplanar stress fields, driving requirements toward more detailed analysis, testing, etc., to properly characterize the system.

Configuration complexity is obviously a driver in determining adequate design. Literature abounds with guidelines in these areas.

4. Bracketing Hand Analysis is Key to Understanding

One of the most important general principles is to make simplified hand analyses to understand the phenomenon and guide more indepth computer evaluations. These should include free body diagrams and flow schematics to provide visualization. A fundamental part of this approach is the determination of the extreme or limiting cases. By establishing the physical understanding of a problem and its bounds, greater insight and more efficiency are established.

It cannot be emphasized enough that the fundamentals can only be grasped if we maintain the ability to be fundamental. Use the computers and testings to aid the human mind, not in place of it. Good design rides on this.

5. People Are the Prime Resource

For verified hardware to result, it must be recognized that people are the prime resource for accomplishing the tasks. The only real resource we have to tape and motivate is the human engineering exhibited in the diverse personalities in the organizations and how they utilize the available tools/resources. Management must recognize where the power is and put its emphasis on the major resource—people. All else are tools for making them more efficient.

Saying this means that the first and foremost task of management and control is leading people, the prime resource. What can managers do? Nothing much new is on the scene, however, basic principles alluded to by Drucker,[26–30] Peters,[24 31 32] Deming,[21] and others, need repeating. First, whatever the individual has of value to the organization is within himself. As Drucker says, "His development is not something done to him, it is not another or better way of using existing properties. It is growth, and growth is always from within. The work therefore must encourage the growth of the individual and must direct it." This means that individual responsibility is the key to performance. The discussions, judgments, innovations, assumptions, etc., that take place at all levels are the ingredients that determine design goodness. The source of this information and judgment is the human resource, the individuals with their individual differences, that must be used, heard, and melded together.

6. Criteria

Criteria or legal requirements must be simple, concise, and direct, providing order to the engineering process; but not overpowering to where it stifles creativity and removes responsibility.

The balance between criteria (formal organizational structure) and creativity (informal organizational structure/leadership) is probably the most challenging task engineering faces. Legal all-encompassing criteria produces order, but if excessive, removes responsibility, kills innovation, suppresses opportunity to find the best solution, and stifles creativity.

"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 and creativity and team effort on the other. The problem is to keep this tension at a healthy level that has an optimizing effect." "Servant Leadership," by Robert K. Greenleaf.

Criteria and requirements are generally written to include guidelines, procedures, and implementation schemes. This ought not to be. Criteria should be very concise and specific, without justification, guidelines, etc., and should be based on sound engineering understanding. There is a need for guidelines, procedures, and implementation schemes including engineering equations, computer codes, instrumentation plans, test approaches, etc.; however, they should be produced as separate documents and not be legally binding. Greenleaf stated the case well in emphasizing the creation of teamwork. Teamwork is the method for insuring the quality product. It is mandatory that government and industry, project and engineering, etc., work as a team. If any group becomes a priest, the judge, excessively binding the others in a legal manner, they destroy the team effort along with creativity. Space engineering is always pushing the edge of technology, requiring the optimum development of creativity in order to meet the combined performance, risks, and cost goals. This means that a constant awareness and struggle is required to balance between the legal (criteria) and creativity (informal) of the individual. This is one of the highest priority tasks.

III. LESSONS LEARNED

The lessons learned are the basis for the principles derived and, in some cases, parallels these principles. Figures 85a and 85b contain a partial list of the lessons learned. Many of the lessons learned reinforce the theories and practices of TQM or quality enhancement. The team approach with open communication is key and can be tagged as simultaneous engineering, etc. The early use of constraints can undermine a design such that its performance and quality can never be fully recovered. What is recovered is bought at a high price. This is part of the system focus which leads to system analysis and testing as discussed previously. One could write a report by rehashing these lessons learned. Most stand alone and therefore are left for the reader. Reference 4 contains a more comprehensive listing of lessons learned and design guidelines.

IV. DESIGN GUIDELINES

Design guidelines are not always generic in nature. Designing a liquid propulsion engine is different from designing an air frame. There are, however, some general design guidelines which are listed on figure 86. For example, one cannot design currently envisioned space vehicles or spacecraft without insuring manufacturability and inspectability. Welds are a more efficient means of connecting structure; however, the design should not feed peak stresses into the welds. Weld lands can be used as a means of reducing excess stress as well as weld shaving. Elimination of three dimensional dynamic coupling is a good design goal. Where it cannot be eliminated, adequate frequency separation should be employed. Design in the linear range should always be the goal, using nonlinearities for operational margins. Margins must be specified and verified. Margin statements can be either deterministic or probabilistic. This leads to the requirements for criteria, procedures and philosophy to match the program. As a general statement, criteria used for design should be deterministic; reserving the probabilistic for sensitivities and reliability; however, modern computers in conjunction with basic statistical code development is making the probabilistic approach a viable option. Limitations of analysis and test must be accounted for in design. All design must be against total cost and should consider flexibility. What is not put in the design must be made safe by operational procedures. Good design accounts for environment variations through robustness of the response or through control of the environments. Instituting automated data base should be a part of good design to enhance verification and operations.

V. ENVISIONAL TASKS

As one looks to the future that includes planet Earth, lunar colonies, and Mars exploration, certain tasks of a broad nature are envisioned. The first is design and implementation of fracture control with all its associated tasks. Implied also is the development of health monitoring systems. Future designs and effective implementation of TQM will require simultaneous engineering including interdisciplinary analysis (system focus). The list on Figure 87 is representative, but not all inclusive. The individual mission requirements, coupled with the design concepts, will determine the range of interdisciplinary analysis. The system focus must use total cost as the criteria that the decision process employs for design selection. Many of the systems proposed for the future must deal with geometric and materials nonlinearity. Analysis techniques, testing techniques, and materials characterization must be developed for these tasks. Combined testing, probably on orbit, must be developed to verify systems. This includes instrumentation, mission planning, and software updates to account for anomalies found. Statistical/reliability applied mechanics techniques must be developed to properly assess risks. All discipline technologies must be extended to cover the new requirements. Robustness and sensitivity techniques must be extended to cover mission requirements in the design process. The customer (requirements) and their continuous interaction with the project is the key to success. TQM is the overall approach that must be used to ensure all these things are done to obtain a low cost, robust system.

VI. PERSONAL LESSONS LEARNED

Most personal lessons learned are not of much value to others due to the situations involved; however, a few encountered have particular value for engineering, especially aerospace engineering.

Most of us envision ourselves as great thinkers, observers, and discoverers. As engineers, we write of our investigations, evaluations, and lessons learned, giving little credit to the influence of others. Yet, if reality is approached, "No Man is An Island," much of what he projects was taught by others. As Deming says, "we cannot generate knowledge; it comes from outside," Norman Cousins, while editor of Saturday Review, and serving as a Presidential advisor, had the opportunity of asking several of the world's great men the question: "What is the one lesson you have learned in life?" Each of us must pose the question and extract answers, many times simple in nature, at other instances complex and multifaceted. One lesson marked clearly in my mind is that I am, to a large extent, what I am because of others. Obviously, our parents, friends, teachers, etc. have all played a part. I do not want to minimize that; however, the examples chosen of lessons others taught are taken from my professional life and will be geared toward an engineering application.

A. Lessons Learned from Dr. von Braun

Dr. Wernher von Braun, the great German space leader who was in the forefront of much of America's early space program through the Apollo lunar landing, taught me a lesson that is deeply etched in my mind. As a young engineer, I was given an assignment associated with clearing the first Saturn I launch vehicle for flight. The results had to be presented to Dr. von Braun. The Saturn I, first stage, consisted of a core propellant tank (Jupiter missile manufacturing) surrounded by eight propellant tanks (Redstone missile manufacturing) and eight clustered engines. The upper stage of this series-burn vehicle was a Saturn IV stage consisting of four R-L10 engines (inert on the first flight). Due to the potential for the vehicle elastic body modes coupling with the control system, producing an instability, and the dynamic complexity of clustered first stage tankage, accurate modal characteristics were required. Analytical structural dynamic analysis, verified by a full-scale dynamic test, was the chosen approach. This being one of the early full-scale dynamic system tests, much concern existed in terms of the elastic suspension system (attempt to simulate free-free modes) coupling and distorting the experimental mode shapes. Early attempts to remove this effect from the experimental data produced errors, poor correlation with analytical data, and control system instability. My assignment was to show that the suspension system was not affecting the data since the analytical mode shapes correlated adequately with the dynamic test, thus it was safe to fly. The problem was that many modes of the clustered configuration were very closely grouped in frequency. If the frequencies matched the test data, the mode shapes did not and vice versa. As any good dynamist knows, if the frequencies are close, then usually the critical match is modal, not frequencies. However, because of the emphasis that had occurred, it was decided that the correlation would be made on frequencies, not modes. Dr. von Braun quickly saw the discrepancy and nailed me to the wall. After some discussion, he said in a nice way: "I think you are trying to fool me; however, I don't believe it will affect the results of your study or the conclusions, so let's hear the conclusions." The conclusions were that the data, both analysis and test, were accurate. Therefore the control system was stable and it was safe to fly. The vehicle flew successfully. The lesson is clear; never shift the emphasis away from a basic for ease of presentation, stick to the fundamentals. At the end of the meeting, someone questioned Dr. von Braun over the wisdom of holding up a launch for two weeks to investigate a supposition. He answered with a question: "What if he had been right? We have time to find out." Such is good engineering.

B. Lessons Learned From Dr. Geissler

Early in my career, Dr. Ernst Geissler, our Laboratory Director, taught me a very embarrassing, but equally permanent, lesson. My supervisor had given me a set of equations to solve and graph the results. He told me that he would not be in the next day and that I was to give the results to Dr. Geissler. This, I did. It turned out not to be simple. Dr. Geissler took the information then asked me to explain it. Since I was only following instructions and had not been told what the equations were for, I had to say that I didn't know. Dr. Geissler obviously knew what had happened, saying in his quite gentle manner: "Mr. Ryan, we always have time to understand the results and what we are doing." Clearly this is a basic that engineering must adhere to.

C. Lessons Learned From Mr. Horn

Helmut Horn, my Division Chief, had a unique way of working problems. Many times, late in the afternoon, he would call me in to explain some problems. His technique was to have you go to the chalkboard and explain algebraically and graphically the analysis and the problem. Somewhere in this exchange, he would take the chalk and start constructing simplified models to use for interpreting your data. In one of these exchanges, I was presenting Saturn V elastic body modal response to the atmospheric winds, including the induced aerodynamic forces. I was treating the problem using the Lagrangian approach and a set of generalized coordinates and generalized forces. His goal was to show that the distributed aerodynamic force and generalized coordinates for one mode could be represented by a single mass spring damper system with a single point time force recoupled from the other modes. This, I was able to do, but with much discussion required for the analogies. As I remember, this went on late into the early evening. All at once, he stood up and shook my hand making the statement: "You have done your homework." Then added: "We must always try to understand our model, our analysis, with a very simple physical representation of the problem. When this works, the answer is simple. If this simplified physical representation doesn't work, then we must be able to explain why it fails and thus justify or verify the more sophisticated analysis." Needless to say, that day is locked in my memory. The capability and complexity of modern day computers and the expanding scope of analysis makes this principle even more important.

D. Lessons Learned From Dr. Rees

Dr. Eberhard Rees, Marshall Center Director following Dr. von Braun, taught a very important lesson in that we must, as managers, have real concern for people. Dr. Rees decided late in a Friday afternoon briefing, preparatory for a Saturday Headquarters meeting, that I needed to accompany the group to Washington Friday night and Saturday. This created some problems for me since I had a Sunday appointment that could not be easily broken. Dr. Rees promised that he would see that I got back. We were using the NASA Gulfstream plane for the trip. Late in the afternoon Saturday, a snow started. The meeting was kind of depressing due to the decisions reached, so after getting on the plane, I slumped down in my seat. Soon, after Dr. Rees got in his seat, I heard him say: "Where is Bob Ryan? I promised him we would get him back tonight." An expression of real concern in a very simple way makes lasting impressions.

E. Lessons Learned From My Dad

When in high school studying algebra homework, I got stuck somewhat. Not wanting to spend much time on the assignment, I turned to my dad whom I knew could work the problem. Instead of working the problem and explaining the solution to me, in his great wisdom, he asked me a question or two that forced me to think the problem through and work it myself. Obviously, I was frustrated for awhile, but in the end, I was happy because I understood the principle. In working with people and getting them to develop, we need to follow this example. Our goal should not be to get the quick answer, but get the answer in a way that develops the person.

VII. FUTURE THRUST (TQM)

TQM is a revolutionary concept that is transforming America through a change of focus, new principles, and better tools, resulting in better quality, lower cost products and services, and, consequently, a better quality of life. This concept fits all of us. We all have a product to sell, a product to produce. Therefore, we all must define what our product is and who the customer is. The process works by identifying what the product is, how the product is made, how it is to be used, and what the total cost is. The concept focuses on bringing a team concept up front to do the job better using simultaneous engineering, and involving the customers and all product disciplines from conception to operation. The team determines requirements, design, processes, etc., with the goal of producing a robust, low-cost, flexible, high-reliability product. The process focuses on reduction of criteria and specs, emphasizing variation reduction about the nominal instead of determining acceptable limits (fig. 88 and 89). It deals with the total (quality) cost function emphasizing the quality lever concepts which focuses up-front funding increases to get the right requirements and design which reduces later costs of manufacturing, production, and operations. This translates into fine turning the system without more total money. There is no more money. It recognizes the principle that "you must lose to gain;" all improvements cost. It means something must be given up to improve. Giving up hurts. We resist hurt. Hard decisions must be made in terms of stringent priorities. If we are willing to pay the cost, TQM offers a breath of fresh air to the solution of our problems, providing a system with many new or innovative tools for accomplishing the various parts of the process. In fact, many confuse the use of such tools with TQM itself. Philosophy, principles, and tools must be adequately differentiated for progress.

Fundamentally TQM is an attitude, an attitude which permeates top management and flows through the entire organization, that says that we can do better and will do better by emphasizing the customer's needs and relying on the people to do the job. Improvement must be continuous; it has many dimensions:

- Reliability
- Maintainability
- Performance
- Durability
- Conformance (to requirements)
- People
- Policy
- Management.

It emphasizes team play. As Deming,[21] the American who was responsible for transforming Japan, says repeatedly, "The orchestra, not the soloist, is the approach." Underlying this is the attitude or belief in the goodness of human nature. Most people want to do a good job, and will if the system will let them. To improve the product, the system has to be changed. This is accomplished in three ways. First, the customer, his needs, and requirements are focused upon. These translate into a product of high quality and low cost. Second, emphasis is placed on the people that do the job. They must be given the necessary authority and be trained "totally" as well as in skills (Deming's principles).[6–9 13 14] Anyone who has attended Deming's course remembers: "Does he know? How could he know? He is only doing his best." This is repeated many times to emphasize the point that "Missing knowledge is the rest of the problem." People want to do a good job, the system does not permit it. Third, understand the process, change it where needed, observe the effects of change, then repeat. It is to plan, to check, to advise, and to repeat the cycle. Just as important is a constancy of purpose that is identifiable, communicable, and implementable by all people in the organization toward product improvement. This essentially places the blame or responsibility for quality on the system, and only management can change the system.

The emphasis on process and management implies that you can only change something in a meaningful way if you understand it. To understand it you must be able to describe it in a simple way, flowing the total process from customer to product. Inherent in this understanding is interpretation of data. Deming emphasizes over and over again that you cannot properly deal with data without knowledge. You can only get knowledge if there is a theory undergirding it as a basis to interpret data. Most of the time this knowledge comes from the outside. You cannot generate knowledge, you can only generate heat (activity). If the system generates fear then you will get the wrong answer, therefore, you must eliminate fear. Emphasis must be placed on controlling variations instead of meeting specification or tolerance limits. This places the responsibility back on the worker, where it should be, and changes the whole attitude on how to approach a job. TQM is a continuous process, a culture, a philosophy, a new way of life. As you can see, some of Deming's 14 principles are derived from his emphasis on constancy of purpose, people, customer, and variance. The guiding principles for an organization derived from these 14 principles are: quality first, customer satisfaction, continuous improvement, management commitment, employee involvement.

TQM utilizes numerous tools, and additional tool concepts are under development. They rely on statistics, teamwork, and people development (training and communication). Up front always is the customer, his desires, his requirements. These requirements must be translated into a product. Quality function deployment (QFD) is one tool available for translating the customer's needs into the manufactured product through a structured format of sequential matrices. Parallel to this must be the application of the tool simultaneous engineering (SE) (a take-off on systems engineering), that addresses concurrently, early in the design stage, performance characteristics, production process factors, and operational issues. Implied as mandatory is the use of teams with all pertinent disciplines represented, interaction, and open communication. QFD and SE are strongly cross-linked. Parameter design is the technique of establishing the optimum parameter levels of a system. The drastic change that inherently resists variation results in the best design. Taguchi,[36] a leading quality expert from Japan, actually deals with design in three steps: (1) system design based on experience and knowledge from specialized fields, (2) parameter design, and (3) tolerance design, i.e., the adjustment of tolerances of the input parameters to get the desired output. Analysis of variation (ANOVA) is a tool that allows you to judge what degree of sophistication is required to reap the rewards of experimental design. A mathematical tool for accomplishing this is signal-to-noise (S/N) ratio. The object is to increase the S/N ratio.

Implementation of TQM is not easy. There are many deterrents which must be understood if progress is to be made. First and foremost, it requires a cultural change. Changes in cultures are resisted. We do not want to move from a known, where we are comfortable, to an unknown. There is always risk (perceived and actual) inherent in change. Change means acting on priorities, making decisions to give up something desirable for an unknown presumed to be more desirable. No one likes the loss required to gain (basic principle). A further problem exists because the employee has a problem in his/her ability to identify the difference between the quality of a product that meets limit specifications versus a product produced under a variation reduction approach. On the surface, limit specifications define acceptability, but the issue of quality is much deeper, which variation reduction addresses. An additional implementation problem occurs because, in general, we are doing a good job. All major sensitivities and contributors have been controlled to achieve top quality. What is left is fine tuning, dealing with small effects that, when combined with other small effects, produce lower quality. "How are we going to overcome these impediments?" is the major question we must deal with if we are going to implement TQM. The elements start with constant management focus, training in skills and of the whole person, teaming, and the development of a new culture that properly considers the customer, the total cost, and the integrity of all workers. It requires in-depth understanding of the total process, formulation of hard questions relative to what and why we are doing this a certain way, priority decision to change that which is not needed, and the ability to communicate our purpose.

In summary, TQM is a process that pays the greatest dividends by involving the customer, leverage dollars, and up-front efforts to achieve high-quality, lower-cost products through a multidiscipline team approach. If constraints or other considerations preclude the up-front high-leverage payoff, it still has merit when applied to a single process (loads analysis, CFD, testing, etc.) that one has under his control. The payoff is not nearly as high but is well worth the effort. The bottom line is: start wherever you are and improve the process. The attitude is contagious and with time will spread. Let it start with you.

- Information in pitch comes from all contractors and NASA centers. Lessons learned are mine based on activities and discussions.

  – Centers

    JSC, KSC, MSFC, GSFC, LeRC, Stennis Space Center

  – Contractors

Rockwell Space Division	Shuttle Systems/Orbiter, Apollo
Rockwell Rocketdyne Division	Shuttle Main Engine
Morton Thiokol	Solid Rocket Motors
Martin	External Tank, Tethered Satellite, TOS, Skylab
TRW	HEAO, OMV, AXAF
United Booster Technologies	Solid Rocket Booster
Perkin-Elmer	HST, AXAF
Lockheed	HST
Pratt & Whitney	ATD
Europeans	Spacelab, Tethered Satellite, HST
Boeing	Space Station, Saturn
Universities	Experiments
McDonnell Douglas	Saturn, Spacelab
Chrysler	Saturn

- MSFC has worked in team mode on problems with contractors. Hard to differentiate contributions, although major source of technical data was the contractors.

- Contractors' efforts, working relations, and technical expertise over the years is greatly appreciated and coveted as we move forward.

Figure 1. Information source.

Three Perspectives

A. 51-L Challenger accident investigation

B. Shuttle safe return to flight activities

- NRC (National Research Council)
- Audits: FMEA/CIL, Weld Assessment (SSME), Structural Audit (SSME, ET), Fracture Mechanics (ET)
- Redesign: SRM, SRB Aft Skirt
- Shuttle Systems Environment Recertification

C. 35 years engineering experience, mostly with NASA

- Have synopsized by projects and problem causes approximately 150 problems

Findings

Failures, problems, in general, were not due to undiscovered or missing theory, but to the neglect or oversight of basic principles:

- Management
- Criteria
- Procedures
- Philosophy
- Test
- Analysis
- Communication/Documentation
- Project

Figure 2. Perspectives and findings.

Problems Experienced and Envisioned

Lessons Learned

Purpose: Using problems experienced, develop lessons learned, and a context within which to design new systems through short summary documentation

Approach: – Develop a matrix of problems experienced by project and discipline

<u>Disciplines</u>

1. Instabilities
2. Forced Response
   - Static
   - Dynamic

   A. Environment

   B. Response
   - Static
   - Dynamic
3. Modeling
4. Acoustical Tuning
5. Modal Tuning
6. Manufacturing/Quality
7. Fatigue (LCF & HCF)
8. Fracture Control
   - Fracture Mechanics
   - NDE
9. Special Cases
10. Development and Validation Testing (Improper)
11. Material Characterization

<u>Projects</u>

1. Apollo
2. Skylab
3. Viking
4. Jupiter
5. Redstone
6. Shuttle

   A. System

   B. External Tank

   C. Solid Rocket Booster

   D. Space Shuttle Main Engine
7. Hubble Space Telescope
8. Gravity Probe B
9. HEAO
10. IPS

- Approximately 100 problems categorized and documented; 50+ awaiting documentation
- Document a summary with pertinent data for each problem
- Develop lessons learned
- Project potential problems for future space endeavors

Figure 3. Lessons learned.

- Introduction
- System focus, underlying perspective

  Requirements
  Trades — Shuttle example
  Constraints

- Basic principles
- Specific examples to illustrate
  - Performance requirements
  - Models and test are limited
  - Bracketing hand analysis
- Problems experienced
  - Sampling of problems by project
- Lessons learned
- Design guidelines
- Envisioned tasks
- References

Figure 4. Agenda.

Philosophy: Systems engineering/integration is the foundation.

All engineering must be seen and implemented using a system focus. The parts are seen as interacting to form the whole. The whole is seen as the sum of its parts performing their function.

This is the foundation for all major principles of design.

Figure 5. Philosophy.

- Subsystem optimization is costly.
- Constraints can undermine design.
- All disciplines must interact, even for subsystems.
- Total cost is the criteria.
- Systems optimization/requirements is the approach.
- What is neglected in design (suboptimized) must be accounted for by good system optimization during operations (pay me now or pay me later).

Figure 6. System focus.

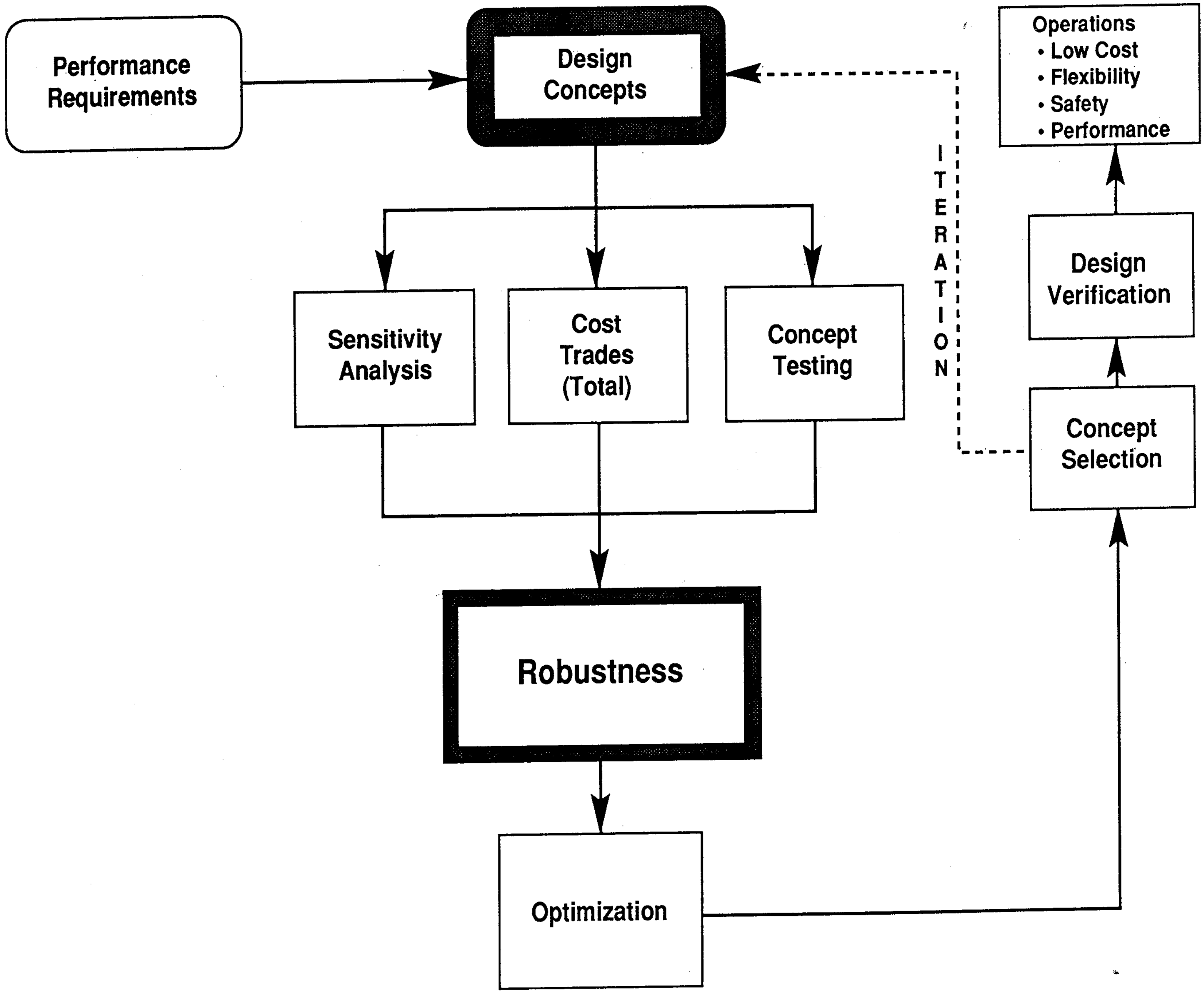


Figure 7. Design and verification A.

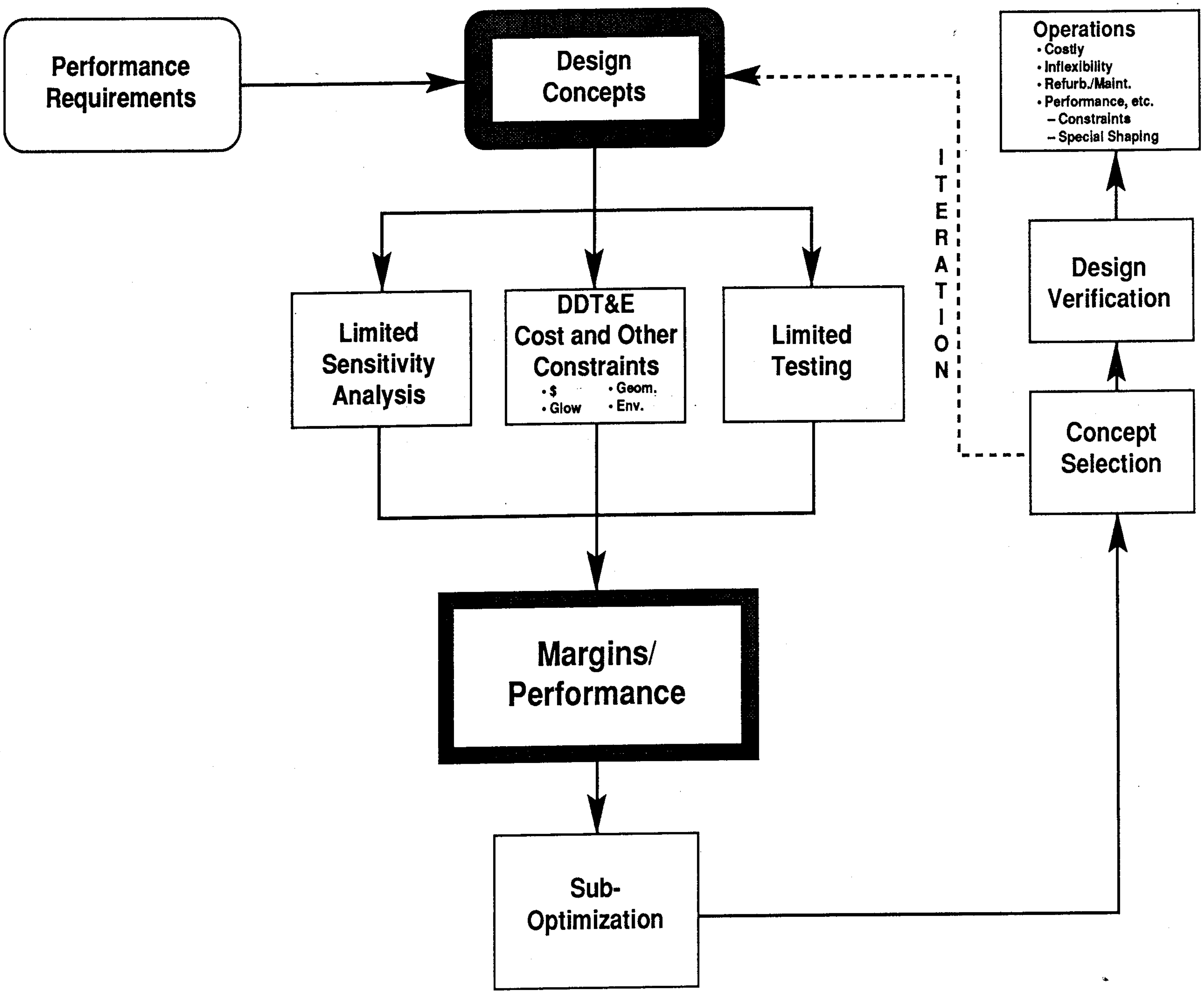


Figure 8. Design and verification B.

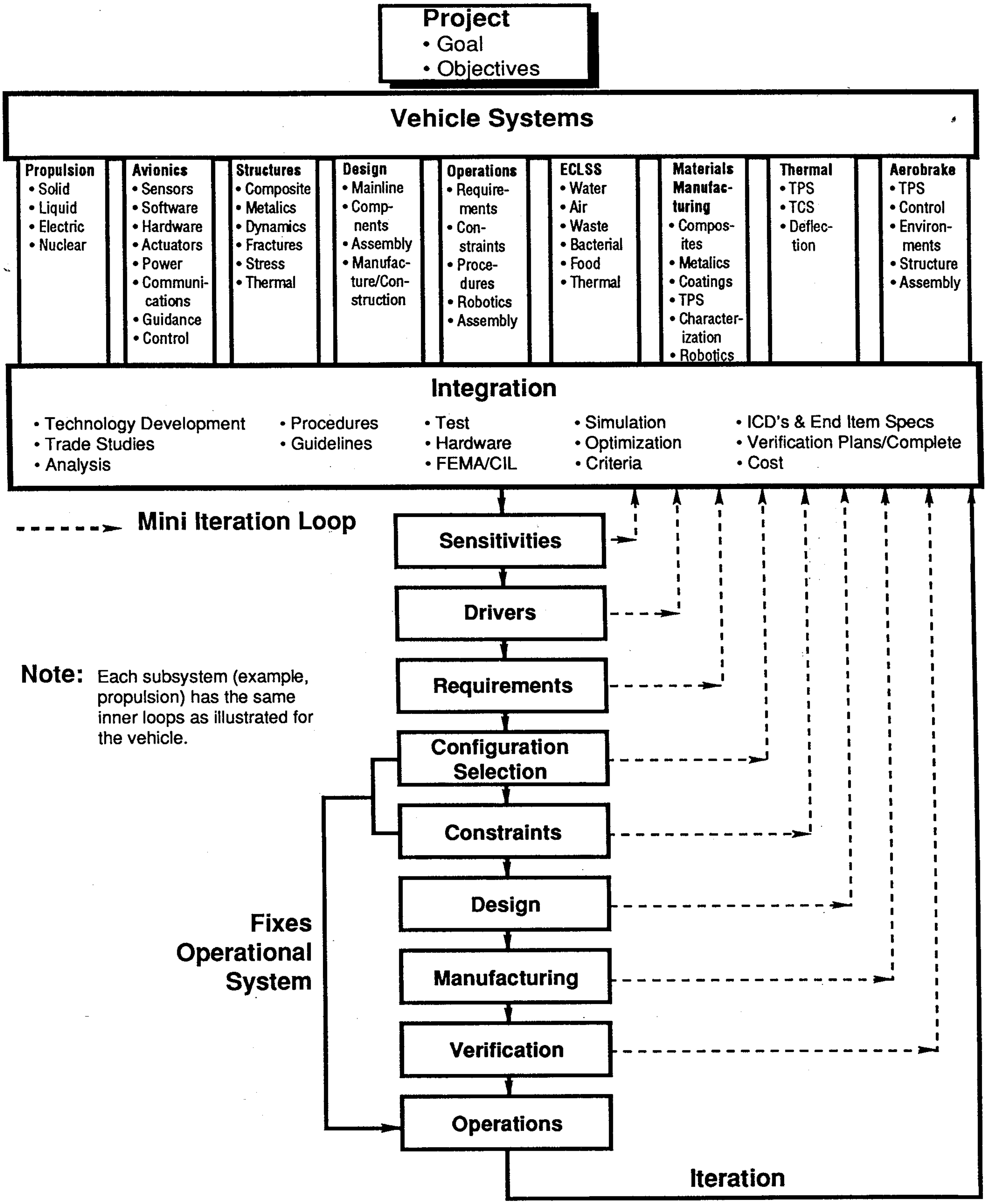


Figure 9. System design.

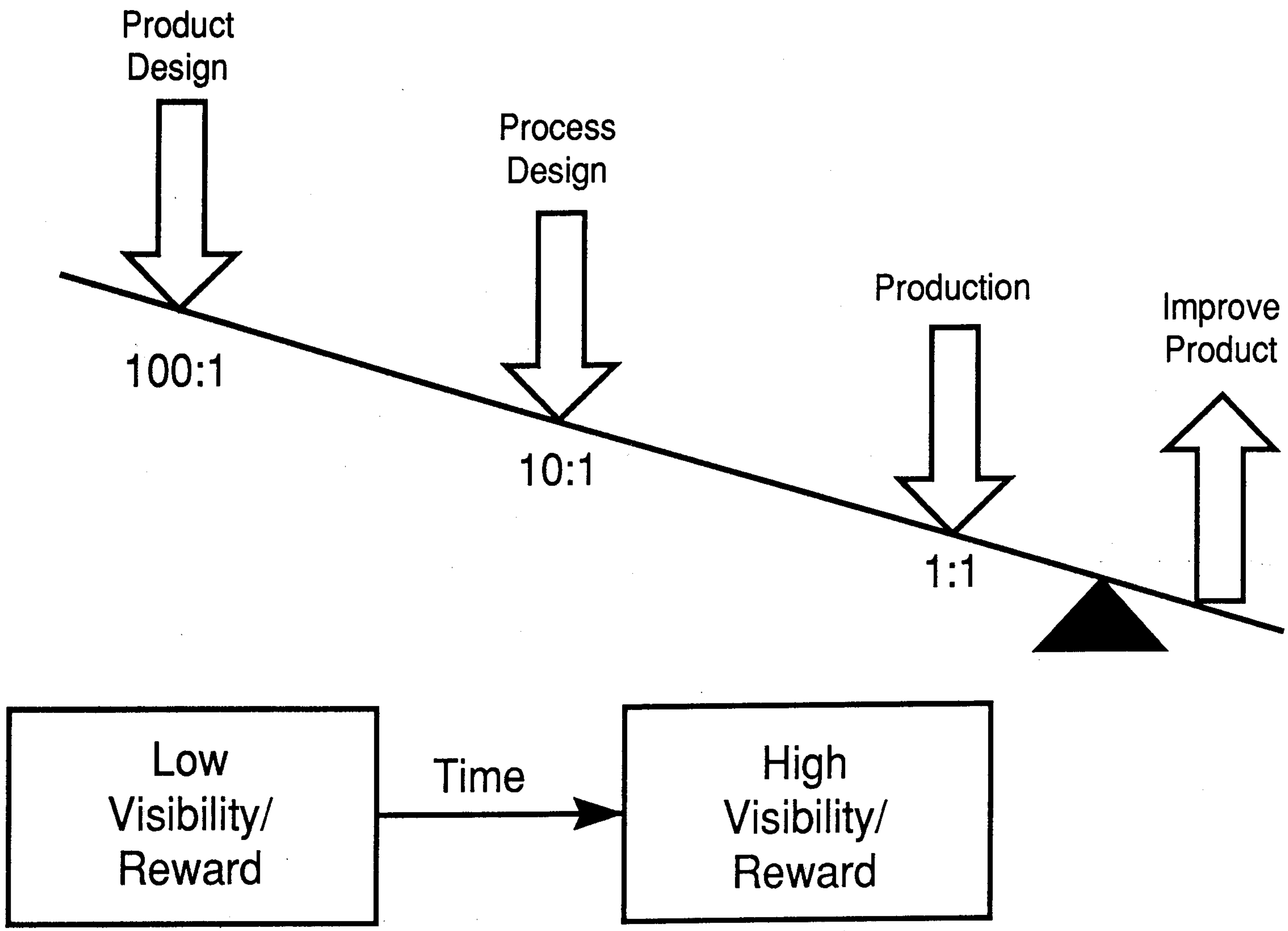


Figure 10. Quality lever.

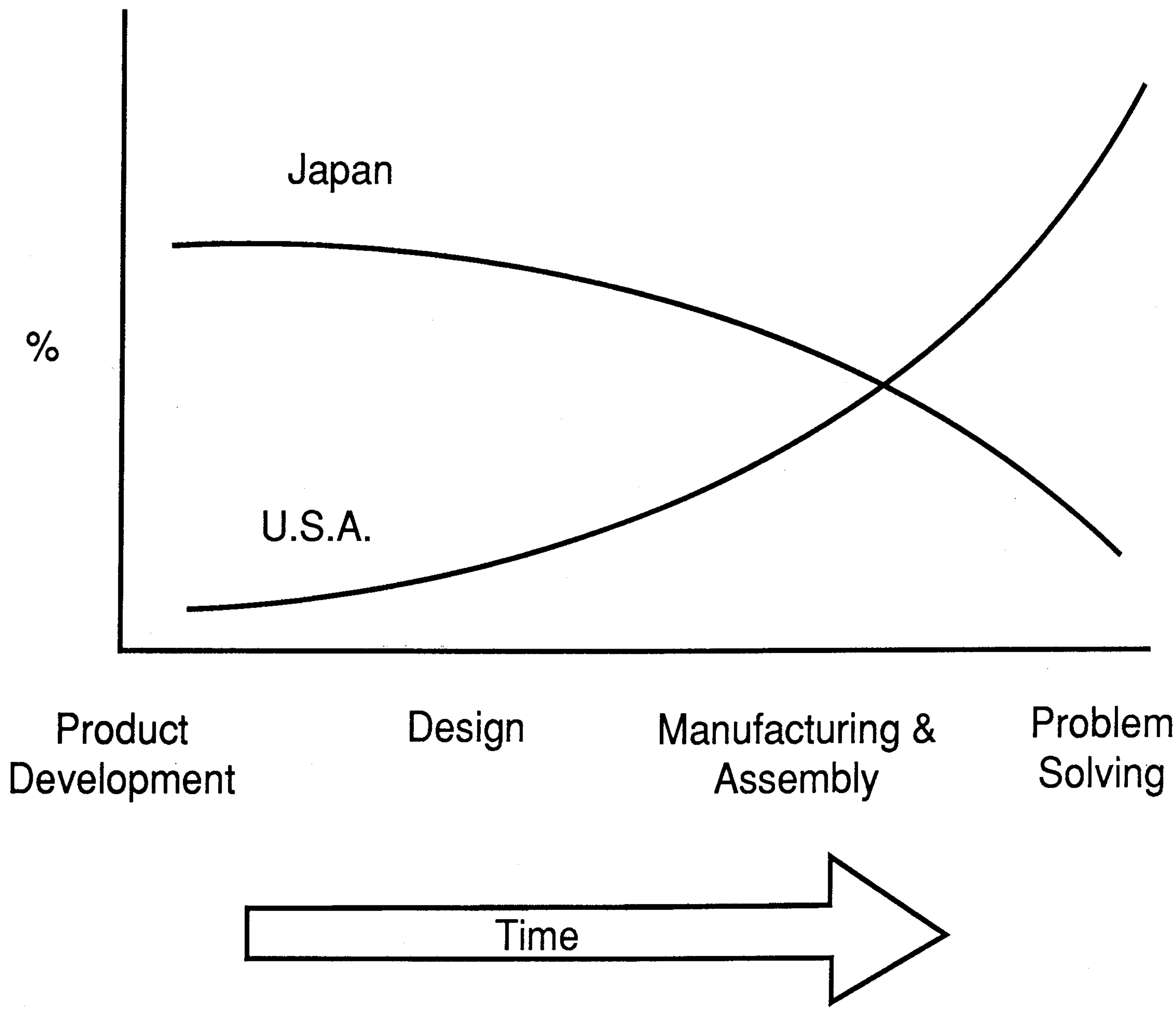


Figure 11. Effort by activity.

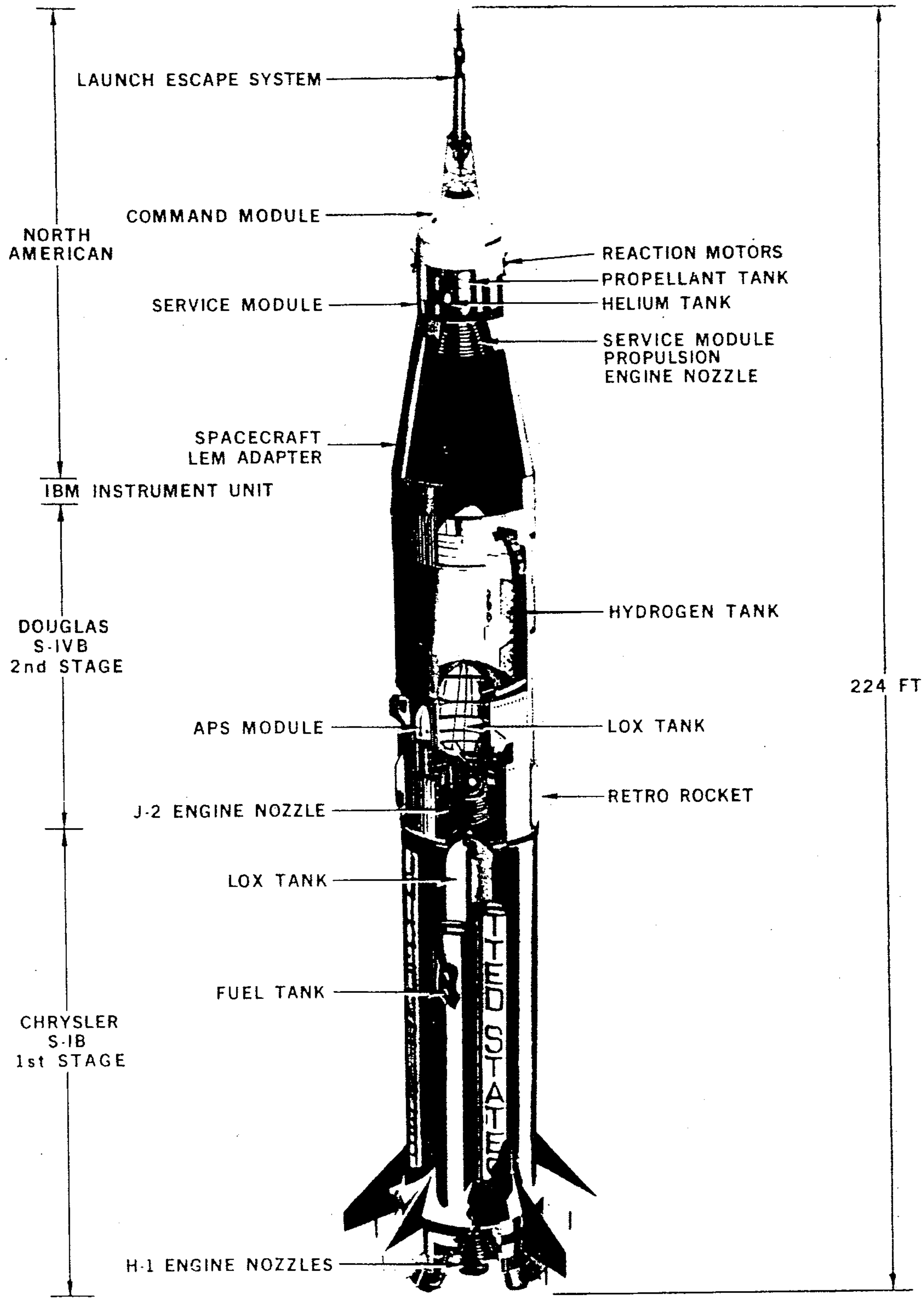


Figure 12. Saturn 1B.

Saturn 1B & V/Skylab Data3

	A	B	C	D	E	F	G	H	I	J
34	Vehicle	Vehicle	Stage	Total	Engine	Number of	Average	Payload	Payload Wt.	
35		No.		Weight	Type	Engines	Thrust	Designation	EO	
36				(K-lb)			(K-lb)		(K-lb)	
37										
38	Saturn 1B	SA-206	S-1B	996.1	H-1	8	203.6	SKYLAB-2	31.0	
39			S-1B I.S.	6.7			0.0			
40			S-IVB	254.6	J-2	1	228.0			
41			I.U.	4.3			0.0			
42			S.C. WET	44.0			0.0			
43			LO Total	1,305.7			203.6			
44										
45	Saturn 1B	SA-207	S-1B	996.1	H-1	8	205.6	SKYLAB-3	32.0	
46			S-1B I.S.	6.8			0.0			
47			S-IVB	256.1	J-2	1	226.0			
48			I.U.	4.6			0.0			
49			S.C. WET	44.4			0.0			
50			LO Total	1,308.0			205.5			
51										
52	Saturn 1B	SA-208	S-1B	1,681.3	H-1	8	205.6	SKYLAB-4	33.0	
53			S-1B I.S.	6.8			0.0			
54			S-IVB	278.9	J-2	1	234.0			
55			I.U.	4.1			0.0			
56			S.C. WET	46.0			0.0			
57			LO Total	2,017.1			205.6			
58										
59										
60										
61										
62										
63										
64										
65										
66										

Note: EO denotes Earth Orbit
ESC denotes Escape

Figure 13. Saturn 1B performance.

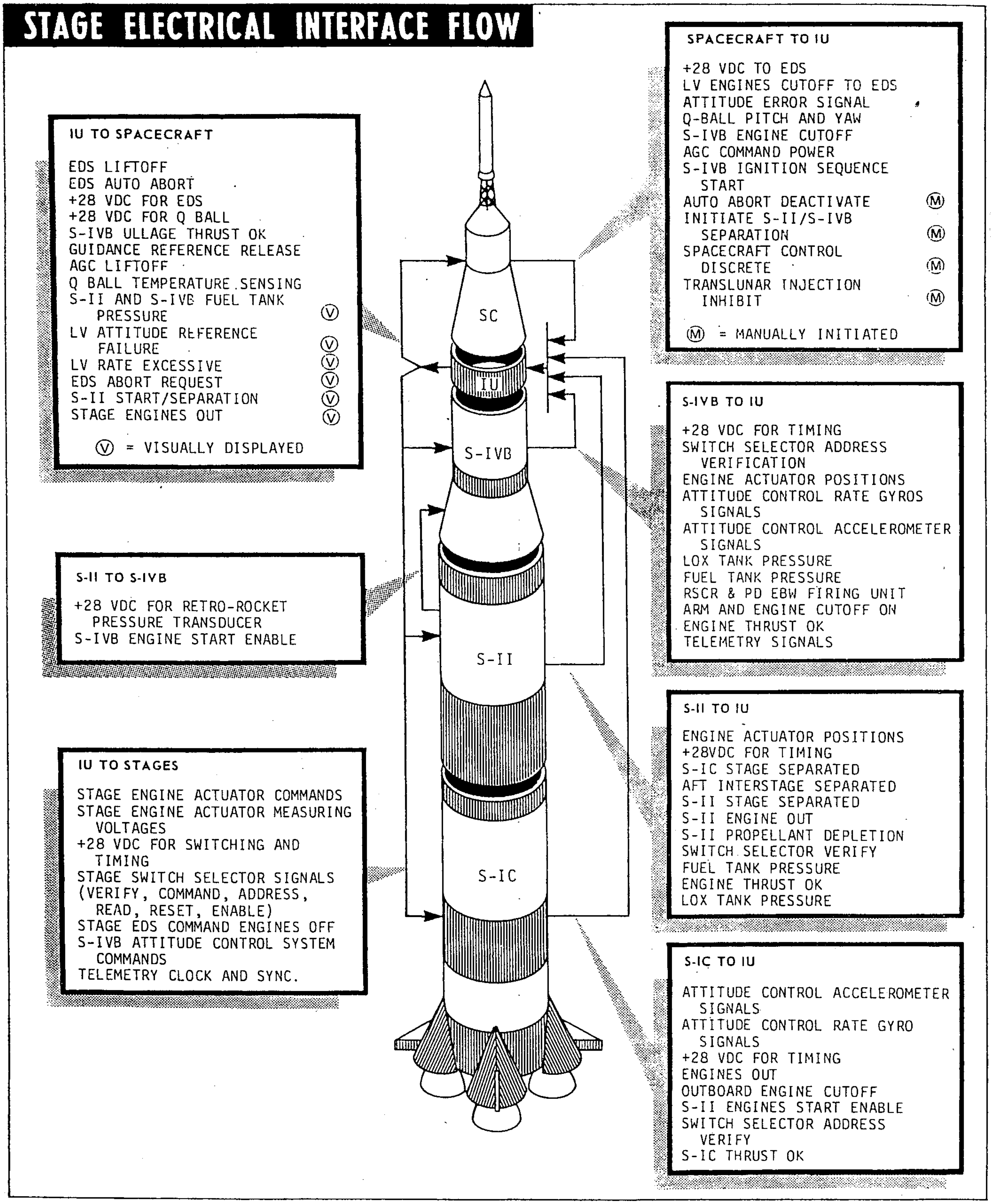


Figure 14. Saturn V.

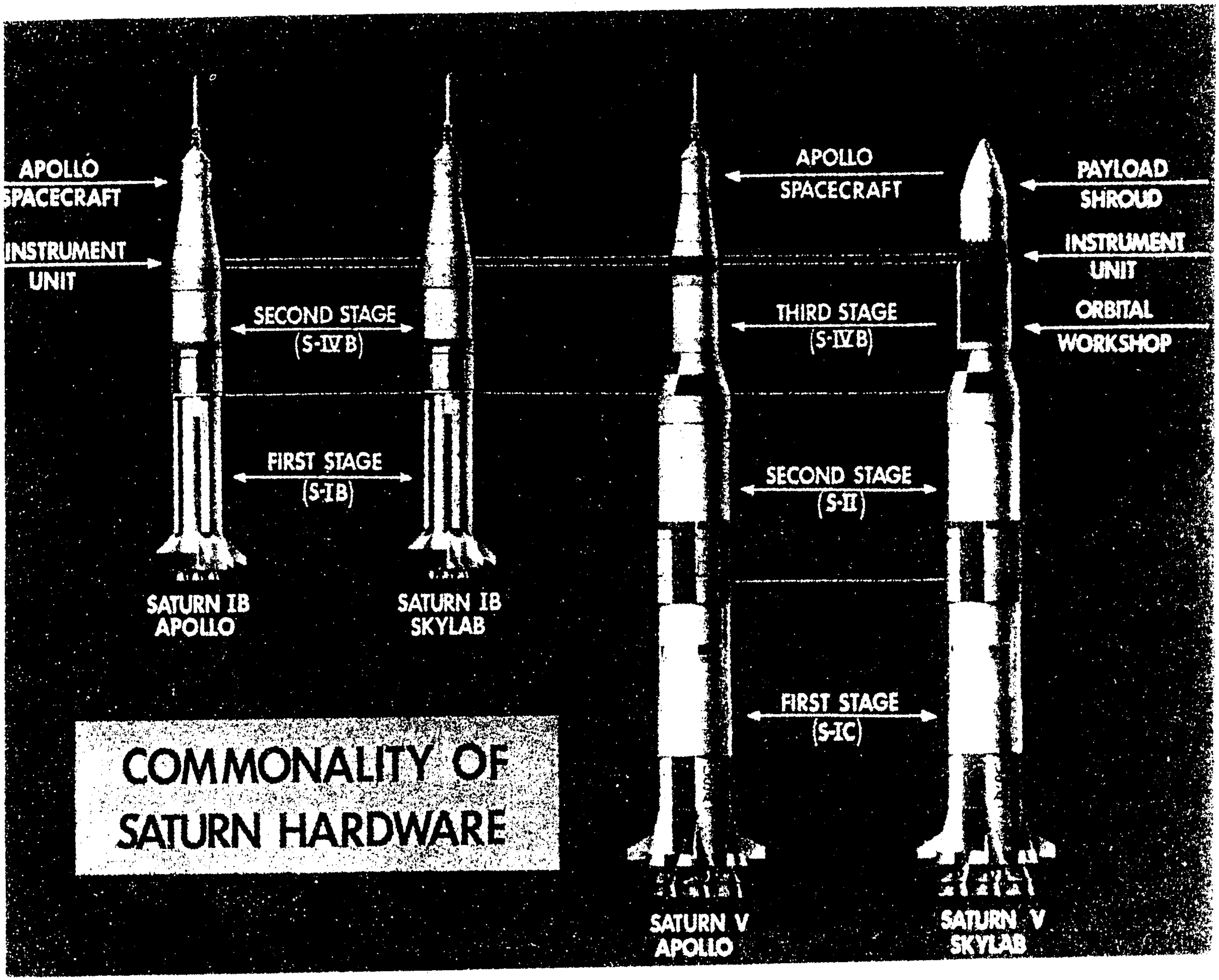


Figure 15. Saturn 1, 1B, and Saturn V.

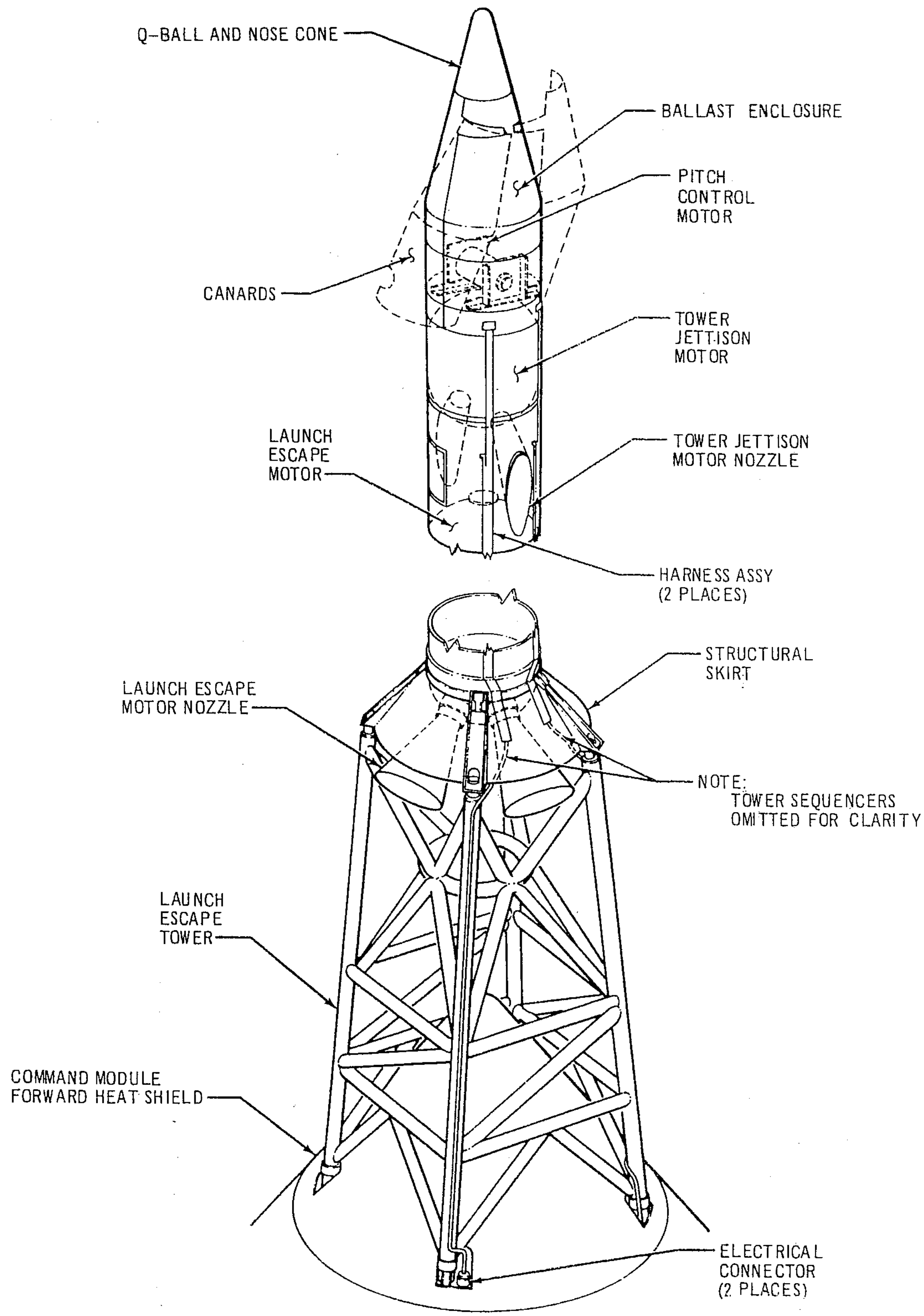


Figure 16. Launch escape system.

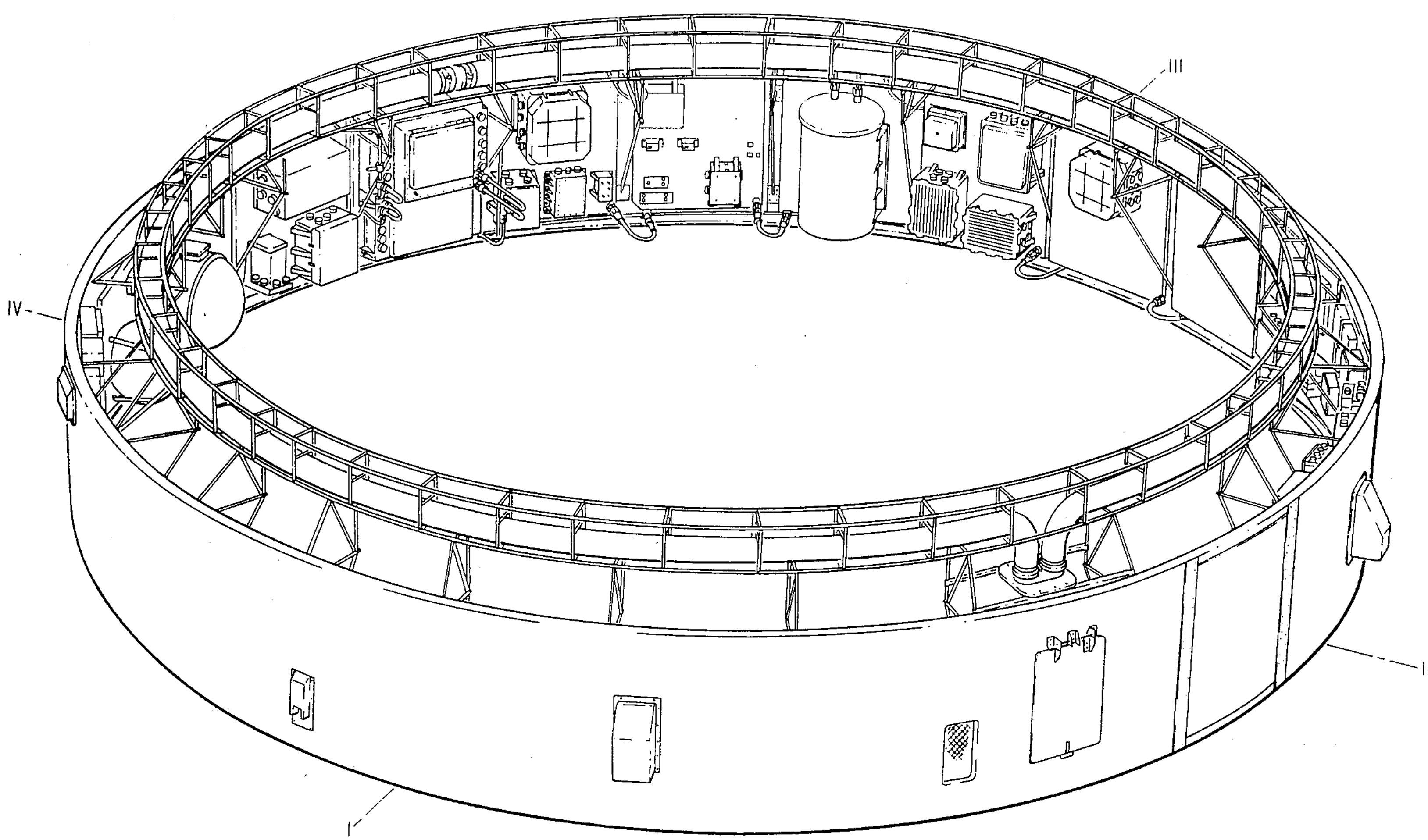


Figure 17. Instrument unit.

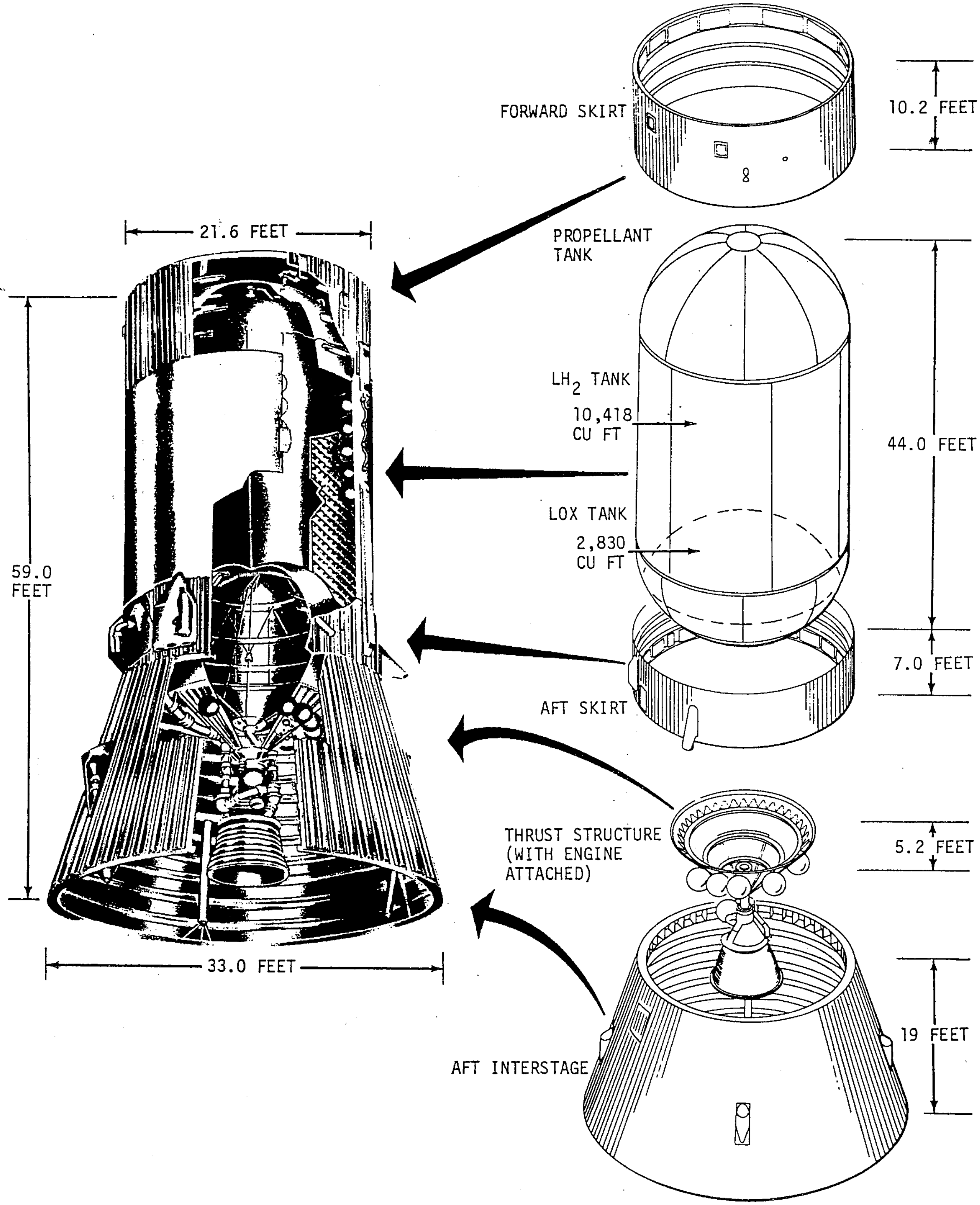


Figure 18. S-IVB stage.

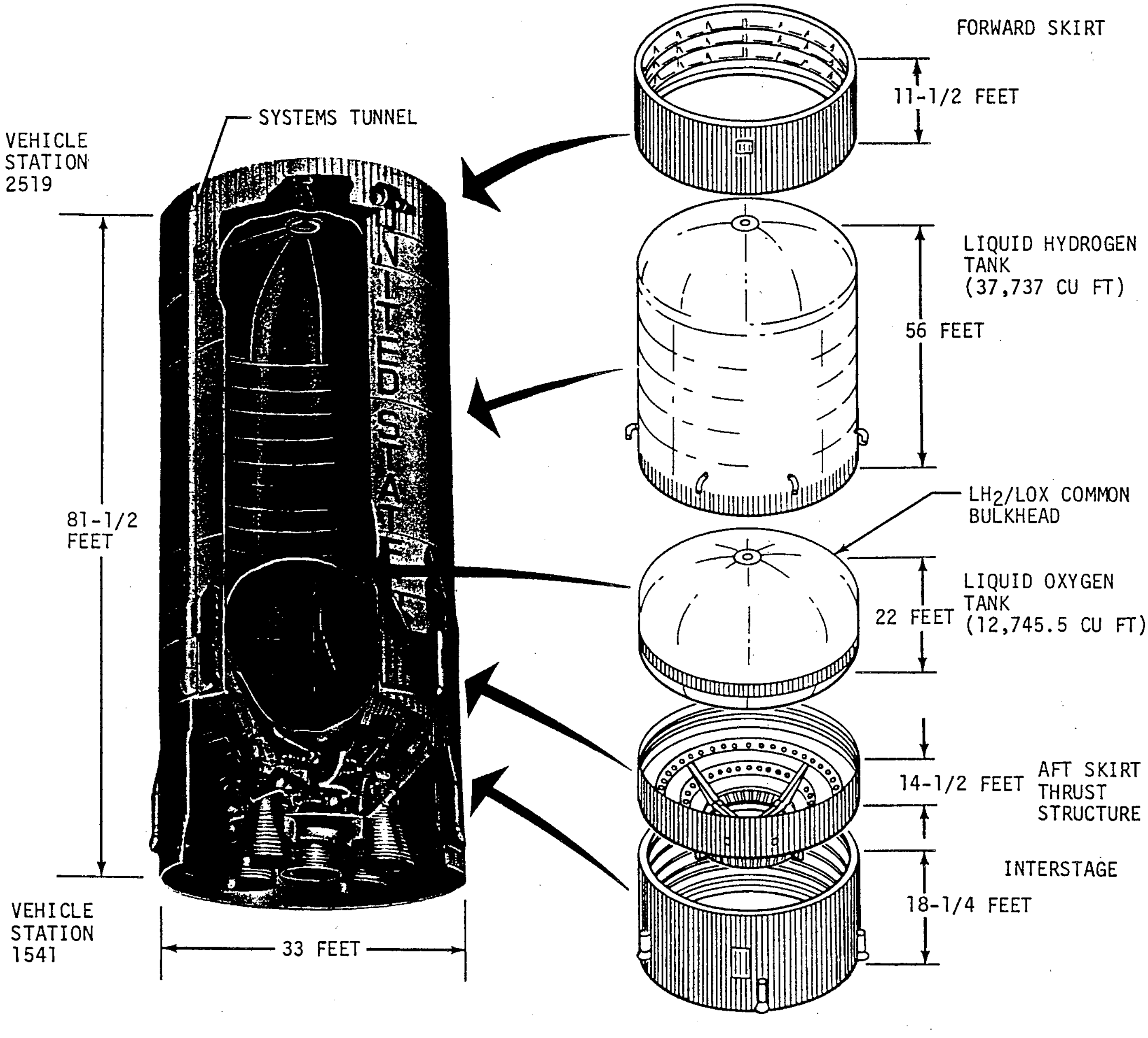


Figure 19. S-II stage.

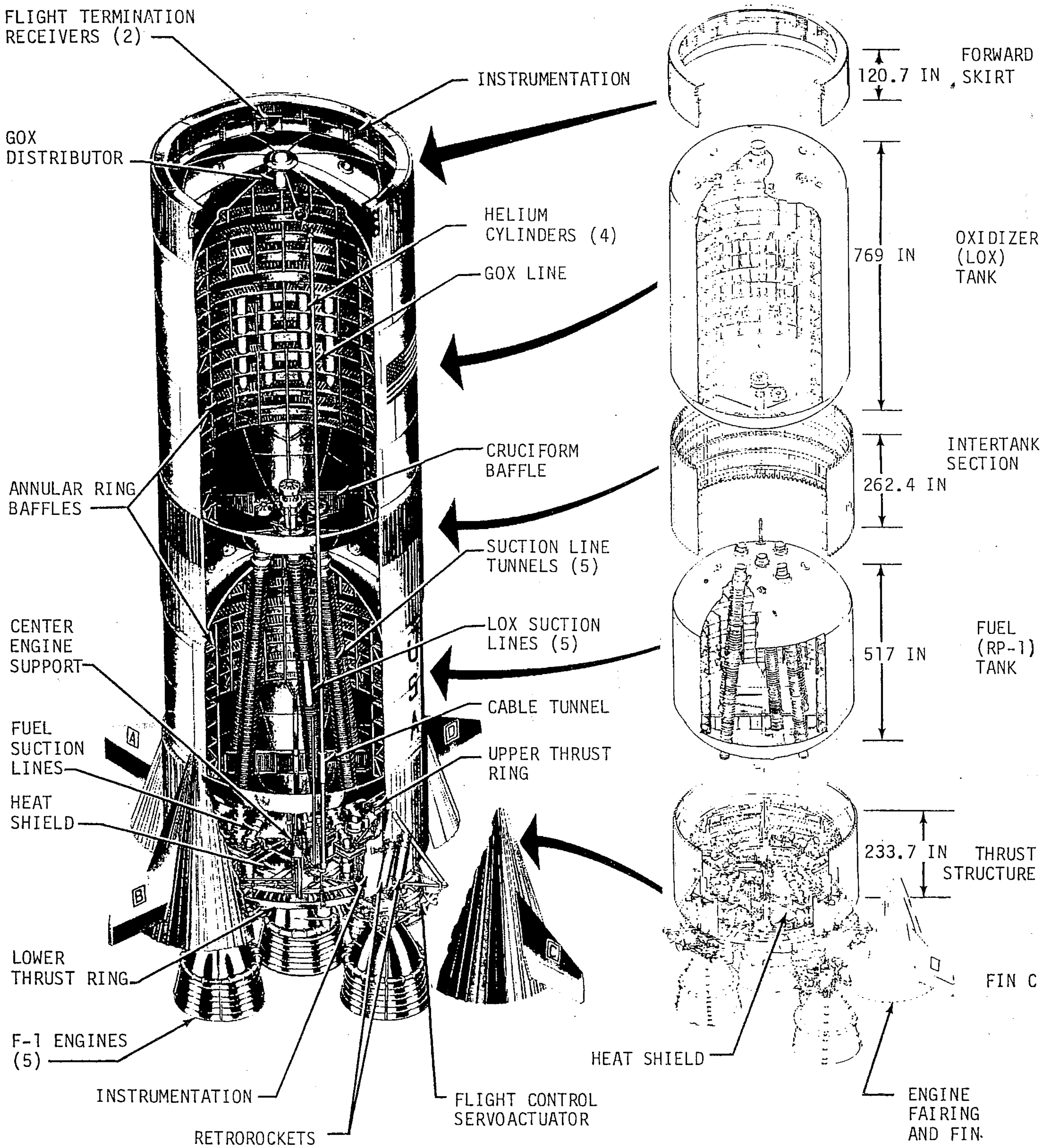
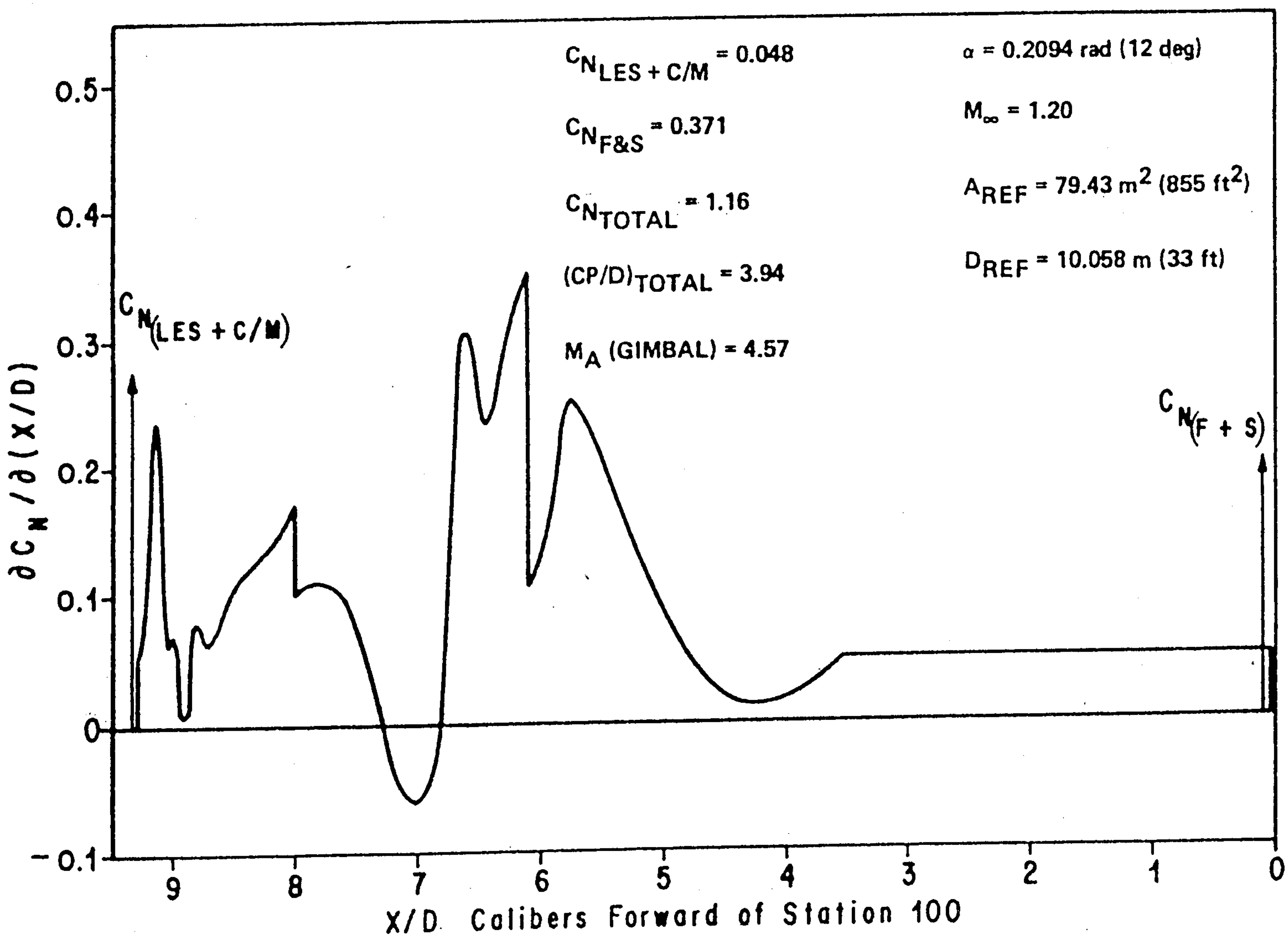
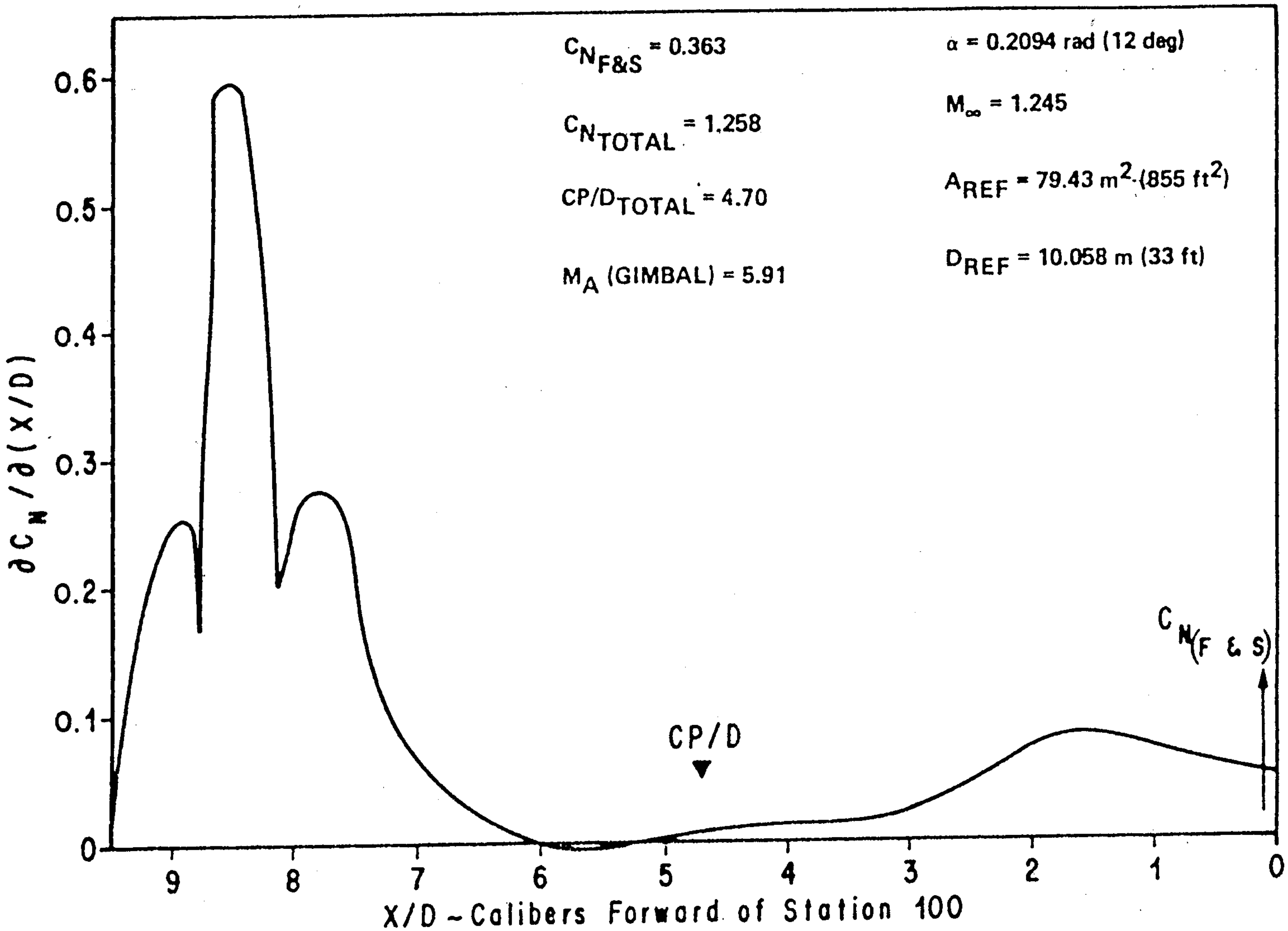


Figure 20. S-1C stage.



Normal Flow Distribution for Saturn V

Figure 21. S-V aero distribution.



Normal Force Distribution for Saturn V Skylab

Figure 22. S-V Skylab aero distribution.

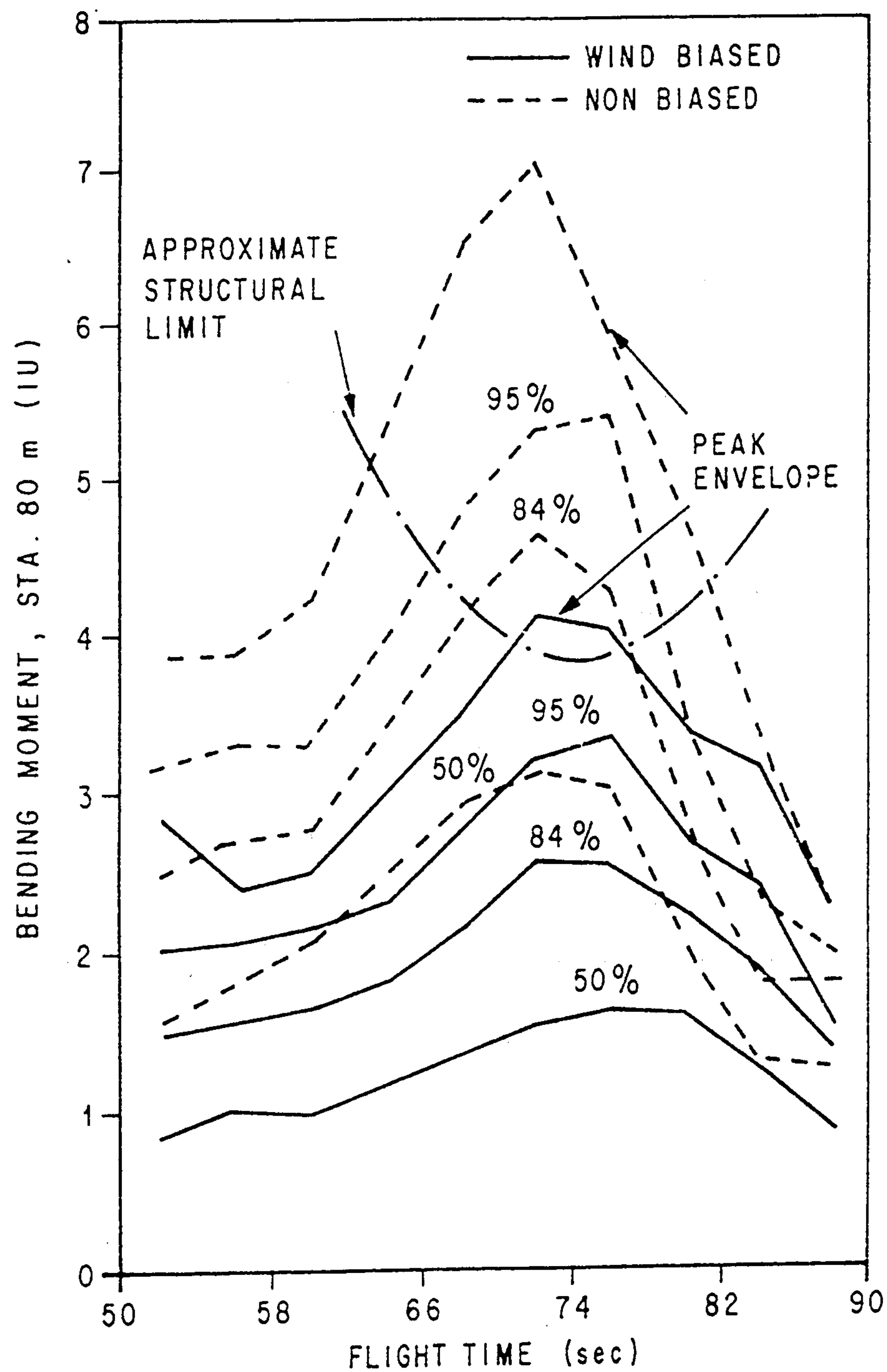
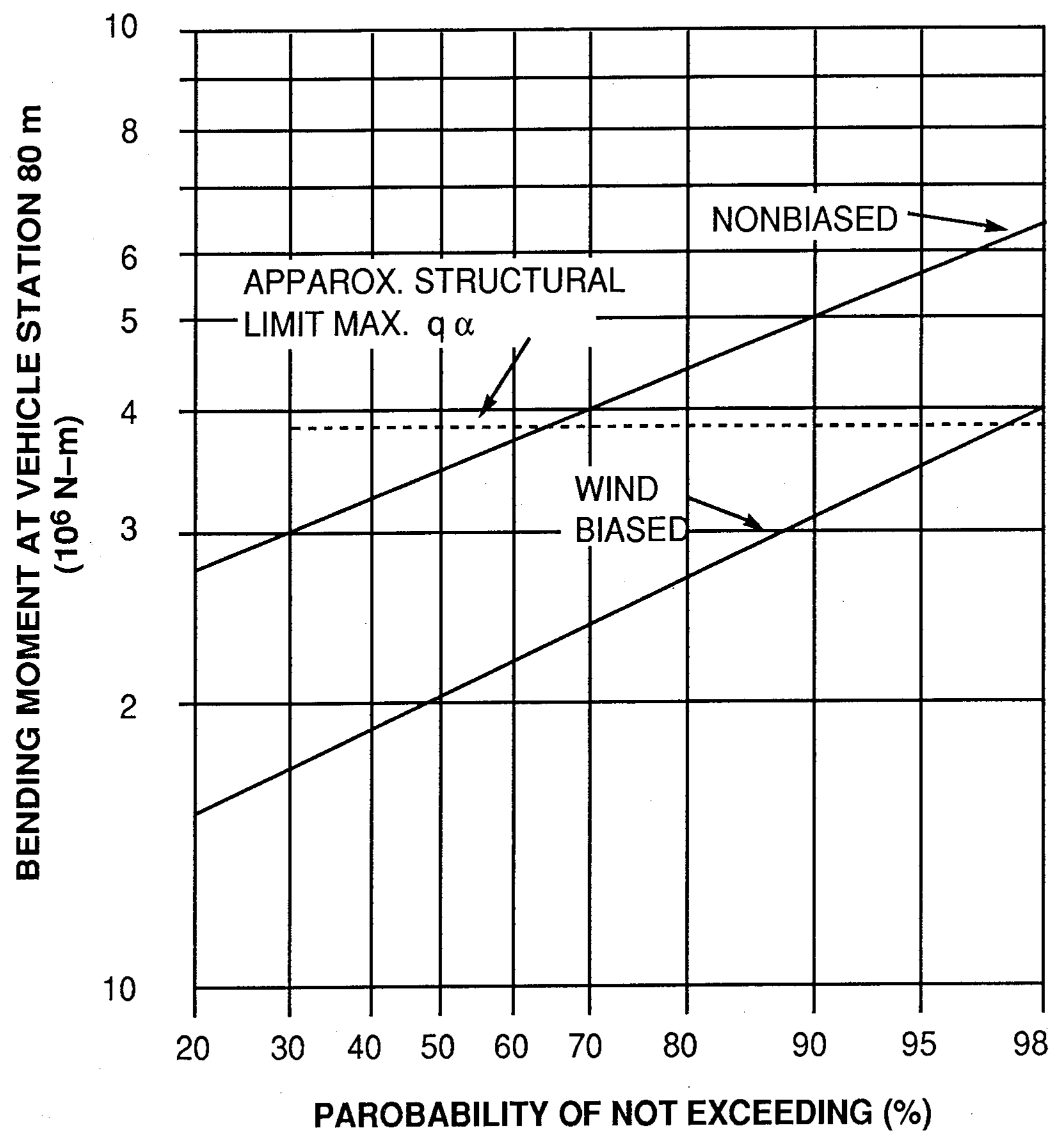


Figure 23. Skylab response to jimsphere winds.



Maximum bending moment at vehicle station 80 m versus probability of not exceeding for March sample jimsphere winds

Figure 24. Skylab maximum bending moment versus probability.

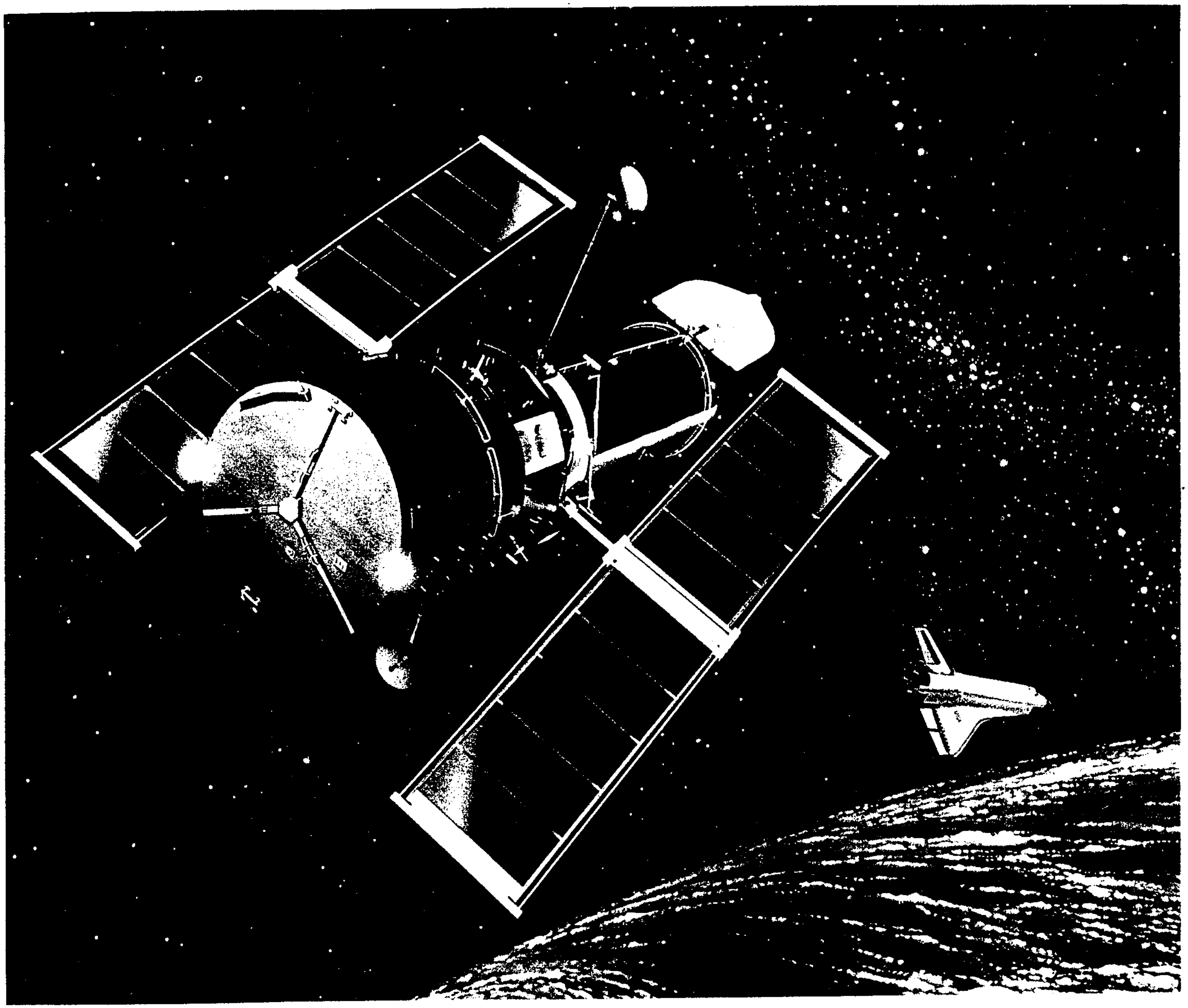


Figure 25. HST SSM.

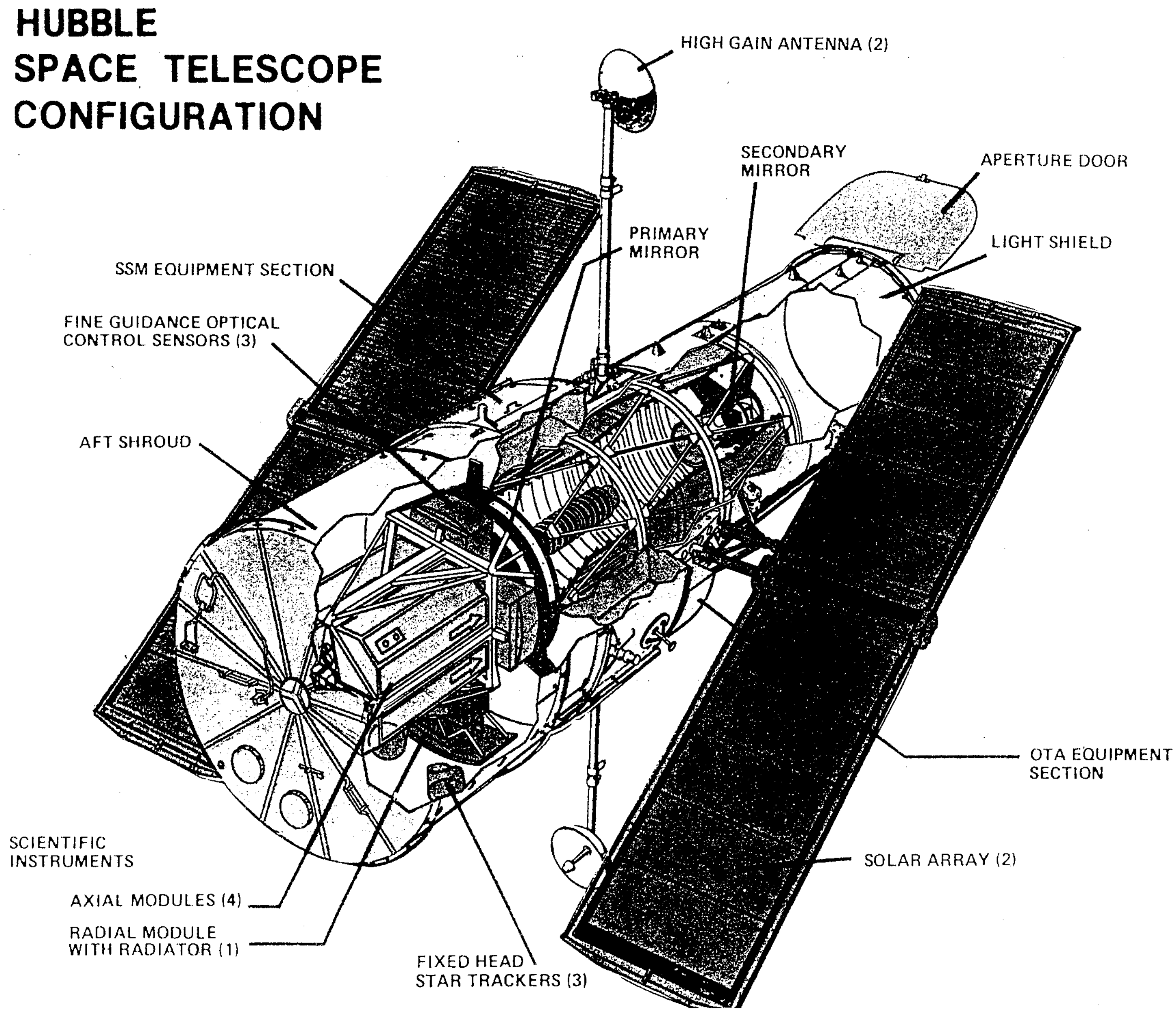


Figure 26. OTA with mirrors.

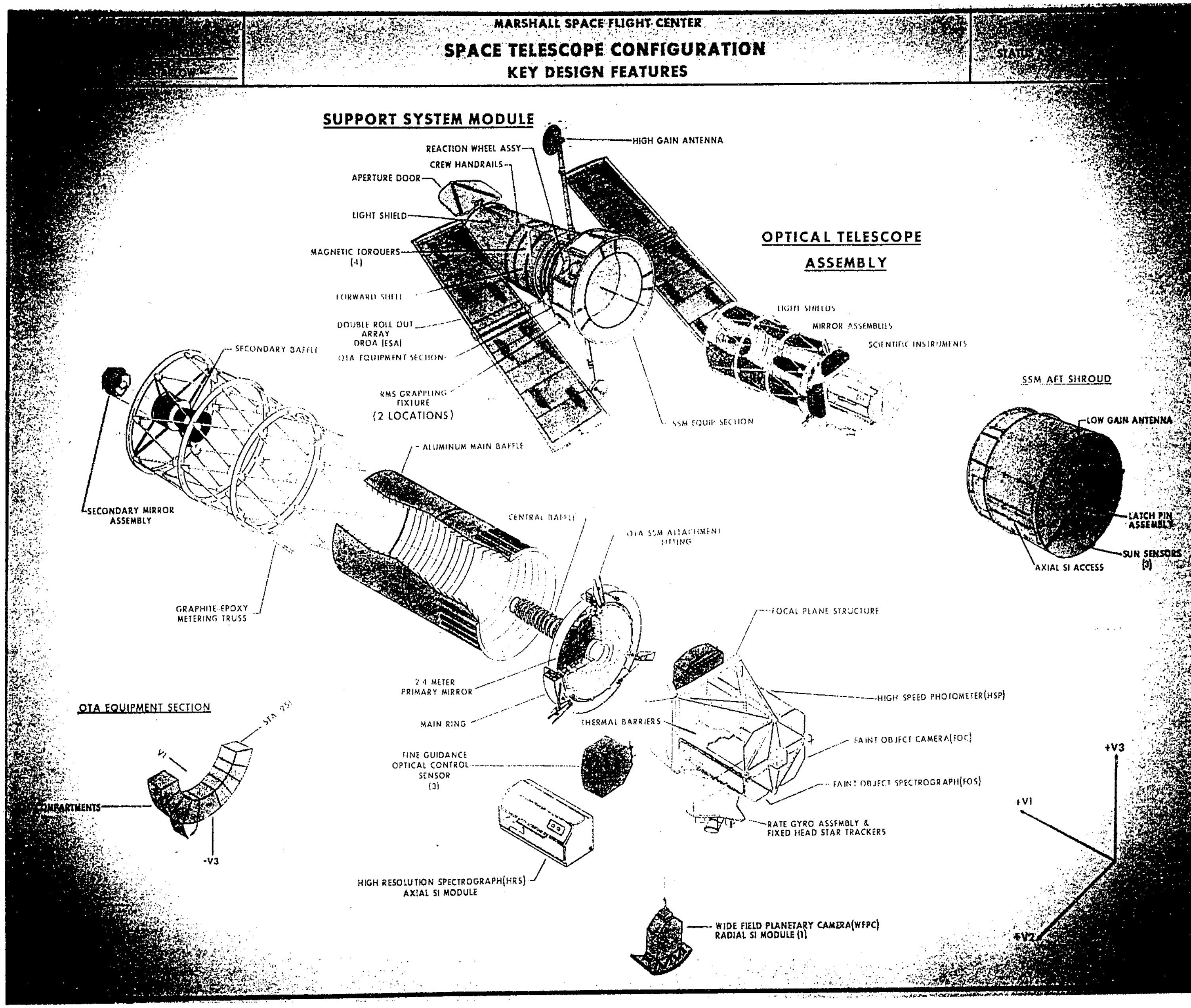


Figure 27. Science instruments.

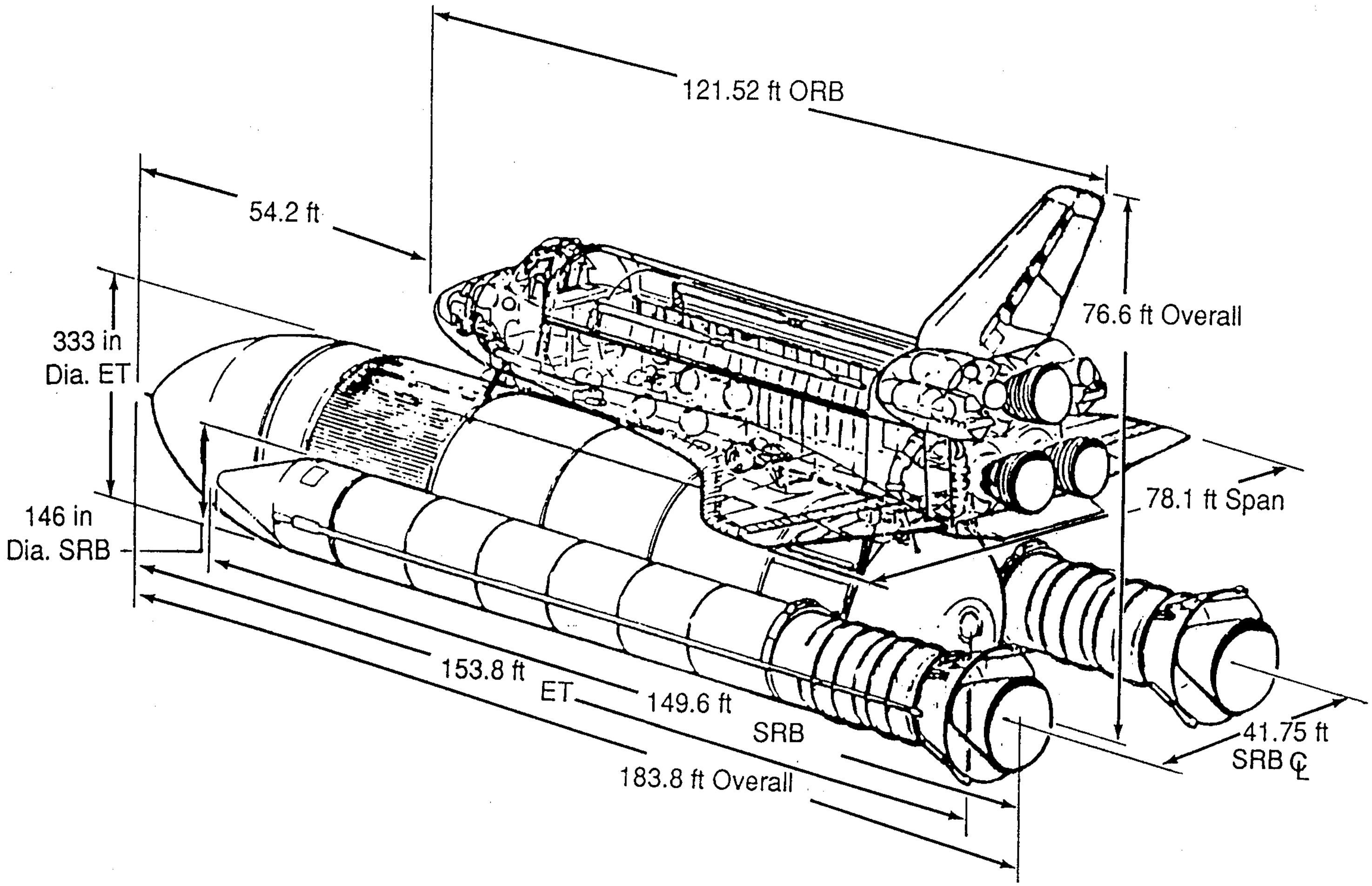
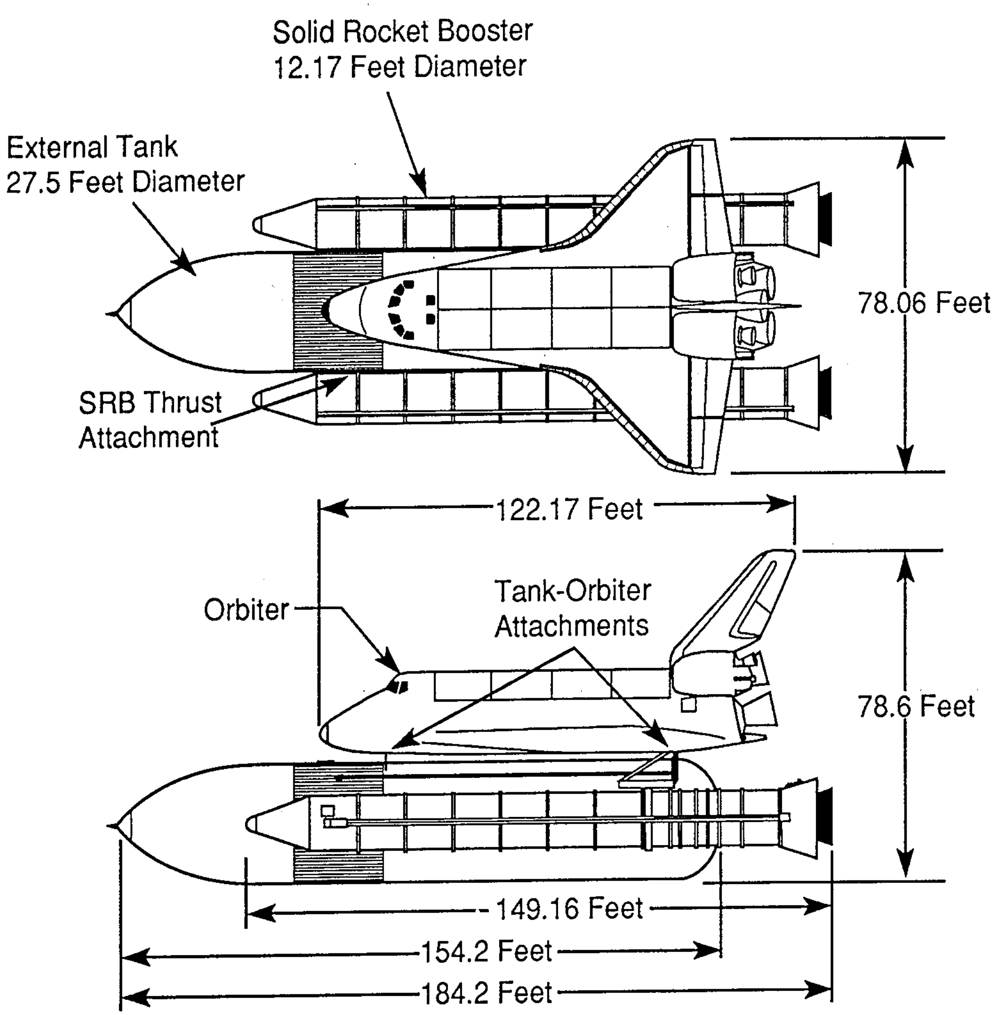


Figure 28. Space shuttle.



Orbiter Weight in Pounds (Approximate)		
Orbiter Vehicle (OV)	Total Dry Weight With Three Space Shuttle Main Engines	Total Dry Weight Without Three Space Shuttle Main Engines
OV-102 Columbia	178,289	157,289
OV-103 Discovery	171,419	151,419
OV-104 Atlantis	171,205	151,205
Solid Rocket Booster Weights in Pounds (Approximate)		
1,300,000, Each at Launch (Propellant Weight 1,100,000, Each). Inert Weight 192,000, Each.		
External Tank Weight in Pounds (Approximate)		
1,655,600 With Propellants, Inert Weight 66,000.		

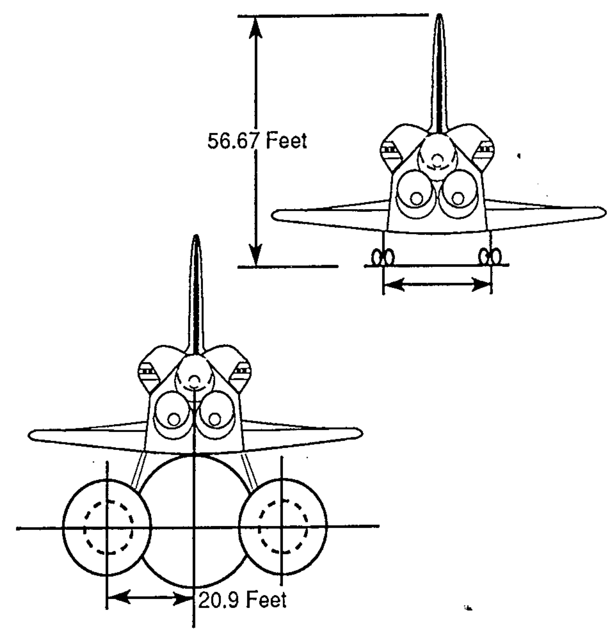


Figure 29. Space shuttle weights.

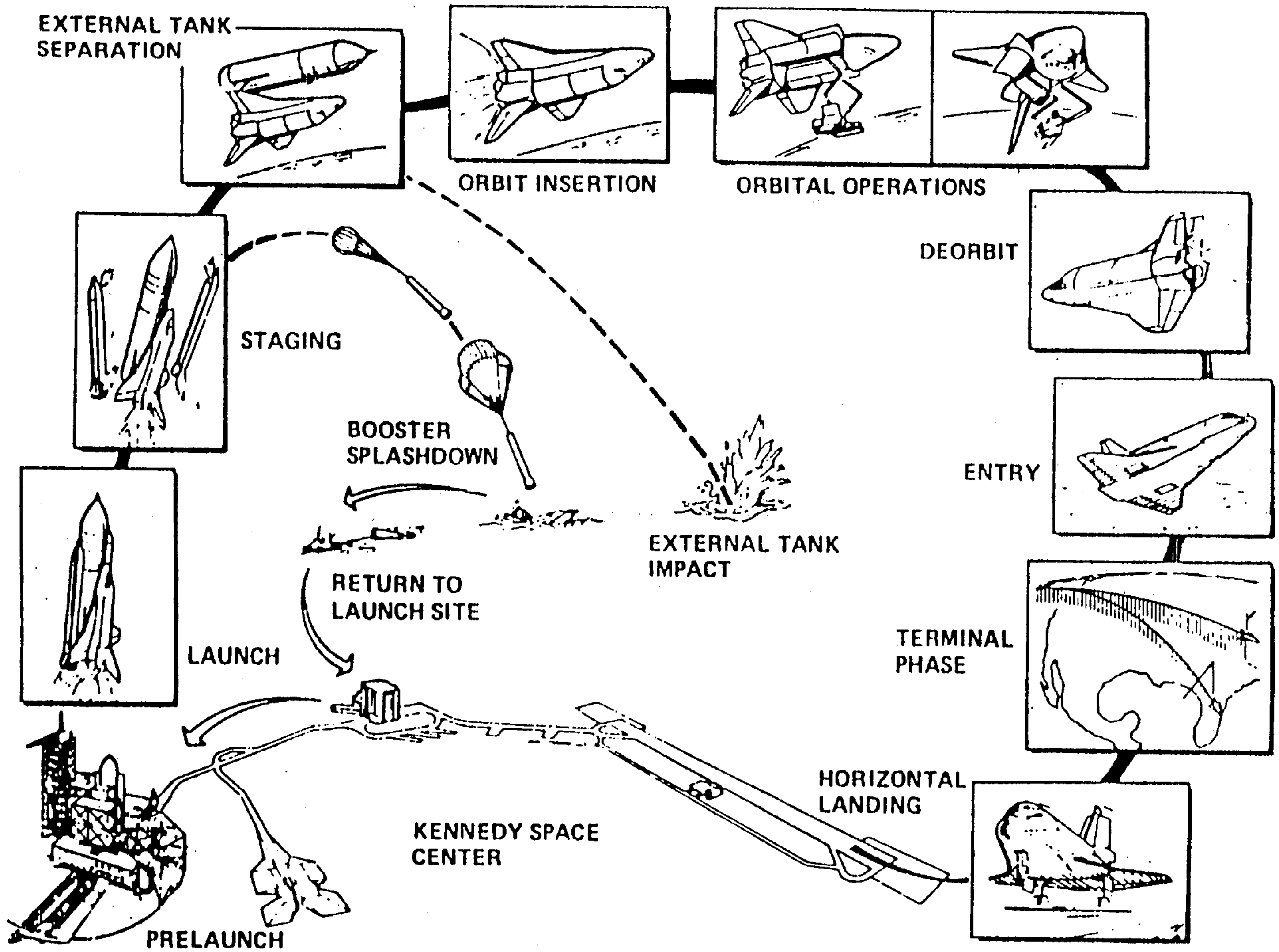


Figure 30a. Typical shuttle mission profile.

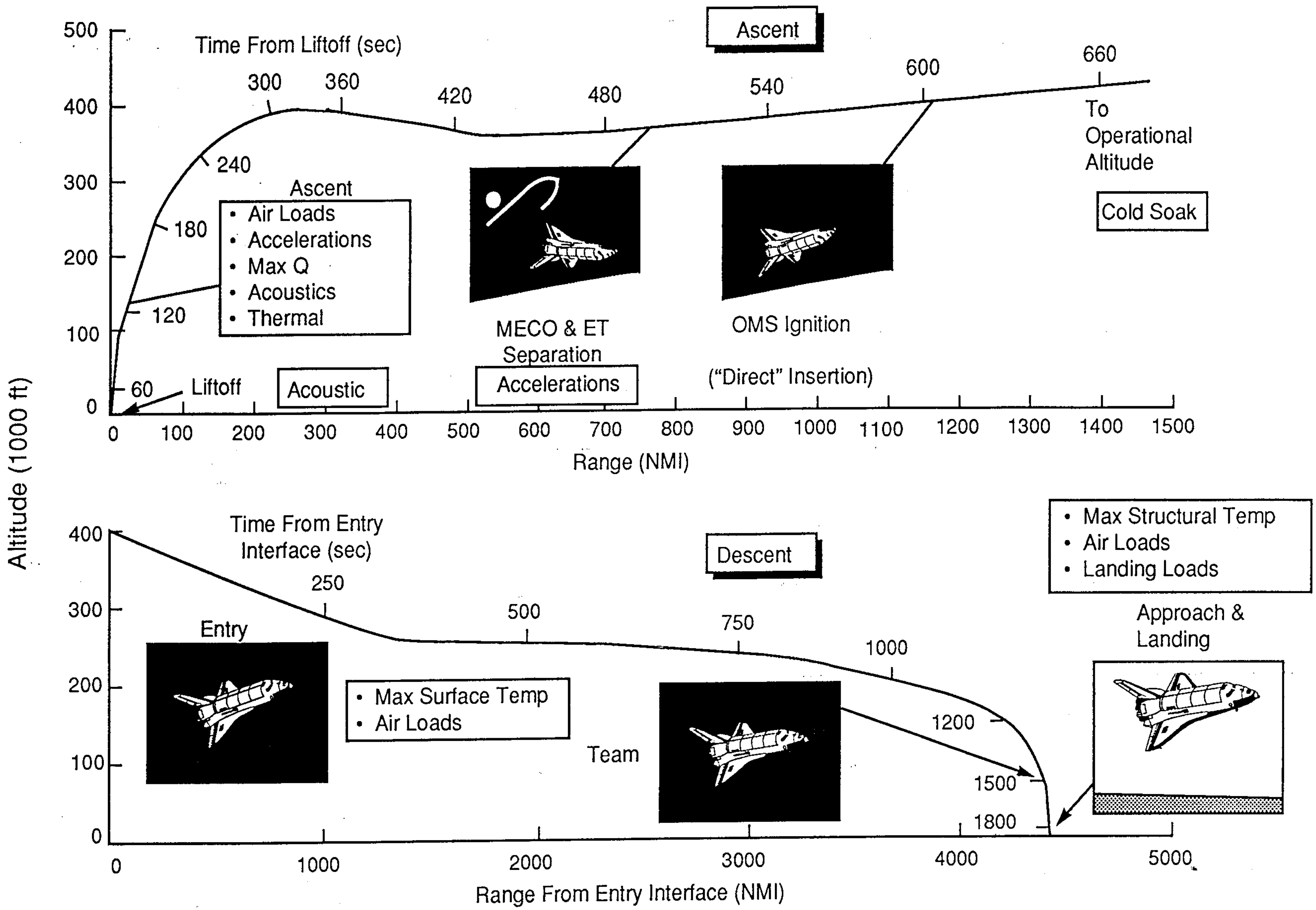


Figure 30b. Typical ascent and descent trajectory profiles.

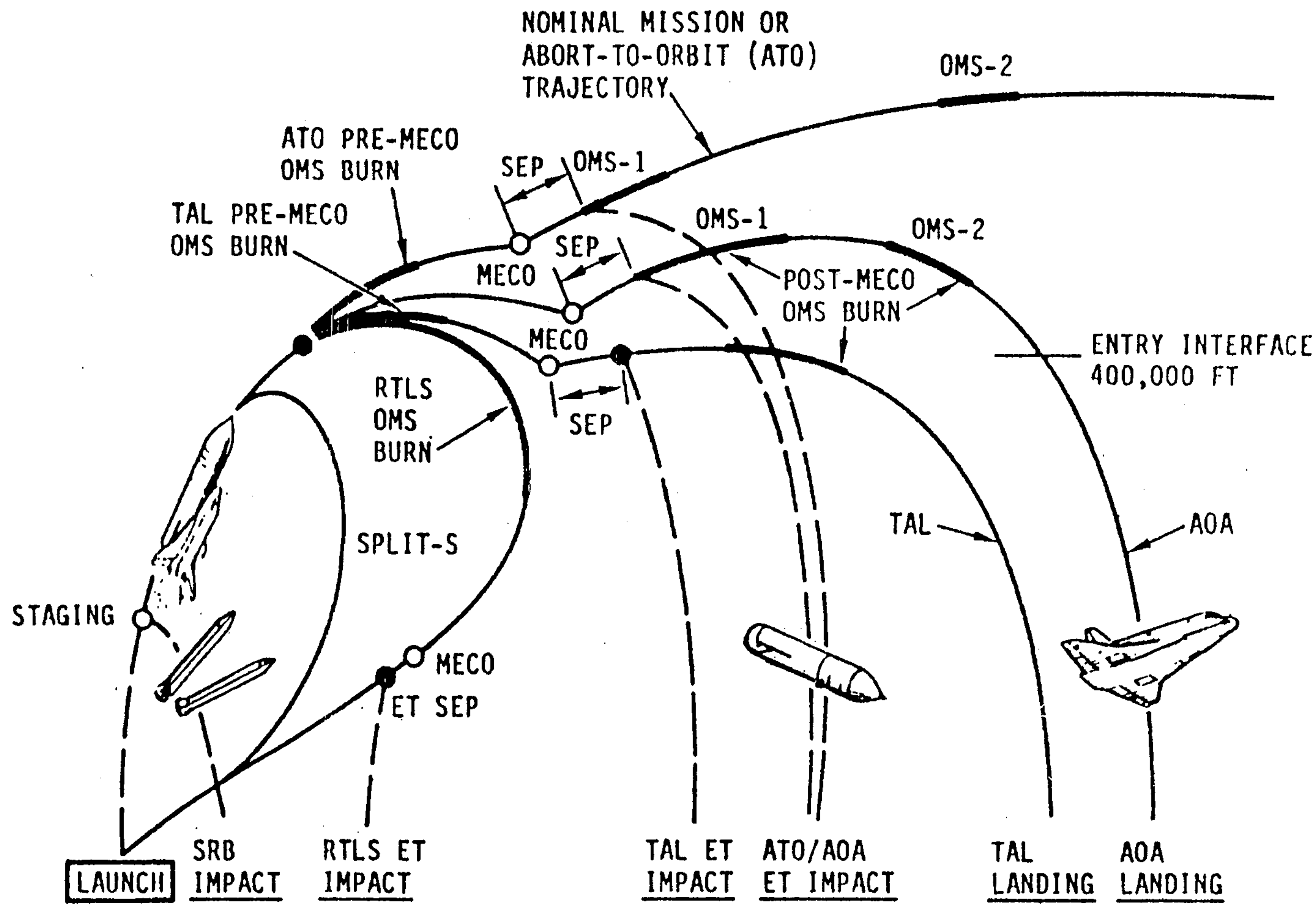


Figure 30c. Typical shuttle abort characteristics.

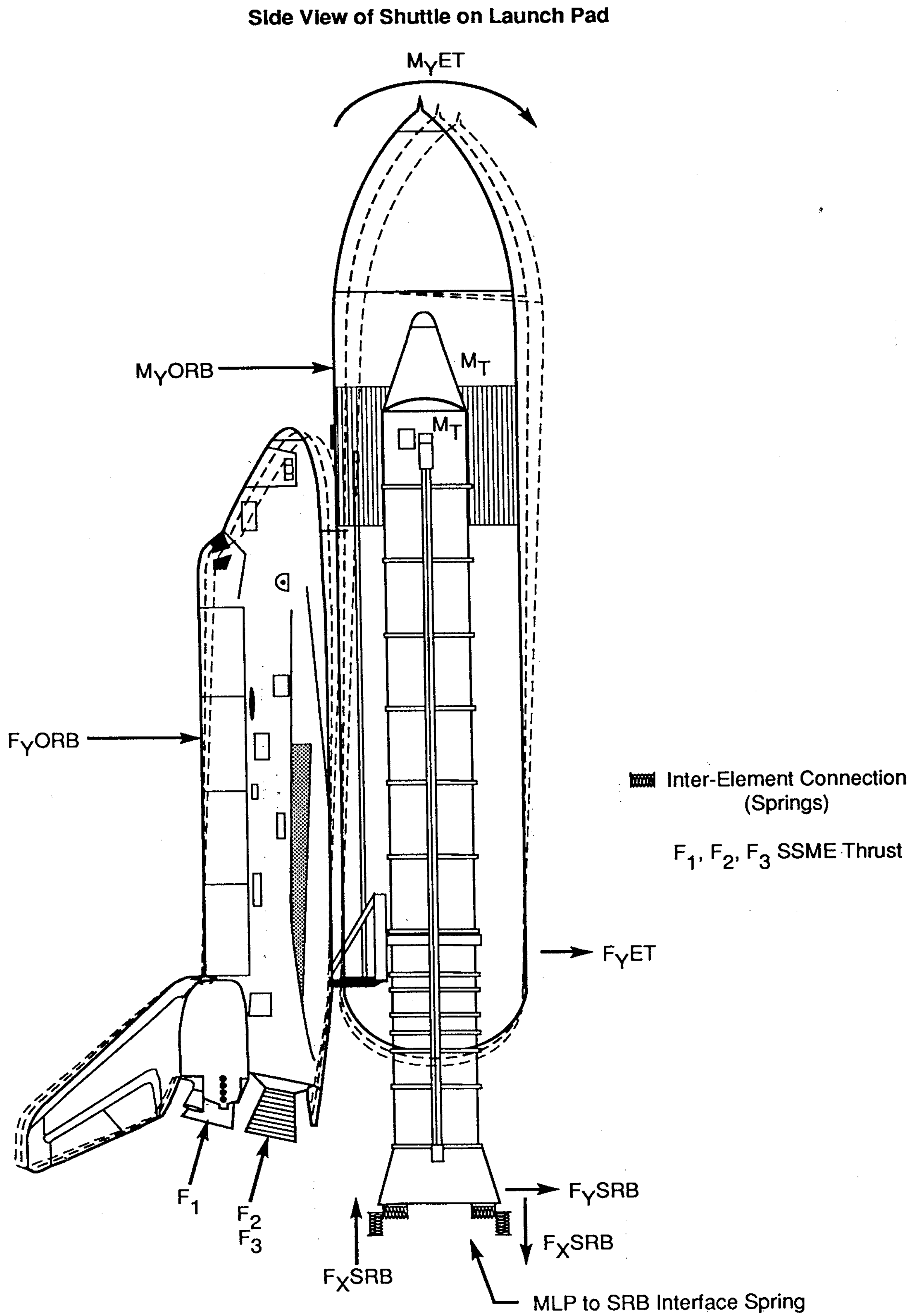


Figure 31. Preliftoff side view.

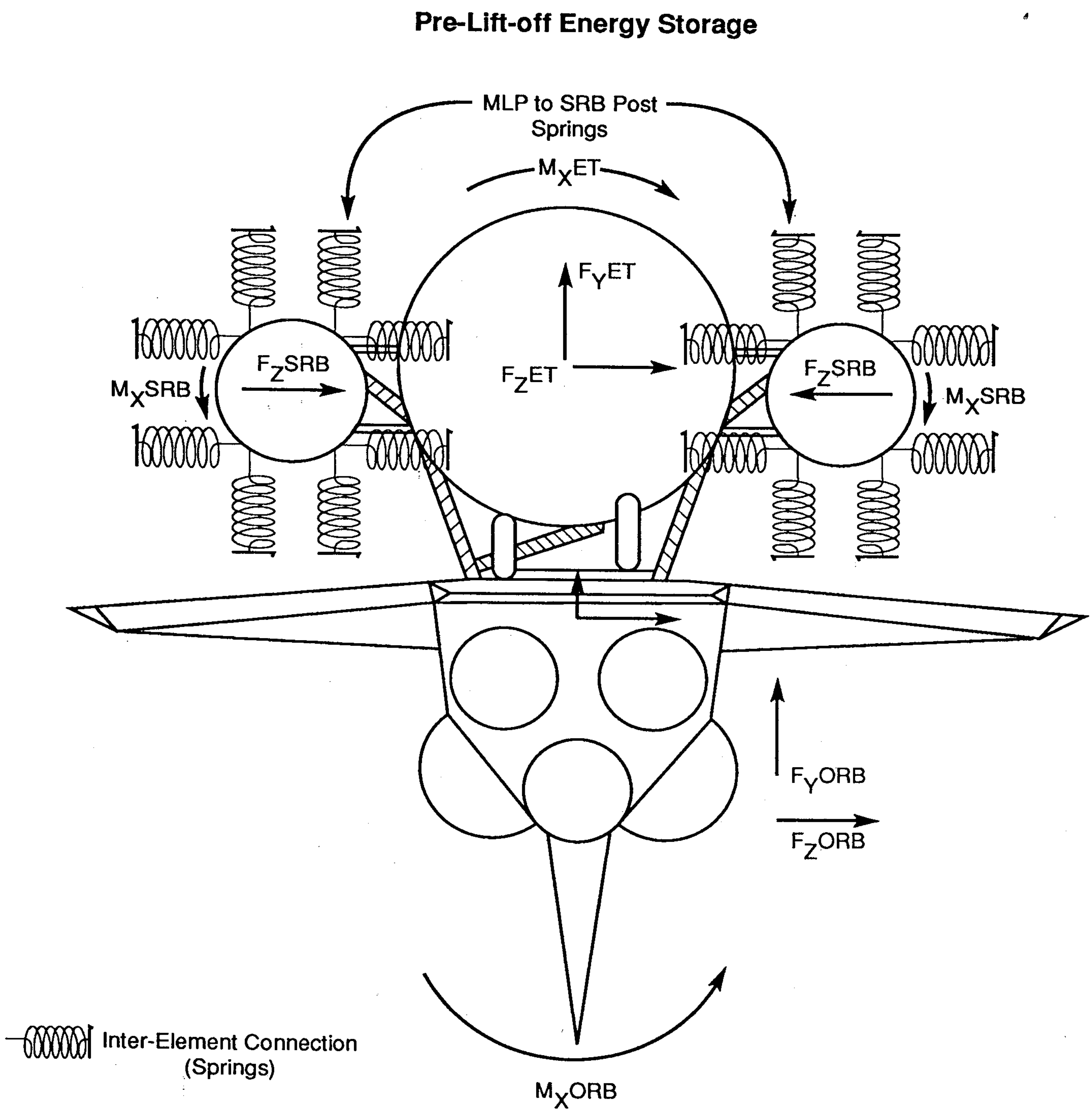
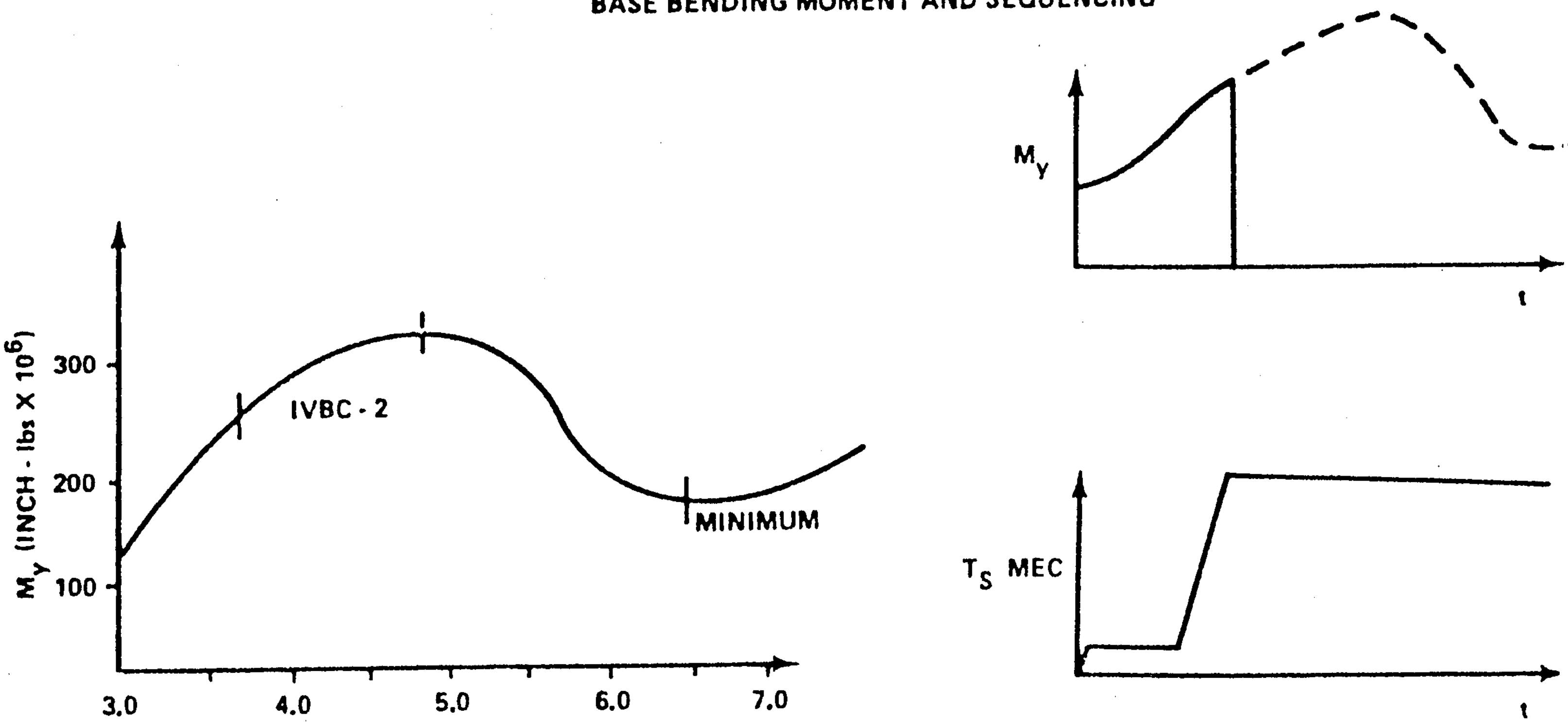


Figure 32. Preliftoff top view.

SHUTTLE LIFT-OFF LOADS COMPLEXITY

BASE BENDING MOMENT AND SEQUENCING



SEQUENCING

- SSME THRUST 90% ON ALL ENGINES – SRB IGNITION TIME BASE
- LAGS UNTIL SRB IGNITION
  - CHECKS IN SYSTEM
  - DELIBERATE OR PLANNED DELAYS

Figure 33. Shuttle liftoff sequence.

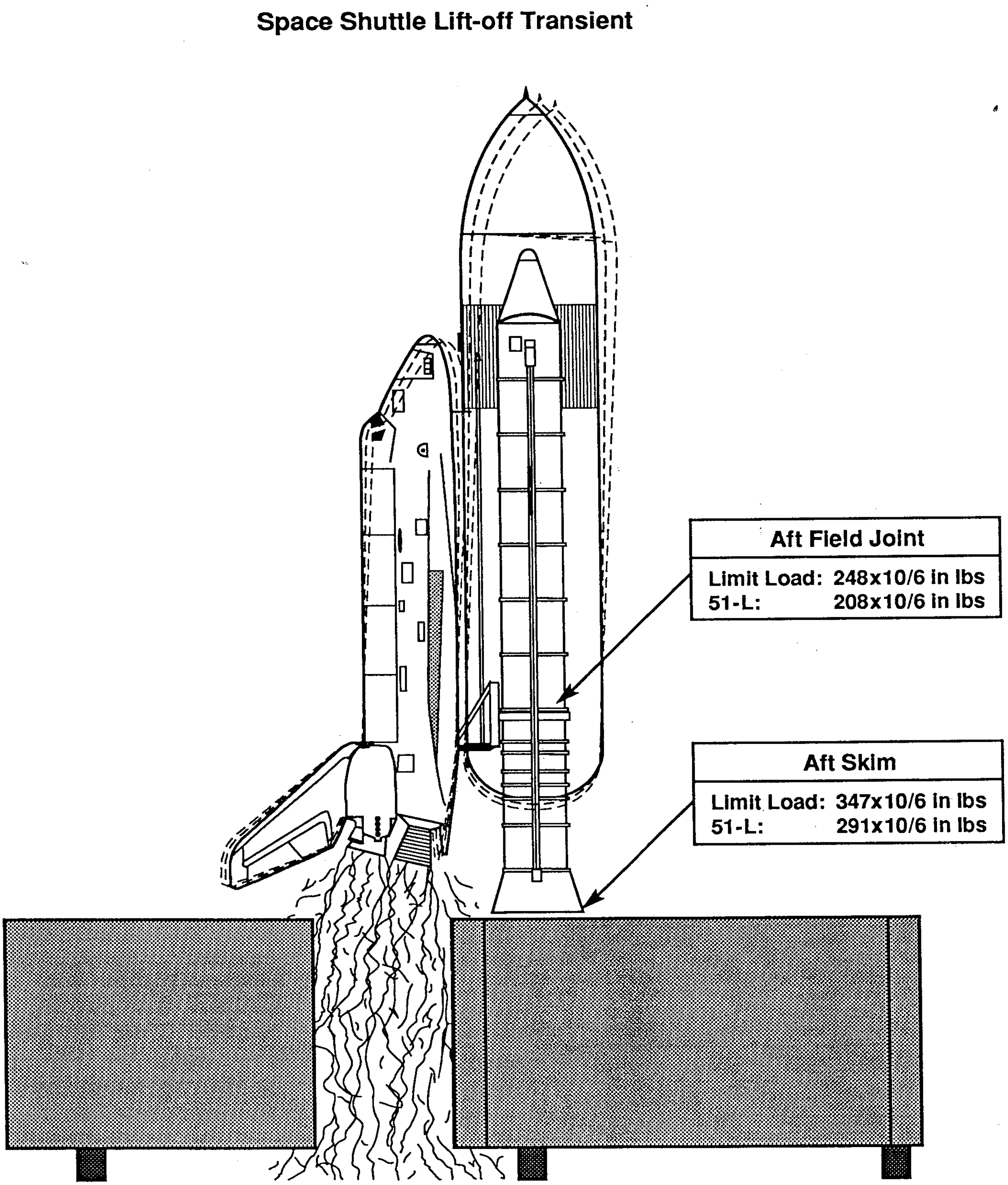
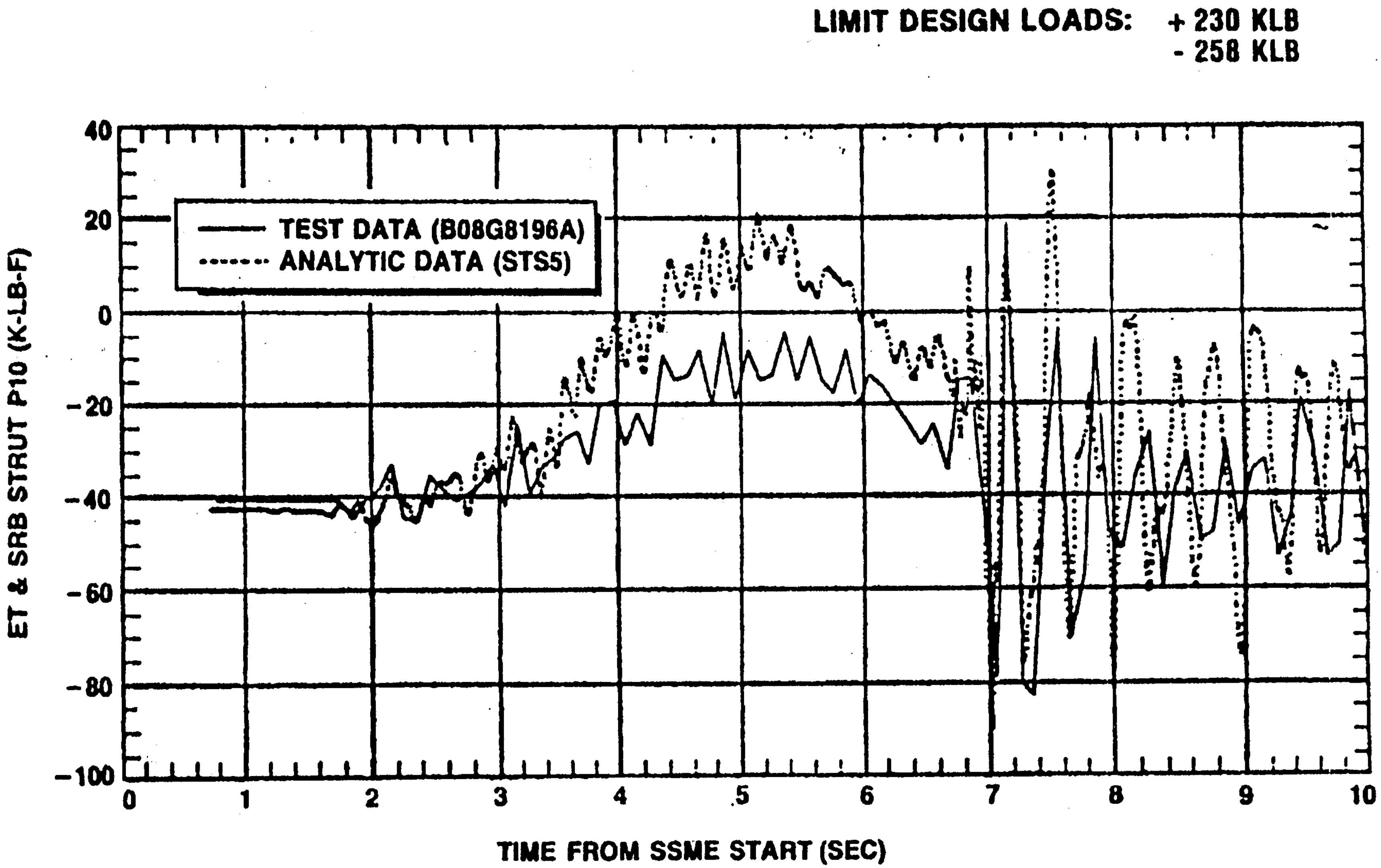
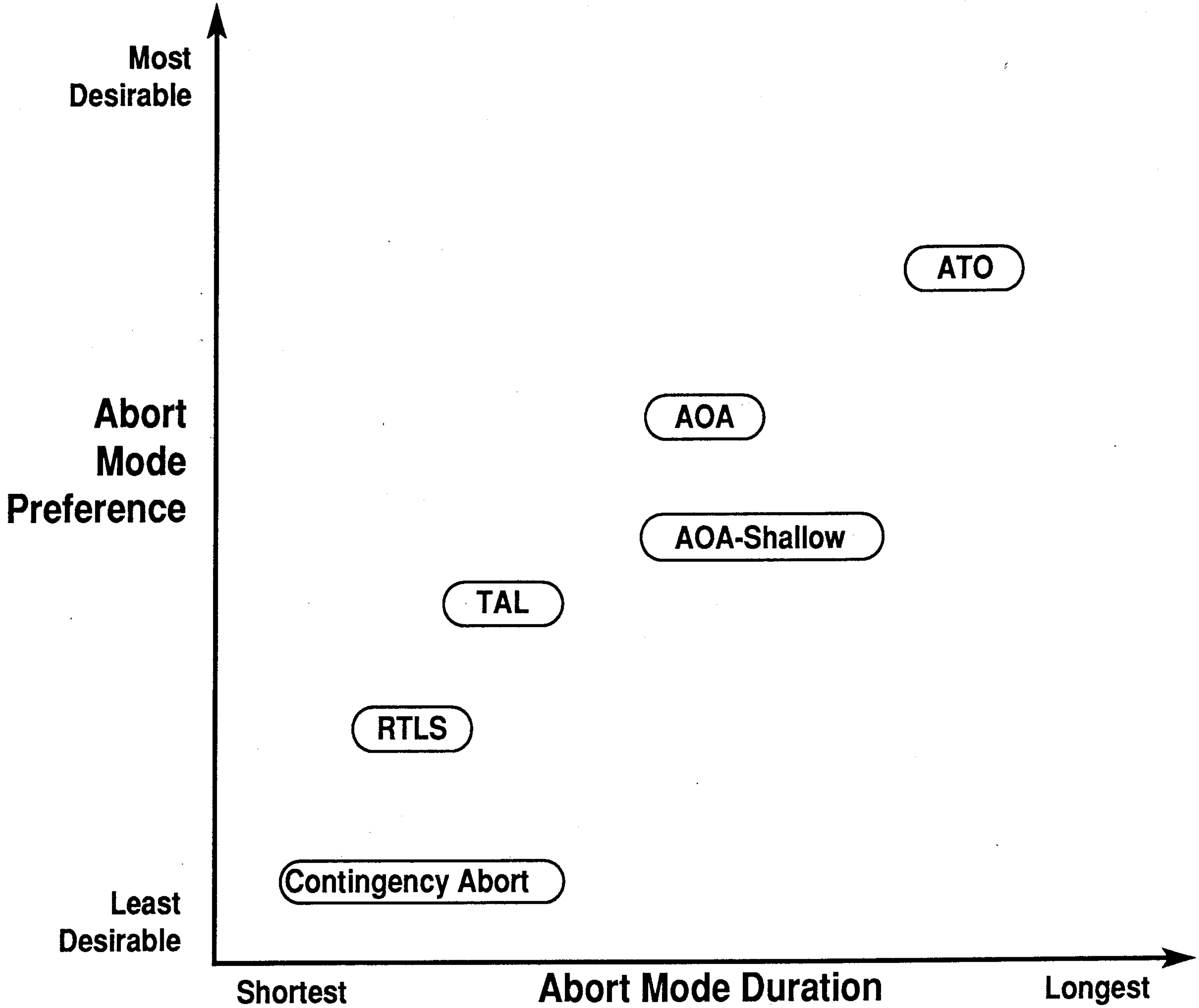


Figure 34a. Shuttle liftoff strut load response.



ANALYTIC AND FLIGHT-MEASURED ATTACH LOADS FOR STS-5 LIFTOFF

Figure 34b. Shuttle liftoff strut load response.



Relative Duration and Order of Preference for Abort Modes

Figure 35. Shuttle abort modes.

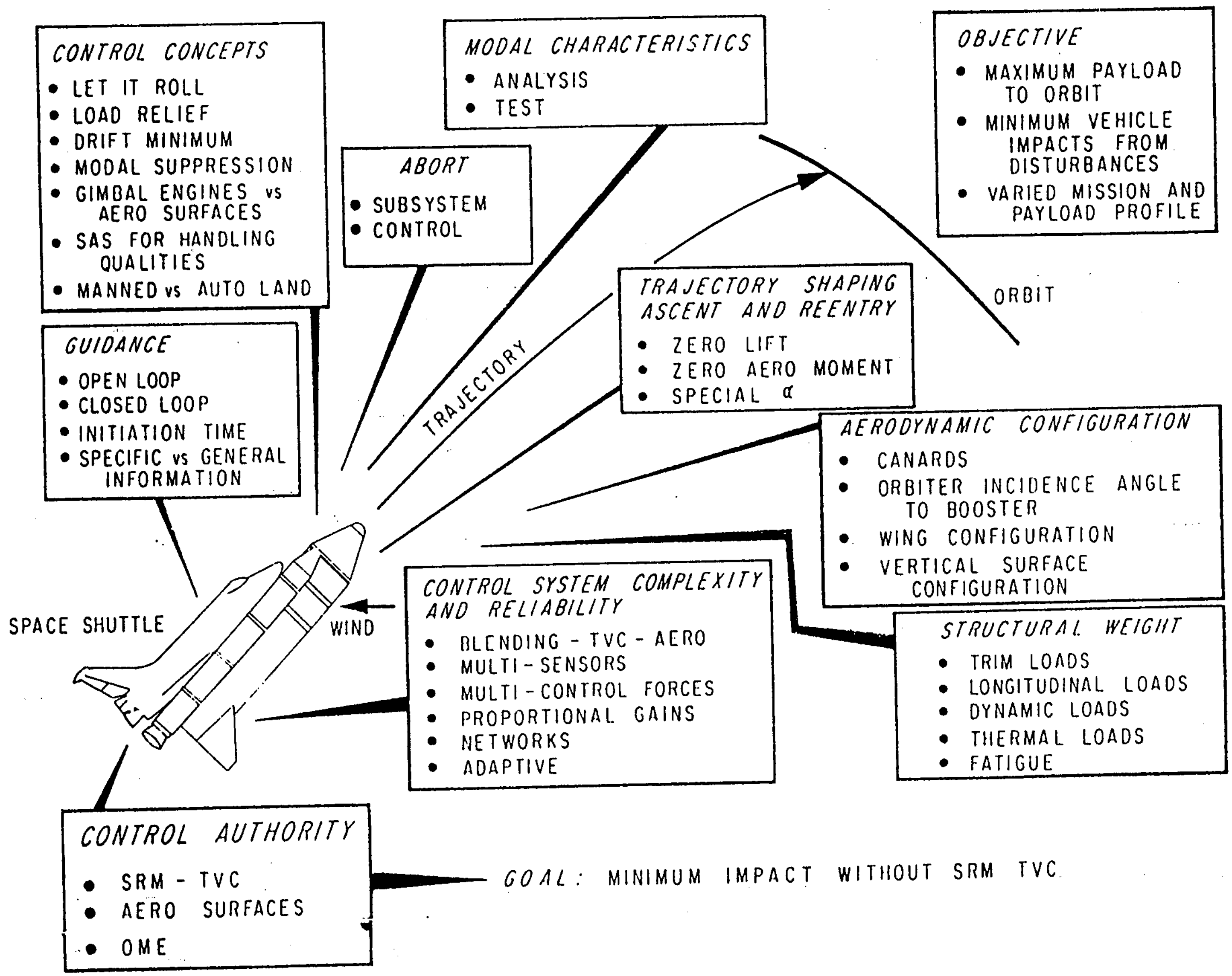


Figure 36. Key shuttle issues.

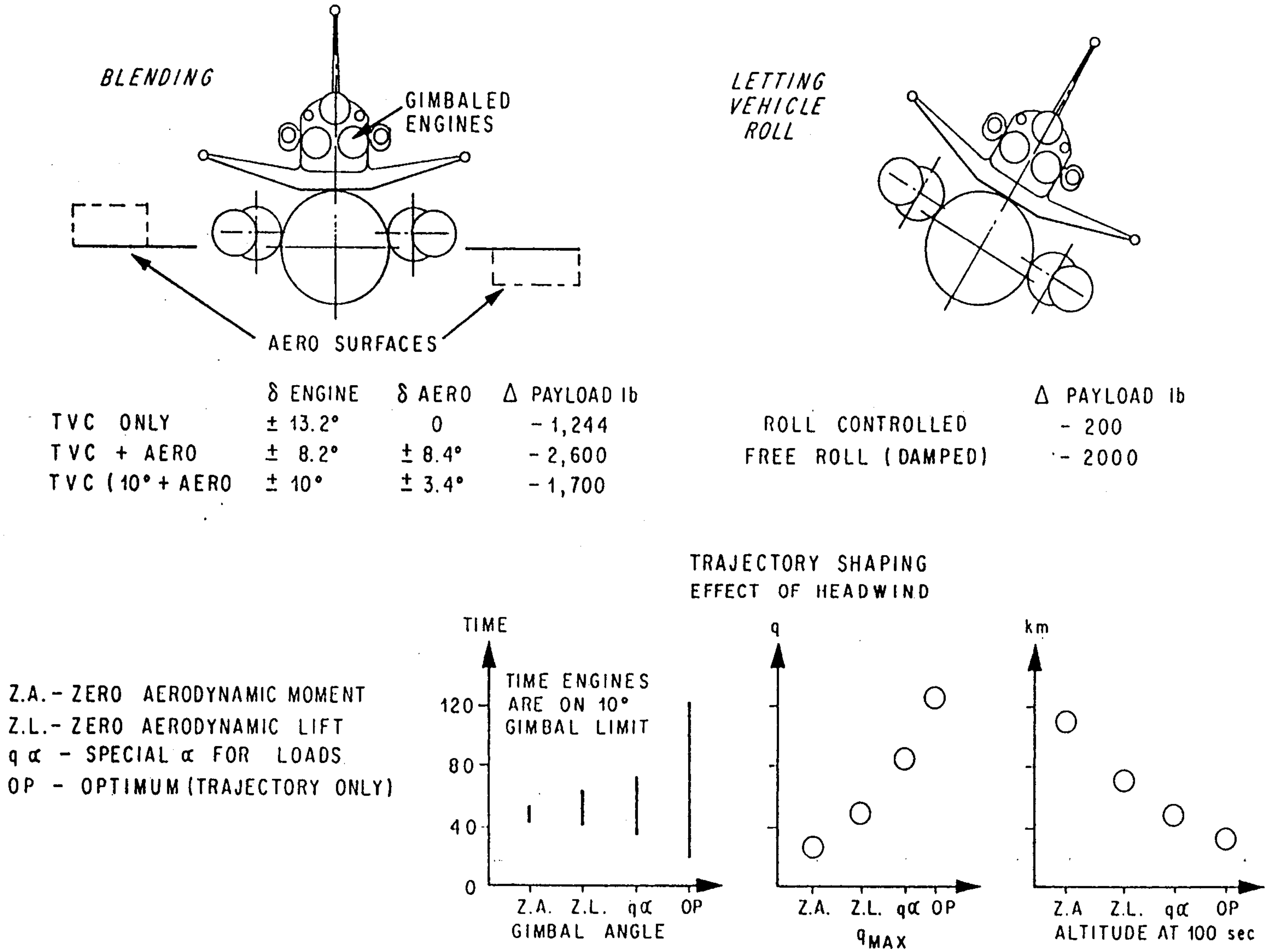


Figure 37. Shuttle trajectory and control concepts.

DYNAMIC CHARACTERISTICS

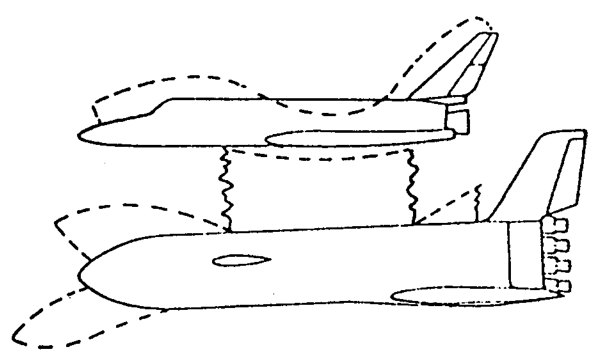
- SEVERAL BODIES, SPRING COUPLED
- MULTI-PROPULSION SYSTEMS
- HIGH MODAL DENSITY-3 DIMENSIONAL - UNCERTAIN PREDICTION
- COMPLEX DYNAMICS ANALYSIS AND TEST

AERODYNAMICS

- GENERALLY VERY STABLE
- GUSTS CAUSE LARGE DYNAMIC RESPONSES
- YAW - ROLL COUPLING

CONTROL PROBLEMS

- TRAJECTORY, STRUCTURAL, CONTROL COUPLING REQUIRES COMPLEX CONTROL FORCE SOURCES
- ADAPTIVE MODE SUPPRESSION
- BLENDING MULTIPLE SENSORS, CONTROL FORCES, DYNAMIC COMPONENTS
- YAW - ROLL COUPLING



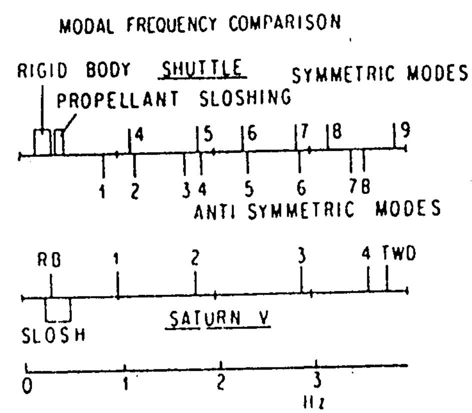
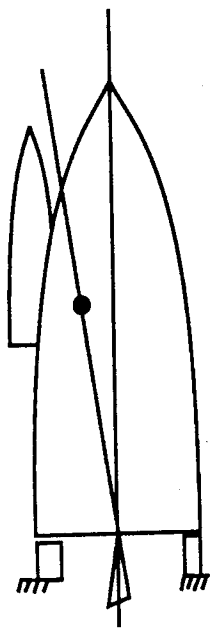


Figure 38. Shuttle dynamic and control trades.

Vertical Orientation

Lateral Acceleration at Liftoff
if Engines Gimabled to Give
Minimum Rotational Transient

or Rotational Transient if Engines
Not Gimabled



Non Symmetric Support and
Holddown Forces

Common Problems

Static Bending Due to Weight
and Wind at Release Leading
to "Twang"

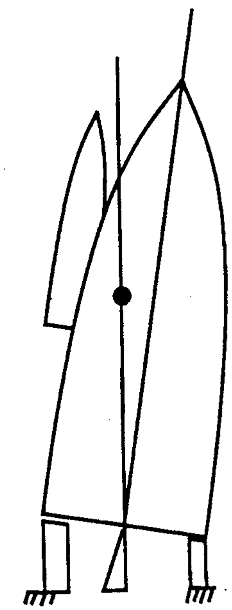
Complicated Geometry to Track-
Such as Wing Tip Below Pedestal

Holddown Orientation with Respect
to Prevailing Winds

Large Aerodynamic Lifting
Surfaces

Tilted Orientation

More Vertical Liftoff



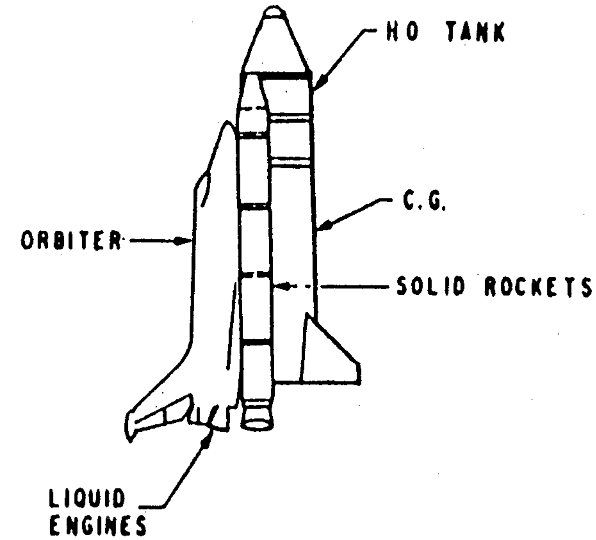
More Complicated Holddown

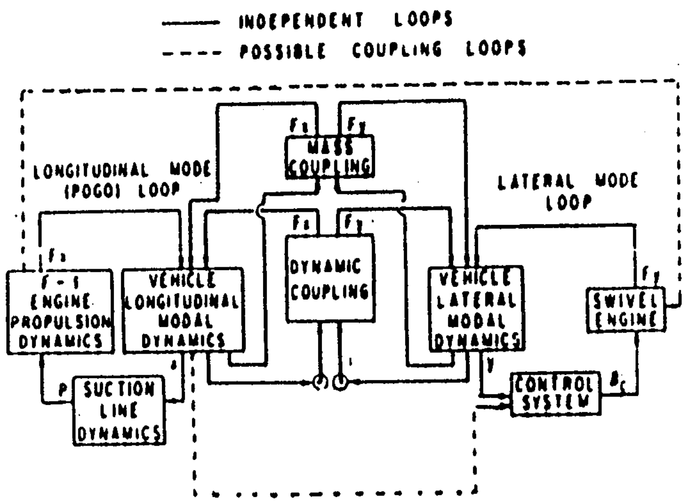
Possibly More Complicated
Reference Alignment and
Control Axis Reference

Possible Fuel Fill Problems

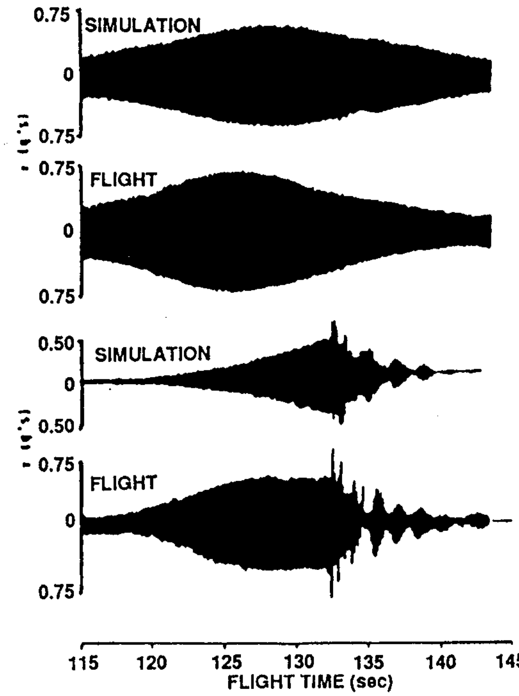
Figure 39. Shuttle liftoff considerations.

HULA POGO





BLOCK DIAGRAM OF LONGITUDINAL AND LATERAL SYSTEM



COMPARISON OF SIMULATION AS-502 FLIGHT RESULTS FOR LATERAL AND LONGITUDINAL LEM ACCELERATIONS RESULTING FROM POGO.

SHUTTLE HAS LARGE POTENTIAL FOR HULA POGO DUE TO STATIC AND DYNAMIC MASS COUPLING (PITCH PLANE ASSYMETRIES)

Figure 40. Hula POGO.

Pre:

Manned vs. Unmanned

Initial:

65 k Payload, Maximum 60 ft Length x15 ft Diameter
Flyback Booster
600 k to 700 k Liquid Engine (Booster and Orbiter)
Orbiter Ferrying Capability
$14B Cost
All-Weather Auto Land, etc.
Cross-Range

Mid:

Constraint on Cost
Elimination of Flyback Booster, Orbiter Ferrying

- Pressure Fed
- Liquid
- Solid

Selection:

1 1/2 Stage Parallel Burn Solid Boosters
Water-Recoverable Boosters
65 k Payload, 60 ft Length x15 ft Diameter (Maximum)
SSME Thrust 470,000 VAC, ISP 453 (High Efficiency, Low Weight, High Technology)
Passive Orbiter Heat Protection Tiles (High Technology)
Modified Delta Wing
Expendable Propulsion Tanks (ET)

Figure 41a. Shuttle evolution.

Constraints:

150 klb Orbiter
$5.5B Cost
Dynamic Pressure (“Q”)
Max “G”
Abort
ET Disposal

Reentry Designs Orbiter
SRB Water Recovery
Expendable External Tank
Reduced Analysis and Test
Volumetric/Weight of Engine
Performance Reserve Allocation

Constraints Impact:

Orbiter Could Not Meet 150 k (165 k) → 180 k → 190 k Inert
- 104% and 109% SSME (Operational)
- Lightweight Tank
- Lightweight Higher Performance Solid

Overpressure
Water Suppression
High Acoustics
Payload at Noise Source
Unsymmetrical Multibody Nonvertical Lift-Off; Stored Energy Release
Strongly Coupled Ascent

Operational Impacts:

Dynamic Pressure
Loads
Ice (Damage to Tiles)
Performance (Payload to Orbit)
Temperature
Weather
Launch Probability
Additional Analysis, etc.

Figure 41b. Shuttle evolution.

Sensitive or Marginal System

- SSME Lifetime (Refurbishment and Maintenance) (Process Control and Inspections)
- Orbiter Tiles (Debris Damage) (Refurbishment)
- Extensive Redesign
- Specific Mission Trajectory Shaping
- Detailed Launch Simulation Go – No Go
- Costly Operations Including Launch Holds
- Marginal SRB Skirt (Flight Instrumentation, Puck Biasing, Inspection)
- SRB/SRM Refurbishment

Under Consideration:

- ASRM with 12,000 lb Performance Improvement
- Engine Upgrades
  - Two-Duct Hot Gas Manifold
  - Large MCC Throat
  - MCC Casting
  - Weld Eliminations
  - Alternate Turbopumps

Figure 41c. Shuttle evolution.

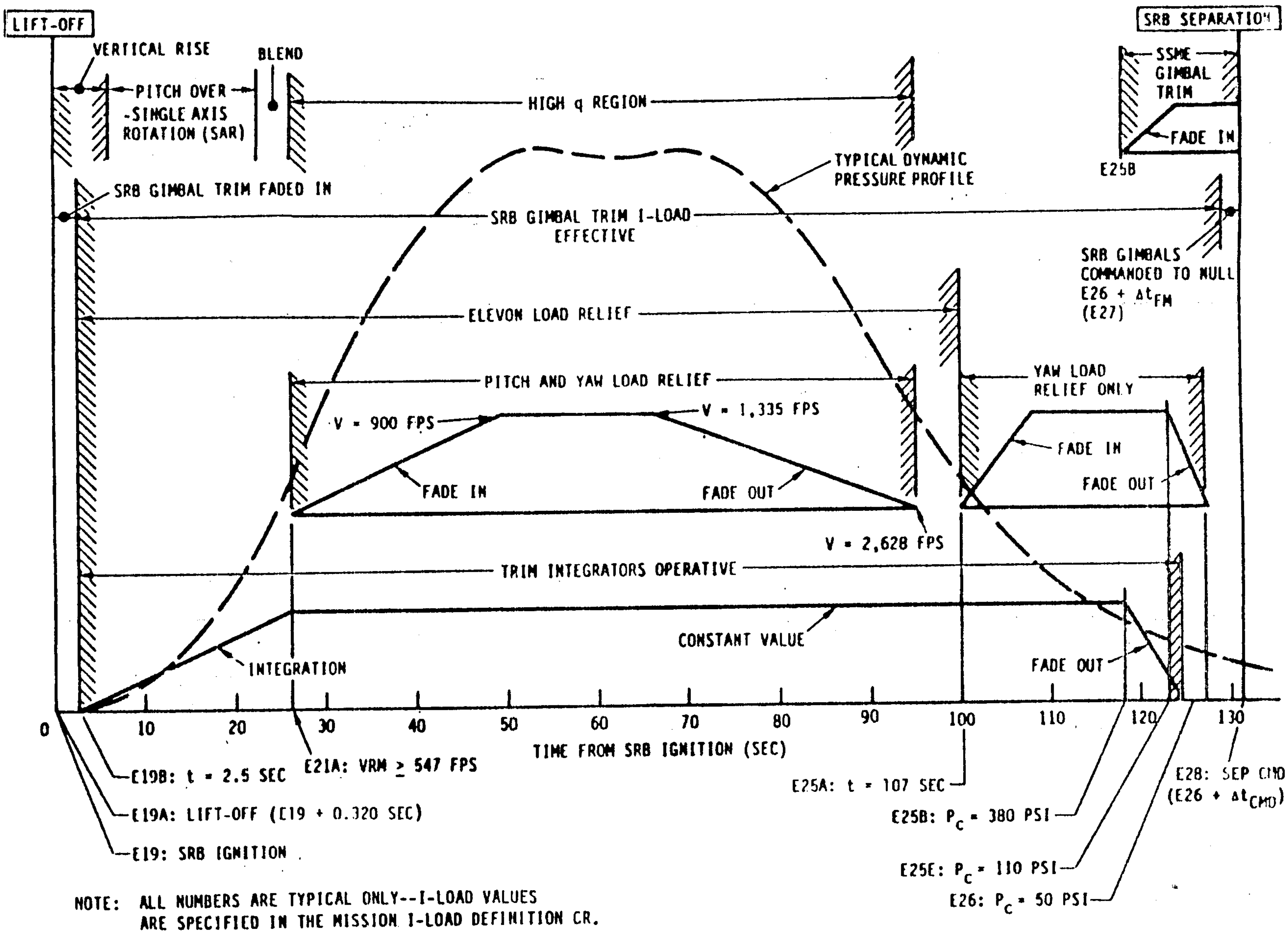


Figure 42. Max "q" coupling phasing.

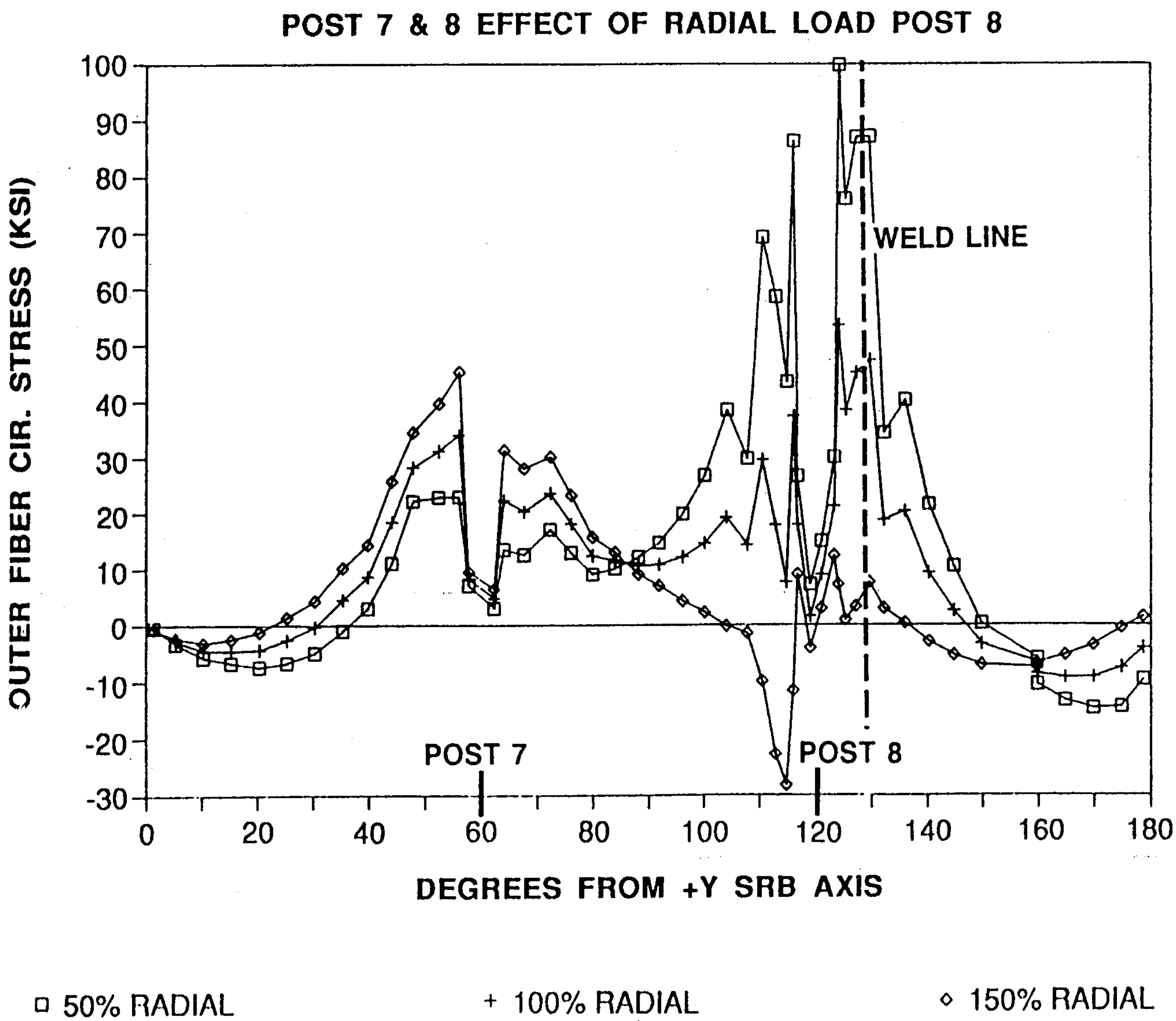


Figure 43. Aft skirt radial load sensitivity.

● **Aft Skirt Post With Axial, Radial & Tangential Load**

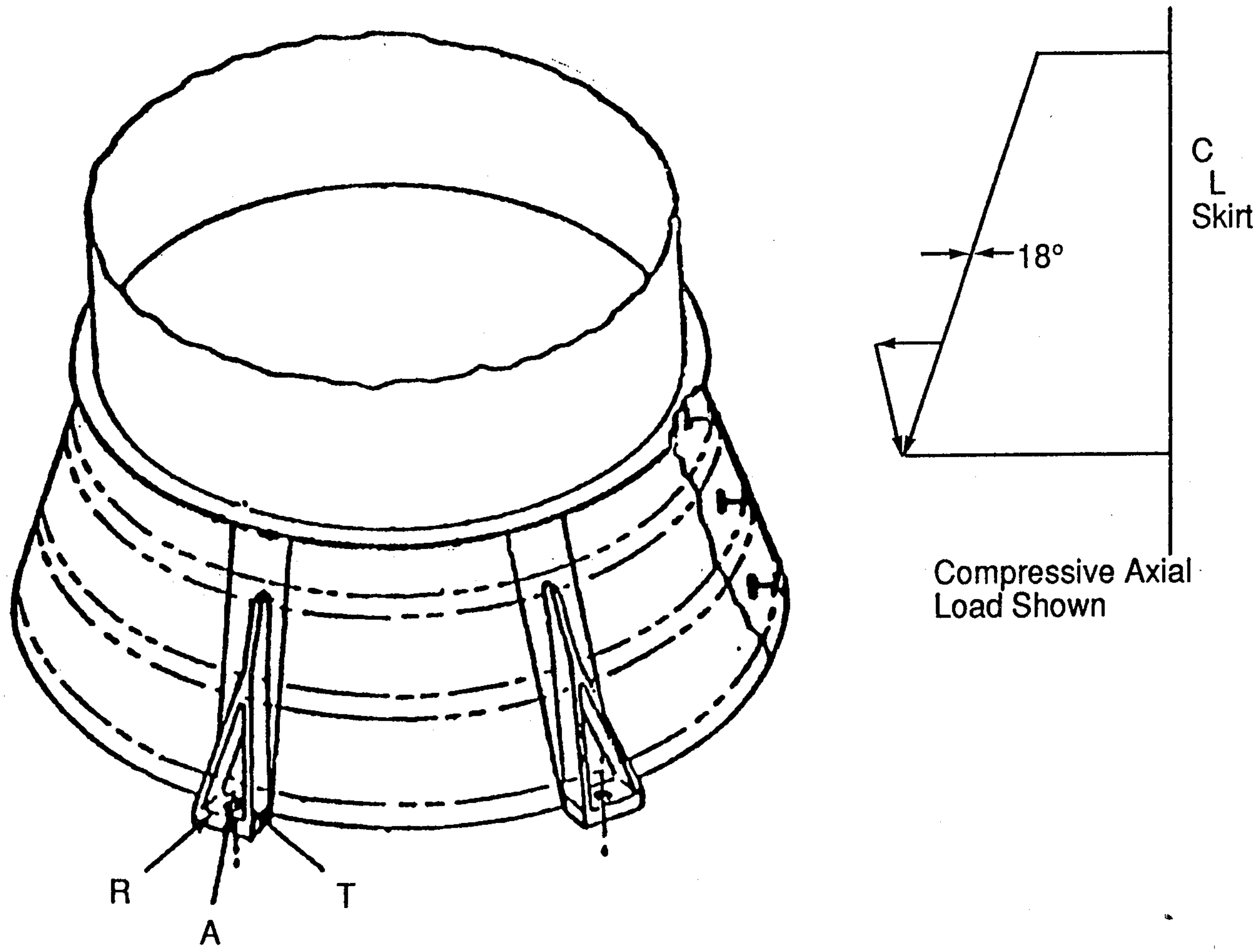


Figure 44. SRB skit load path.

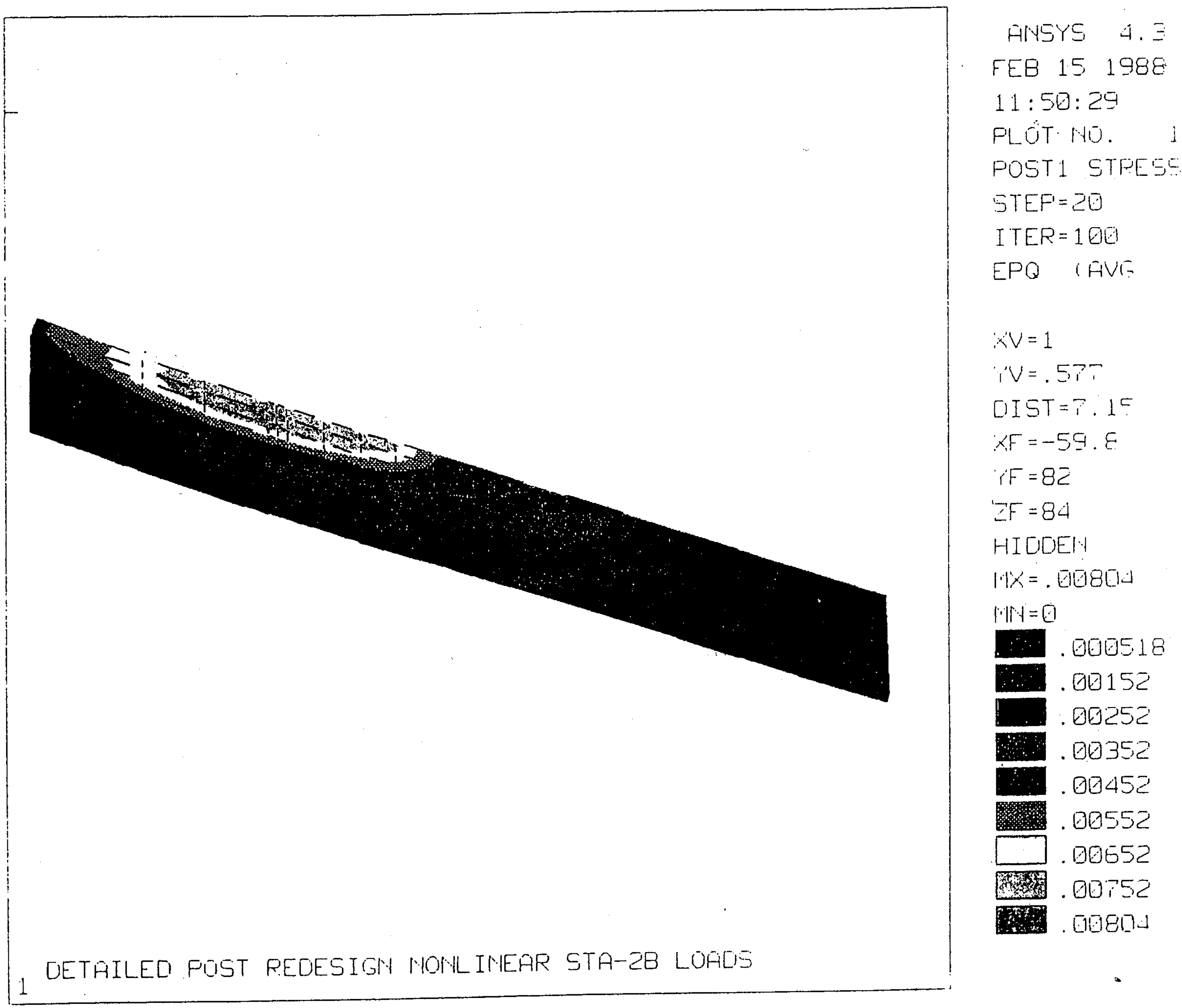


Figure 45. SRB skirt stress distribution through skin.

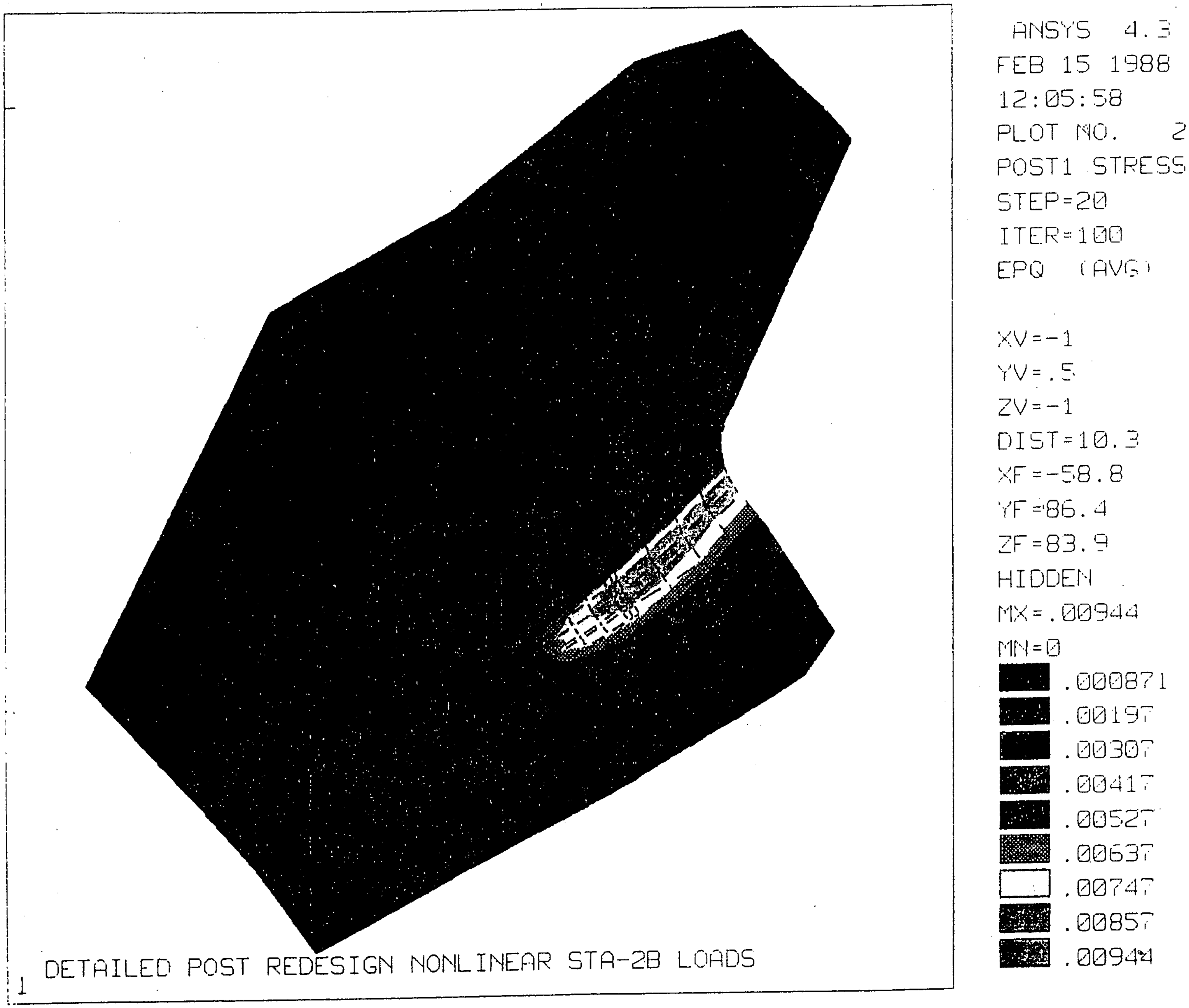


Figure 46. SRB skirt stress distribution along skin surface.

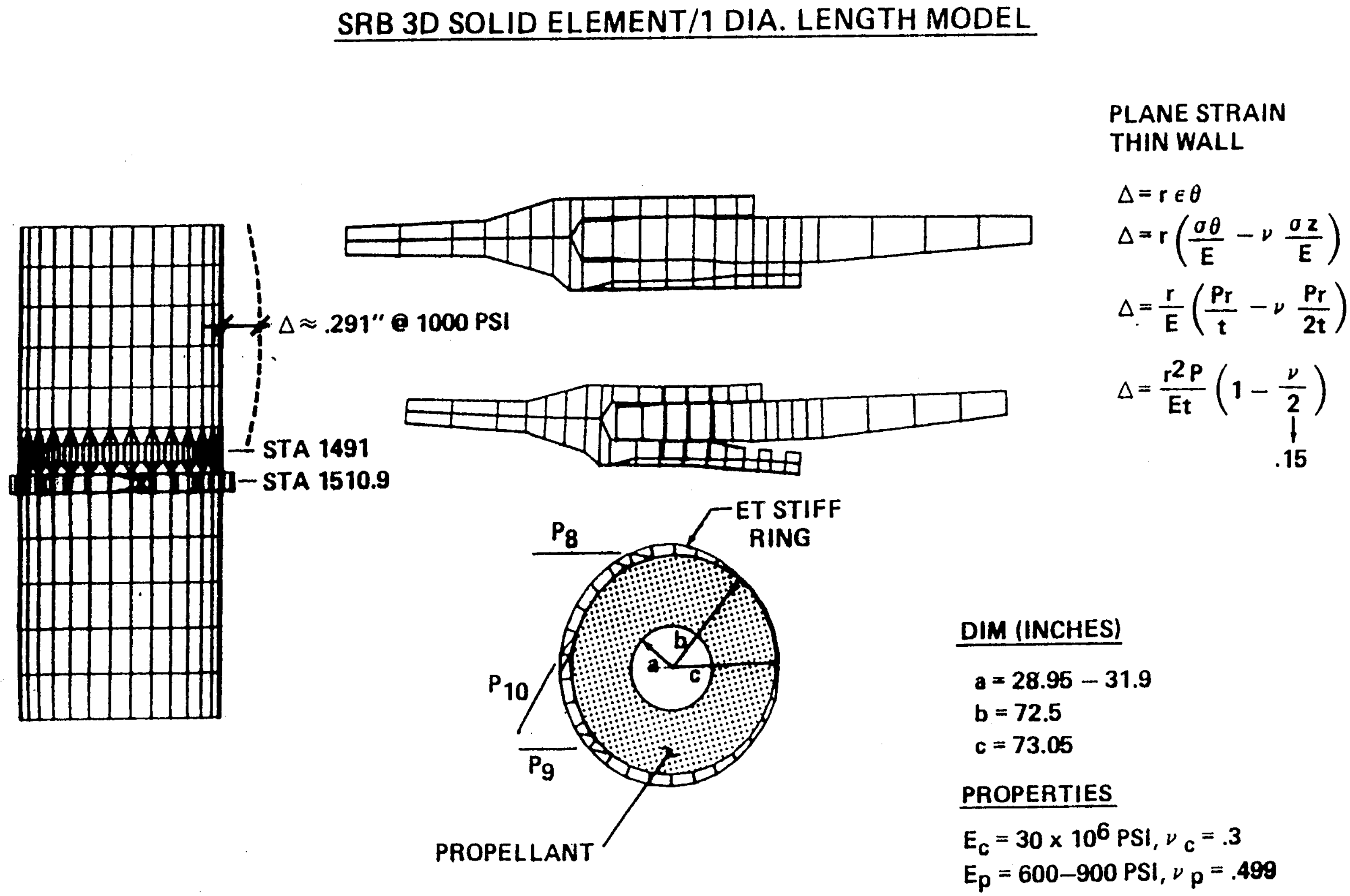


Figure 47. SRM o-ring/segment joint.

ED5285

ORGANIZATION: NASA/ED22	MARSHALL SPACE FLIGHT CENTER	NAME: J. TOWNSEND
CHART NO.: 25	51–L ANALYSIS OVERVIEW	DATE: APRIL 25, 1986

DETAIL REGION A -- STS 51–L RIGHT SRM FIELD JOINTS

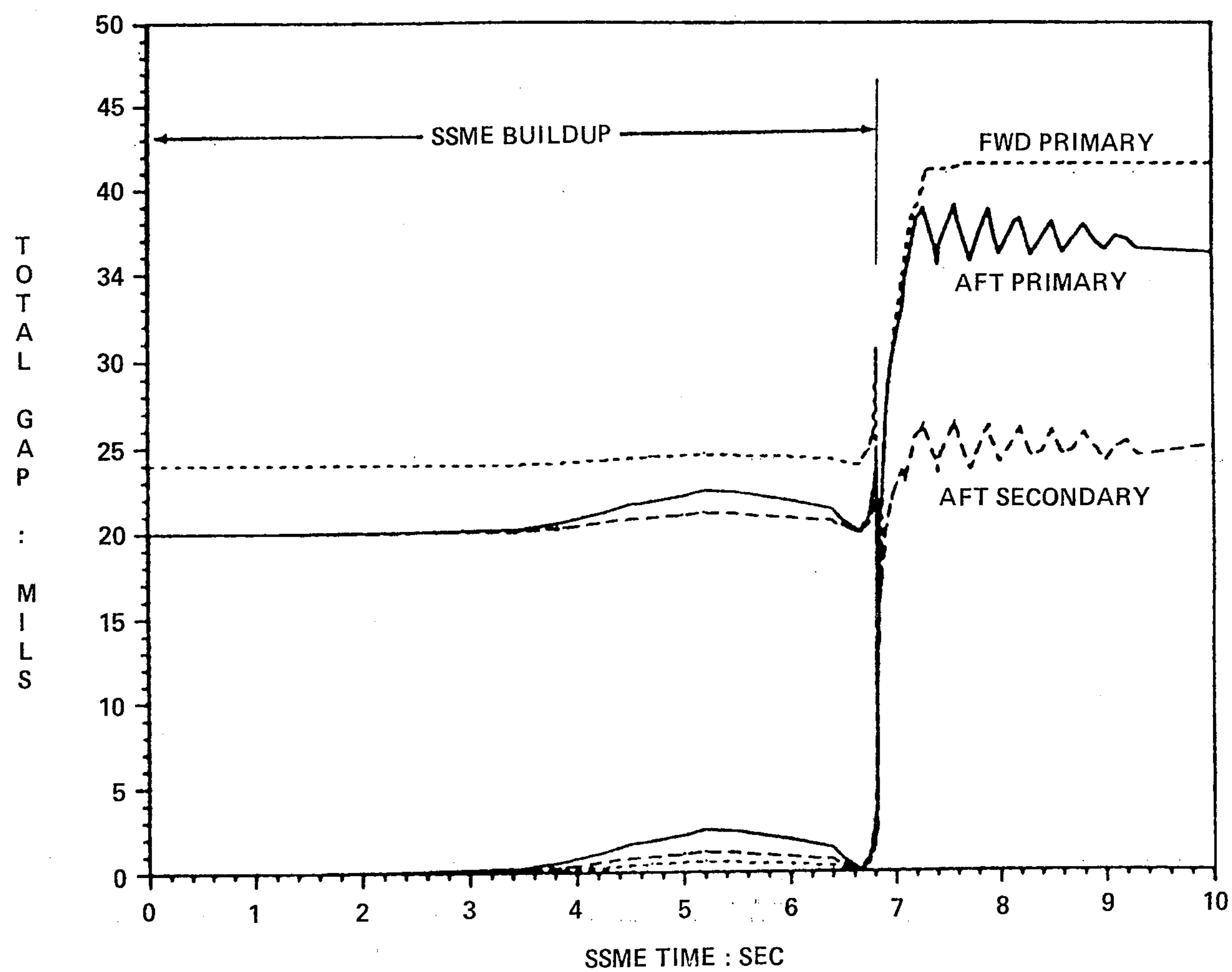


Figure 48. SRM o-ring/gap opening through liftoff.

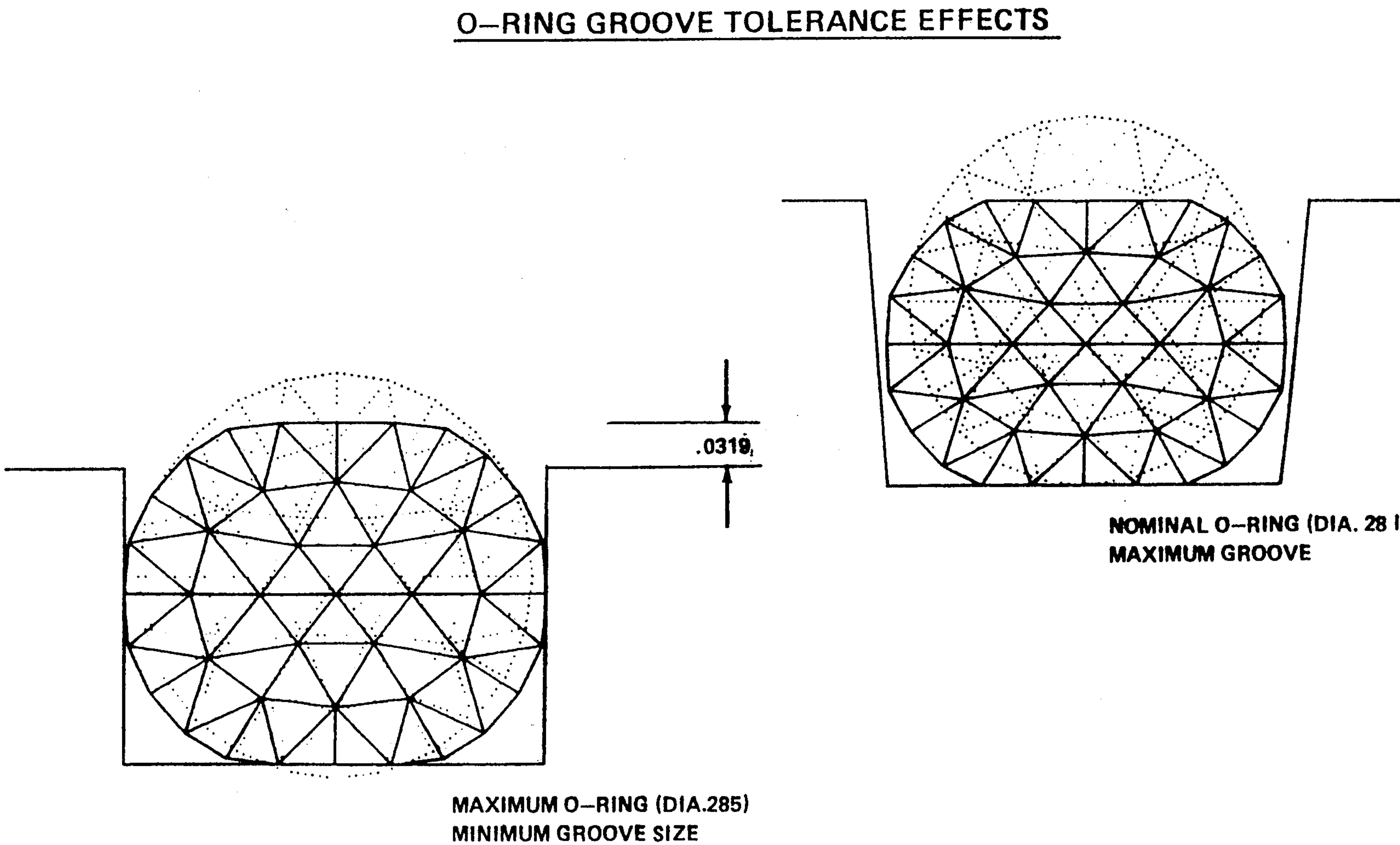


Figure 49. O-ring groove tolerance effects.

C-2

O–RING DISPLACEMENT SHAPES FOR VARIOUS STATES OF COMPRESSION

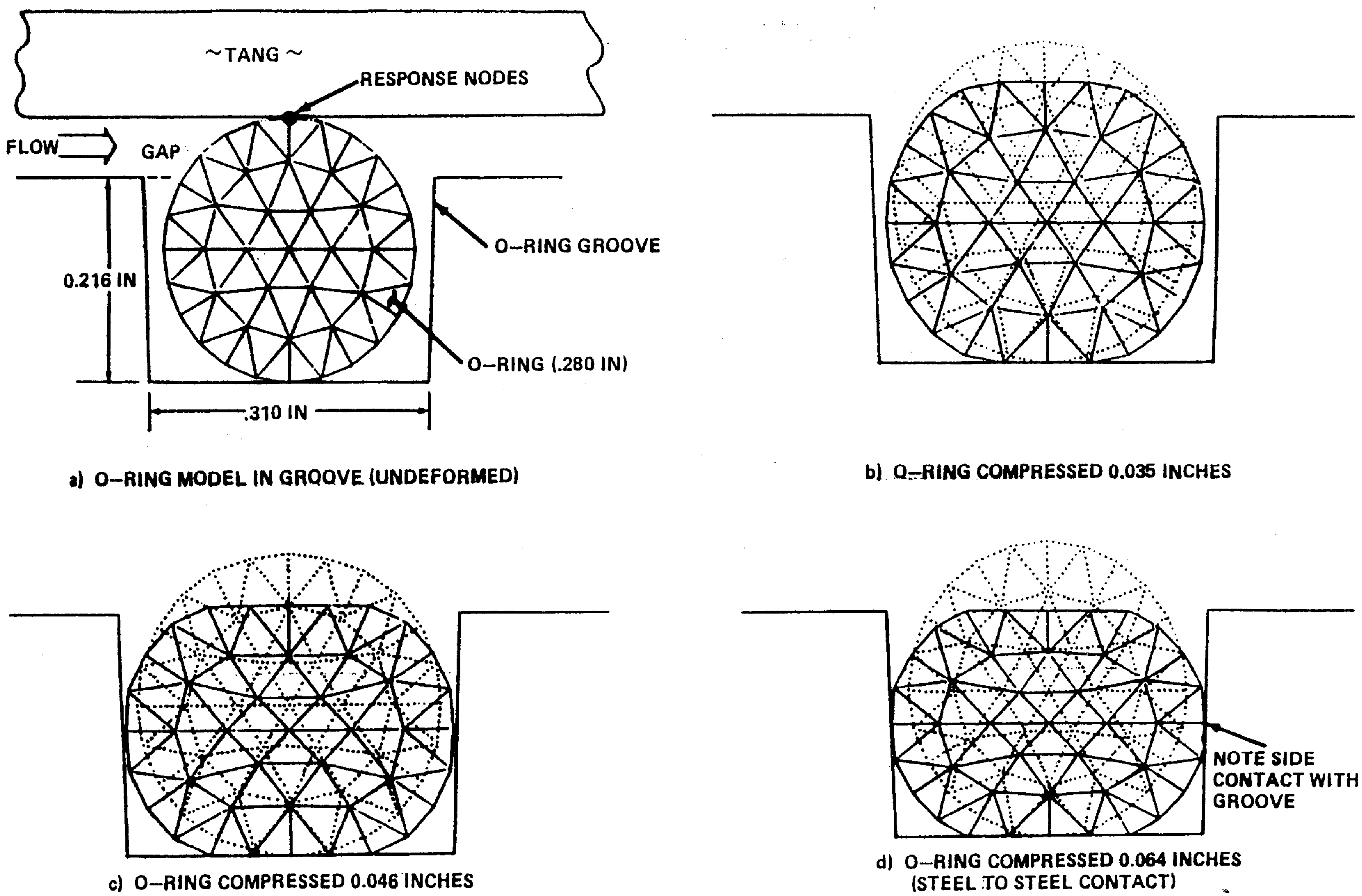


Figure 50. O-ring displacement for useless states of compression.

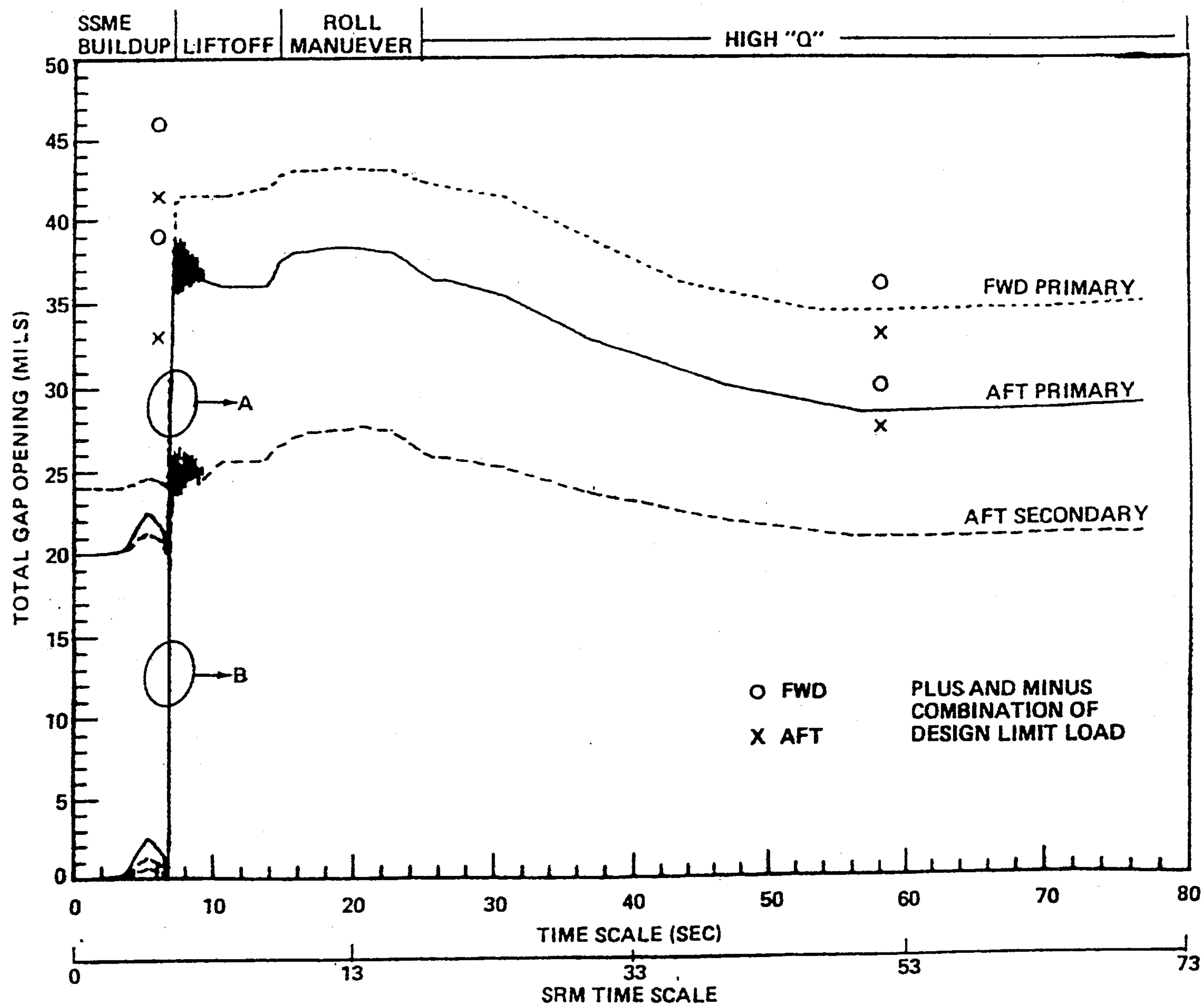


Figure 51. Shuttle liftoff transient.

ED5266

ORGANIZATION: NASA/ED22	MARSHALL SPACE FLIGHT CENTER	NAME: J. TOWNSEND
CHART NO.: 8	**51–L ANALYSIS OVERVIEW**	DATE: APRIL 25, 1986

LIFTOFF SEQUENCE OF EVENTS

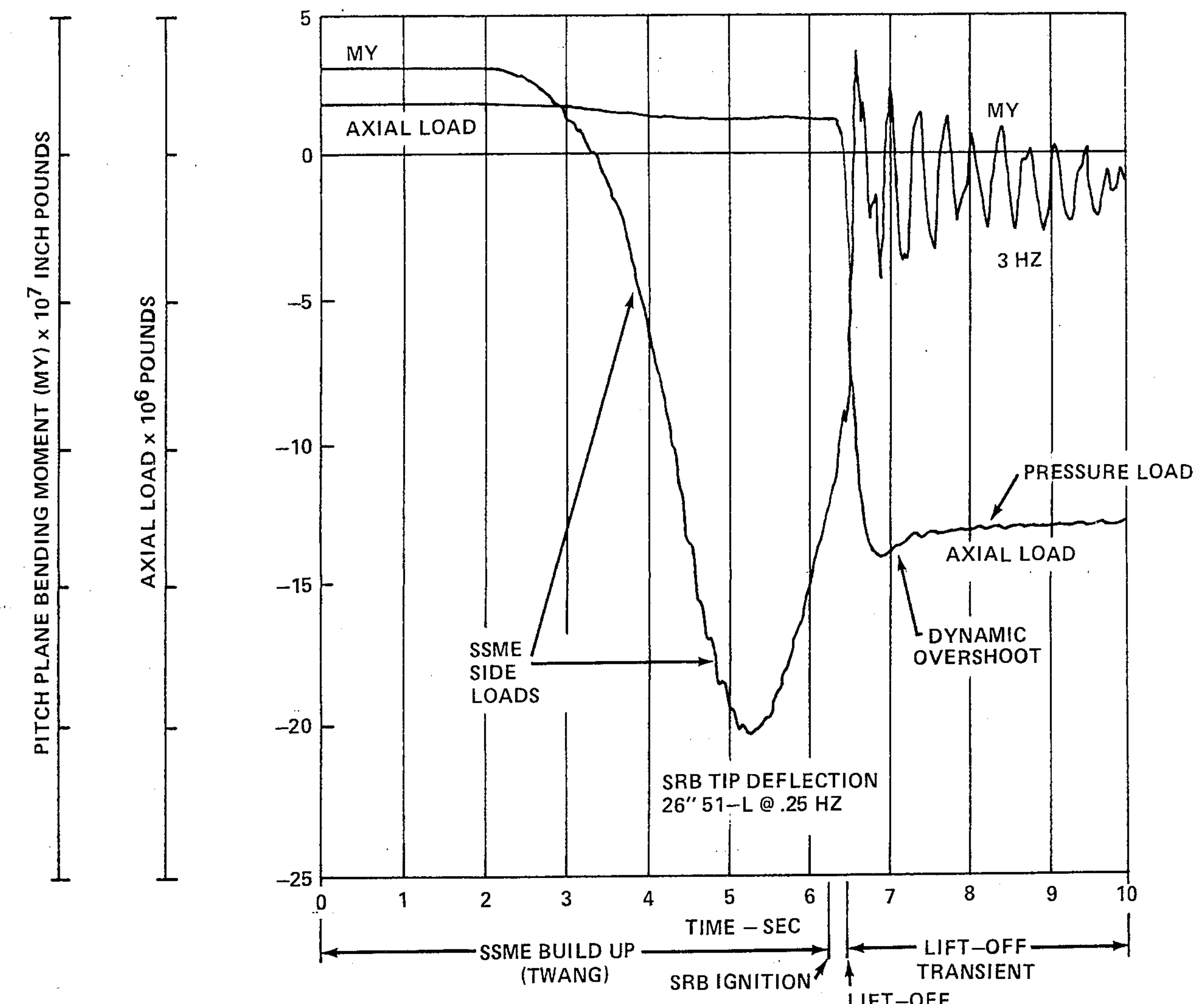
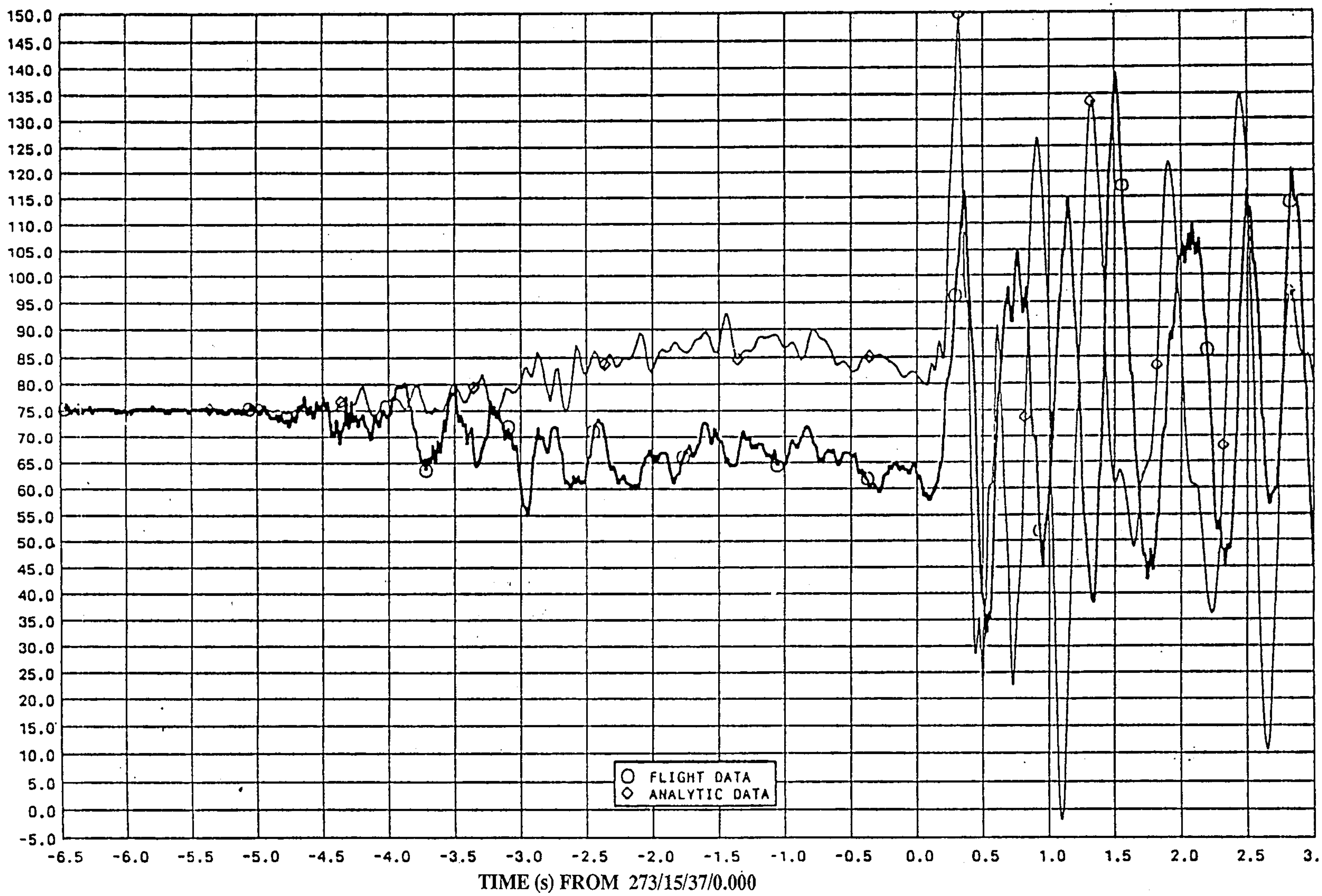
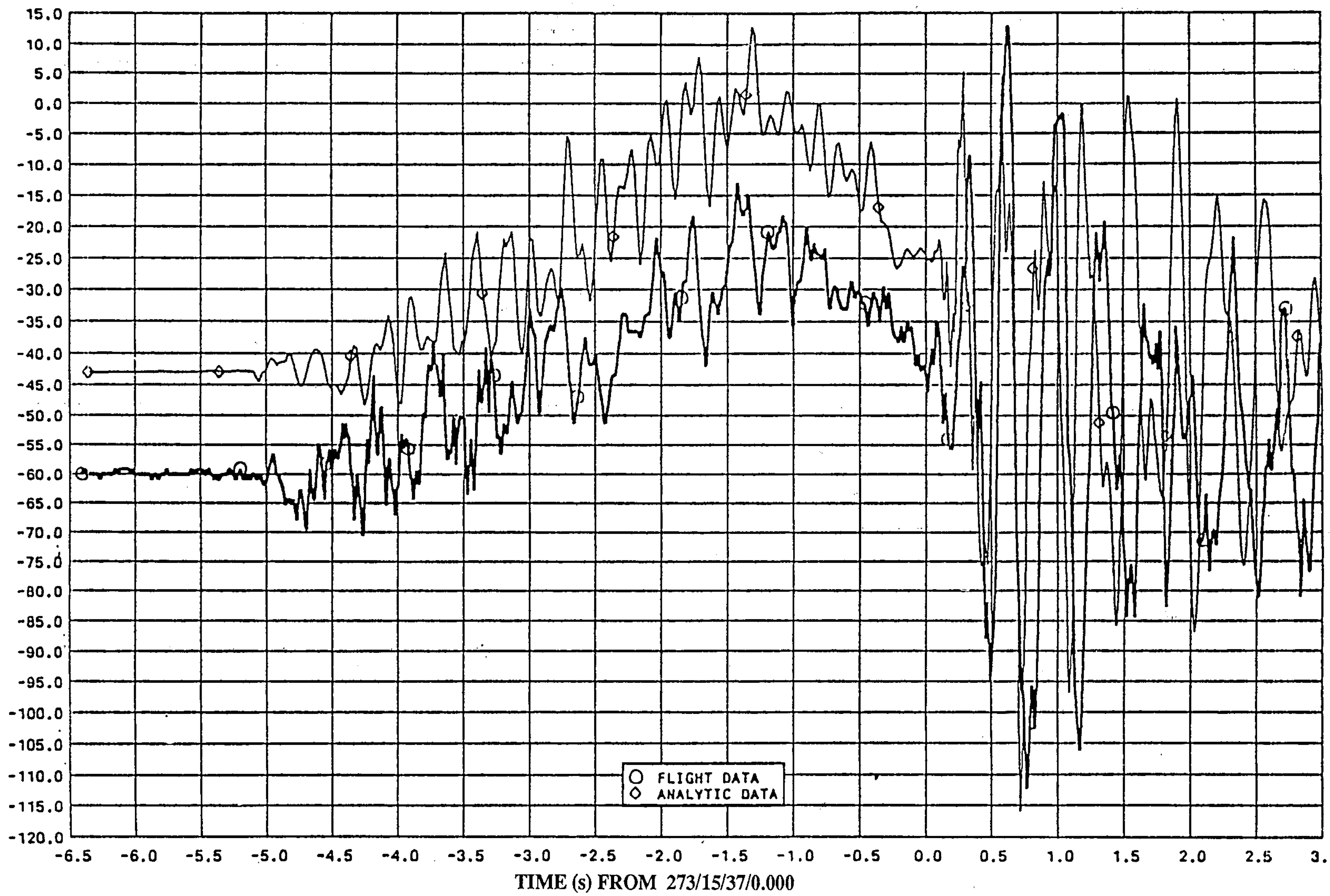


Figure 52. Liftoff sequence of events.



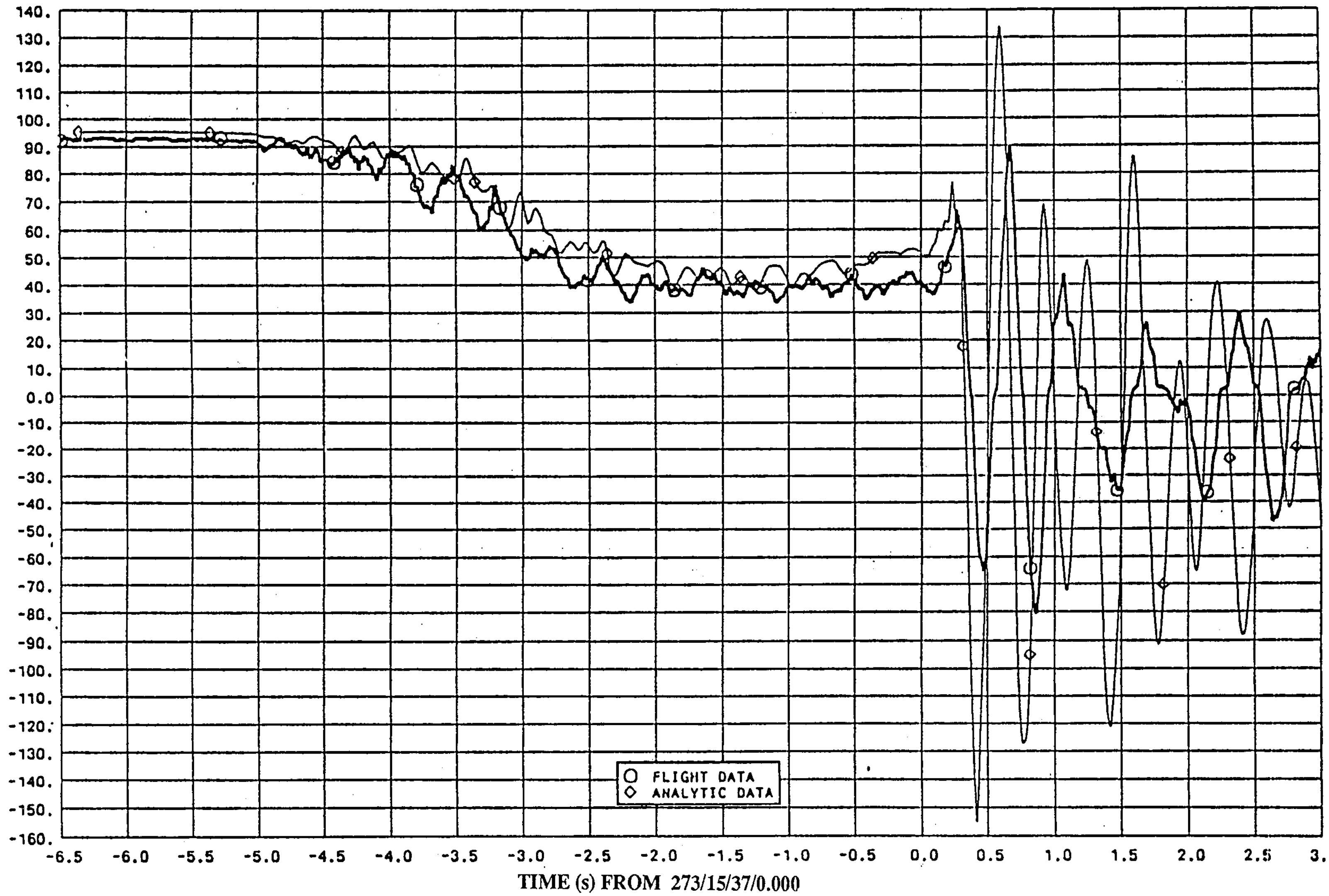
STS-26 ANALYTIC AND TEST DATA FOR P9 FROM GAUGE
BO8G8198A

Figure 53. Analytical to flight strut load compressions.



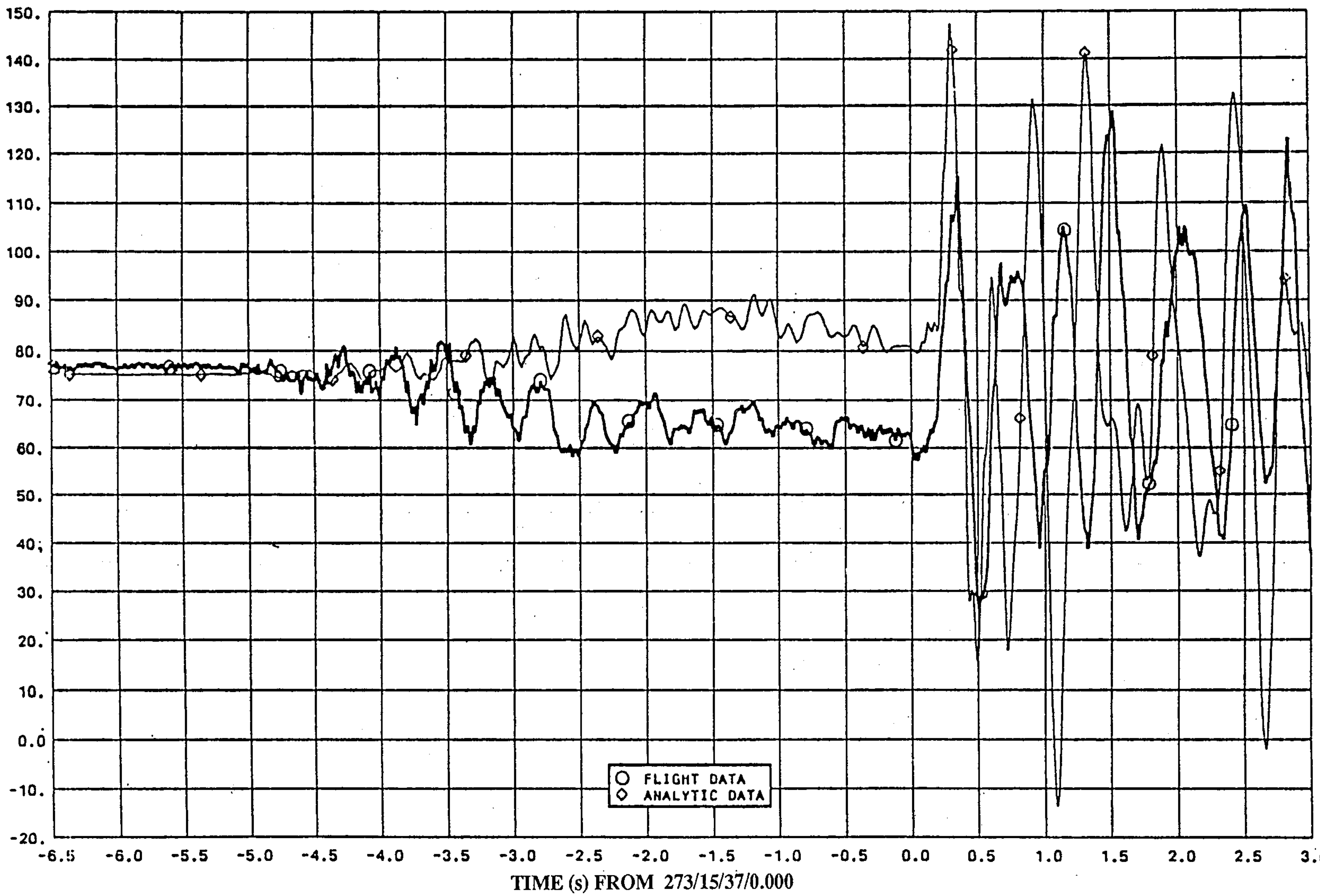
STS-26 ANALYTIC AND TEST DATA FOR P10 FROM GAUGE BO8G8196A

Figure 54. Analytical to flight strut load compressions.



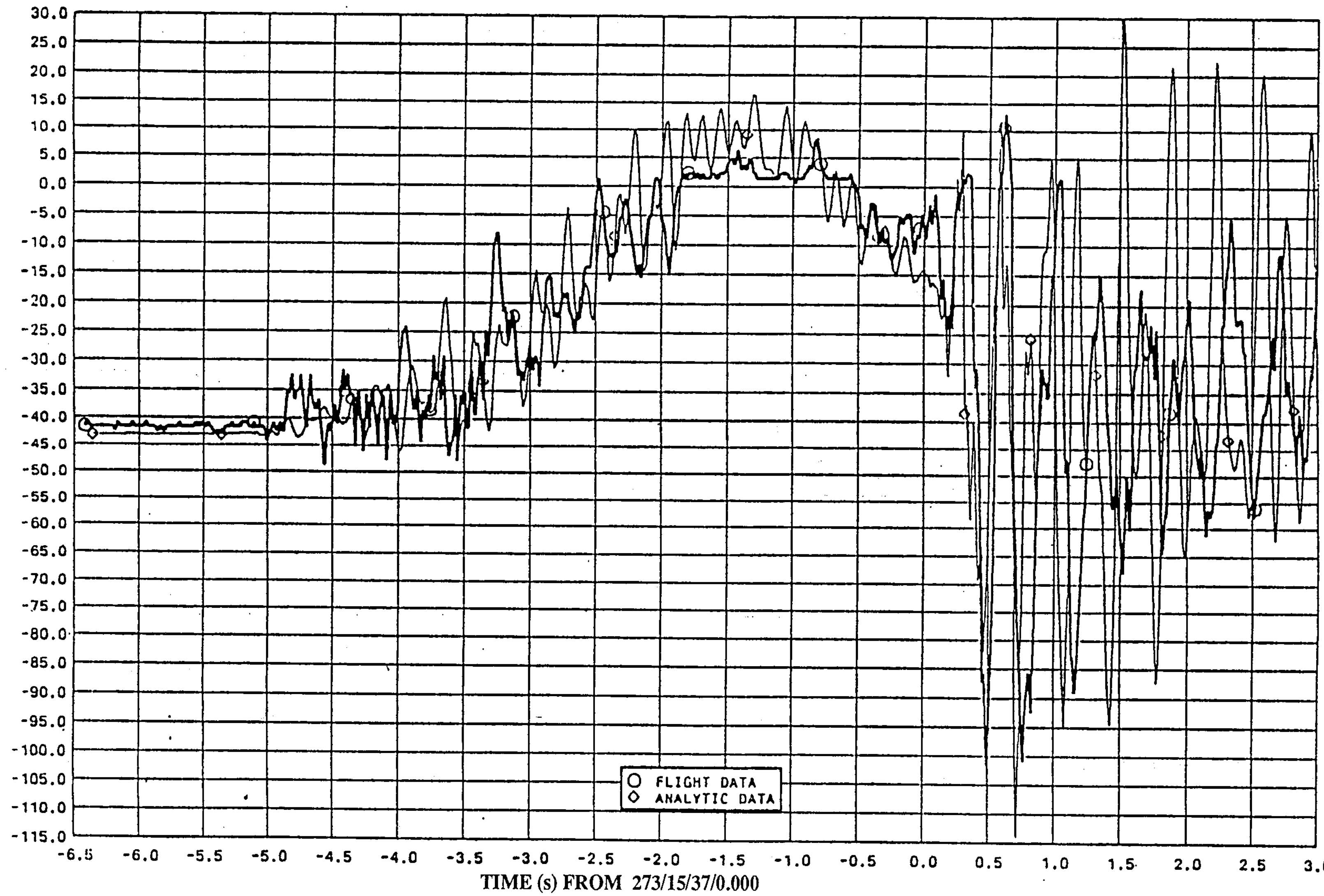
STS-26 ANALYTIC AND TEST DATA FOR P11 FROM GAUGE
BO8G8194A

Figure 55. Analytical to flight strut load compressions.



STS-26 ANALYTIC AND TEST DATA FOR P12 FROM GAUGE
BO8G7198A

Figure 56. Analytical to flight strut load compressions.



STS-26 ANALYTIC AND TEST DATA FOR P13 FROM GAUGE BO8G7196A

Figure 57. Analytical to flight strut load compressions.

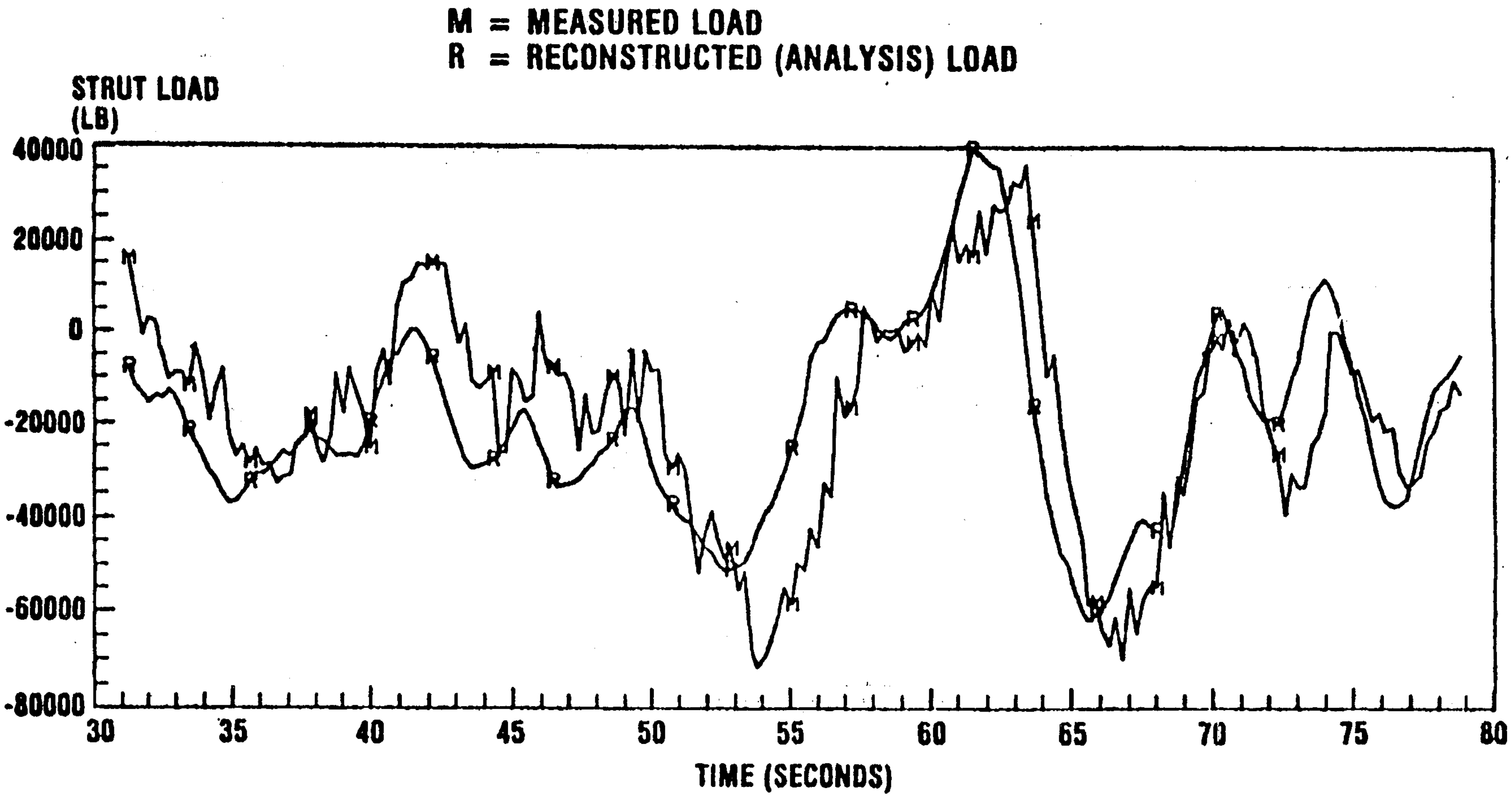
STRUCTURAL EFFECTS/FINDINGS

- PRIMARY PARAMETER DETERMINING FIELD JOINT GAP OPENING IS RADIAL PRESSURE

• MOMENT	7%	
• SHEAR	1%	
• STRUT LOADS	7%	AFT FIELD JOINT LIFTOFF
• RADIAL	65%	
• LINE (PRESS/THRUST/ACC'L)	20%	

- EXTERNAL LOADS AND DYNAMICS HAVE A SMALL EFFECT ON SEAL GAP OPENING
- THE FORWARD FIELD JOINT HAS THE HIGHEST LOAD AND SEAL GAP OPENING (8 MILS MORE THAN AFT FIELD JOINT)
- GAP PEAKS AT LIFTOFF THEN DECREASED DURING MAX "Q" TO APPROXIMATELY 80% OF LIFTOFF VALUE – MAJOR GAP OPENING OCCURS WITHIN 600 MILS OF IGNITION.
- THERE IS A VEHICLE STRUCTURAL DYNAMIC OSCILLATION DURING THE LIFTOFF TRANSIENT OF APPROXIMATELY 3 HZ. THE OSCILLATION ADDS ± 2 MILS TO THE SEAL GAP OPENING.

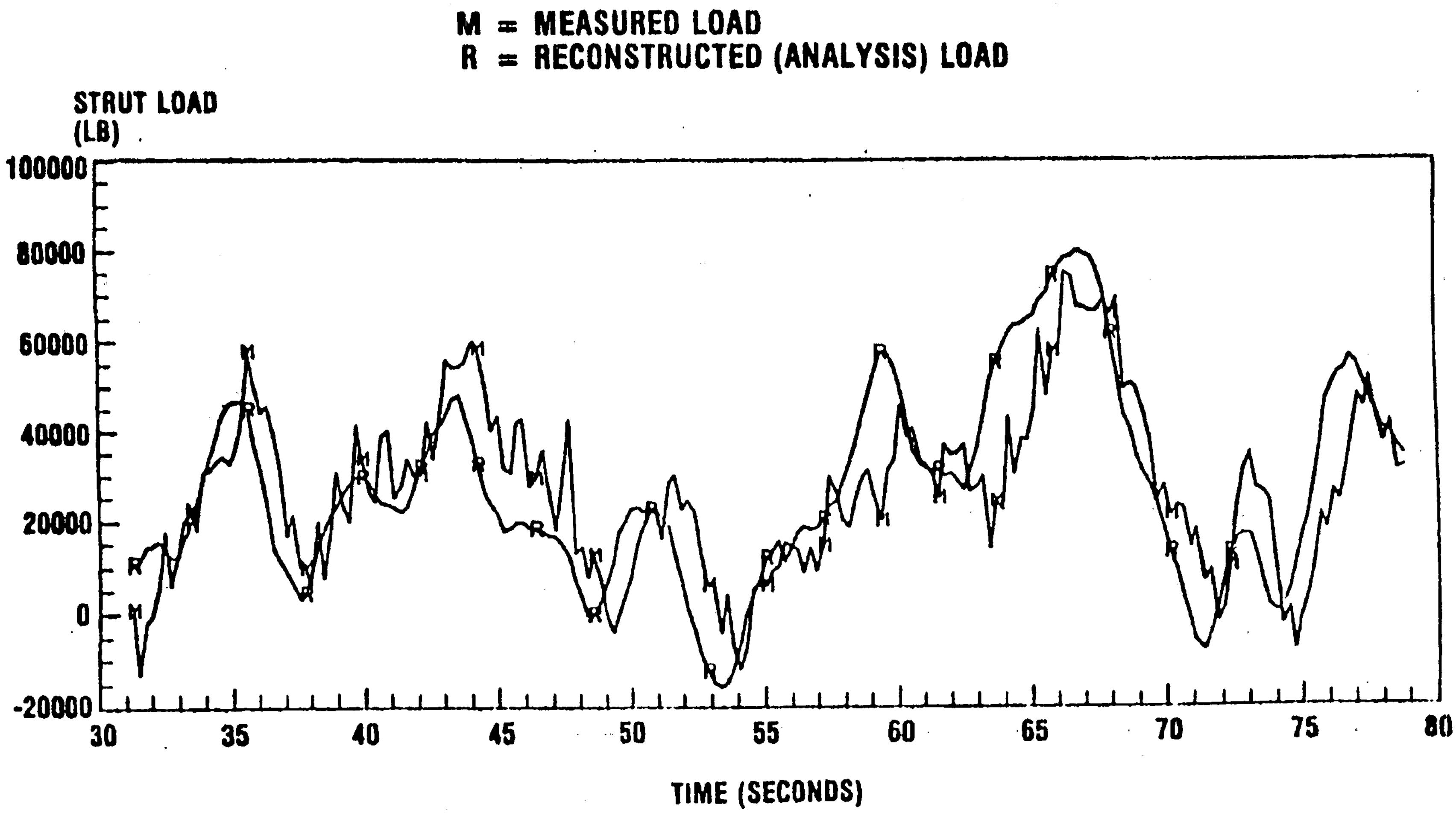
Figure 58. Structural effects findings.



LIMIT DESIGN LOADS: + 230 KLB
- 258 KLB

COMPARISON OF MEASURED VS RECONSTRUCTED FLIGHT LOADS P10 STRUT - STS-3 FLIGHT

Figure 59a. Max "q" strut load reconstitution.



LIMIT DESIGN LOADS: + 230 KLB
- 258 KLB

COMPARISON OF MEASURED VS RECONSTRUCTED FLIGHT
LOADS P13 STRUT - STS-3 FLIGHT

Figure 59b. Max "q" strut load reconstitution.

Static Moment Balance of Misalignments at Lift-off
Orbiter Control Only
Solids Canted 15 in Yaw

	δ_Y Trim (deg)	δ_R Trim (deg)	δ_{MAX} Trim (deg)
Solid Misalignments in Roll*		5.87	5.87
$\frac{.5\sqrt{2}}{2} = .3535$ /Solid			
Solid Misalignment in Yaw*	.62**	2.6	3.2
$\frac{.5\sqrt{2}}{2} = .3535$ /Solid			
Solid Thrust Differential	.29**	1.2	1.49
$\frac{4.2\%\sqrt{2}}{2} = 2.96\%$/Solid			
Lateral CG Variation (.0508 m)	.62 **	2.6	3.2
RSS Total			8.47

* Mutually Exclusive

** δ_R Required to Cancel Roll Moment Due to 1 $\delta_Y = 4.18$

Figure 60. SRM thrust vector misalignment effects.

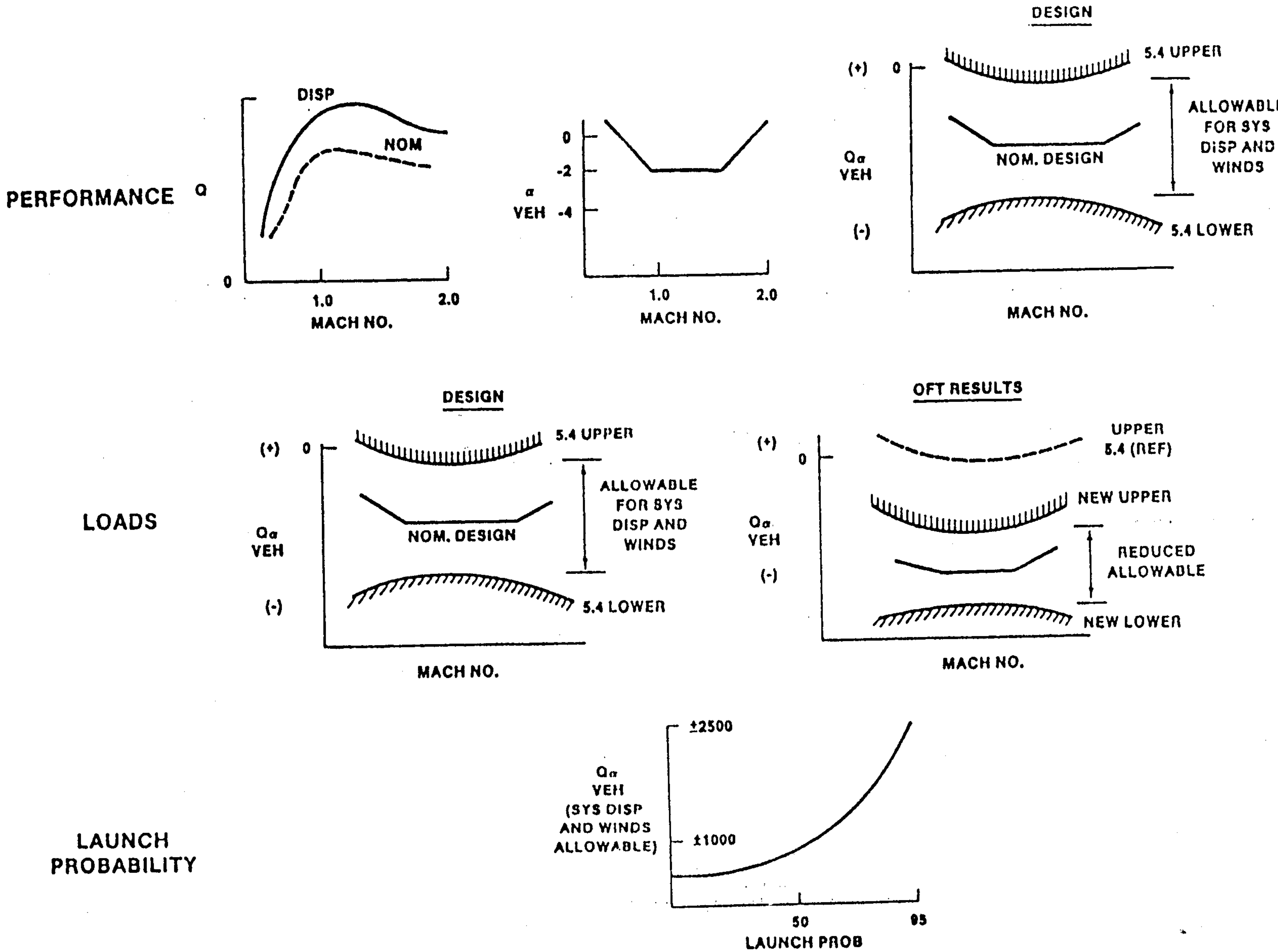
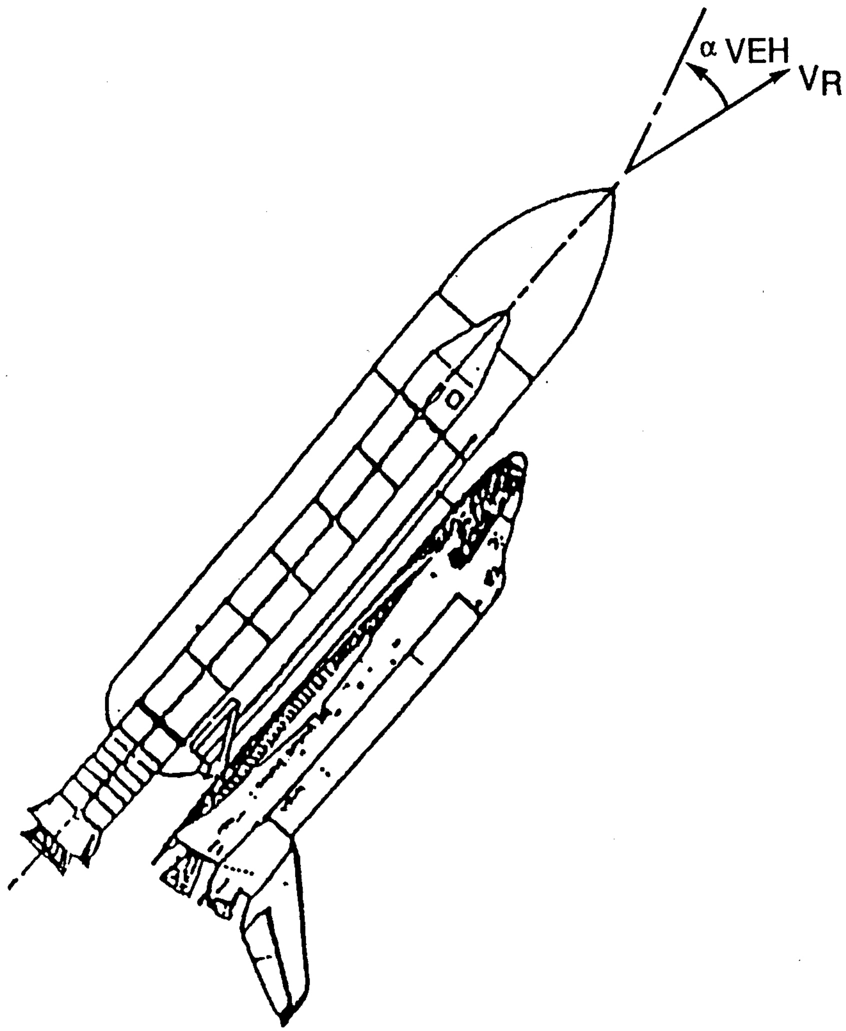
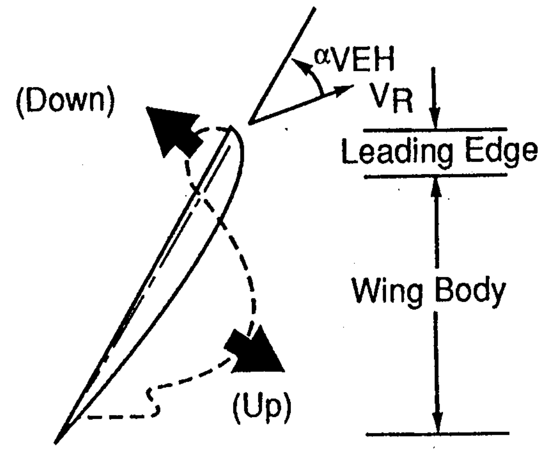


Figure 61. Ascent parameters.



- Original Design Achieved Optimum Balance (Performance, Loads, Launch Probability) at $\alpha_{VEH} \approx -2°$
- General Features of Wing Load are:



- If α_{VEH} Shifts More Negative:

  Leading Edge Loads Increase

  - External Tank Loads Increase (Protuberances)
  - Wing Body Loads Decrease
  - Trajectory Tends to Loft (Performance Loss)

Figure 62. Loads and performance relationship.

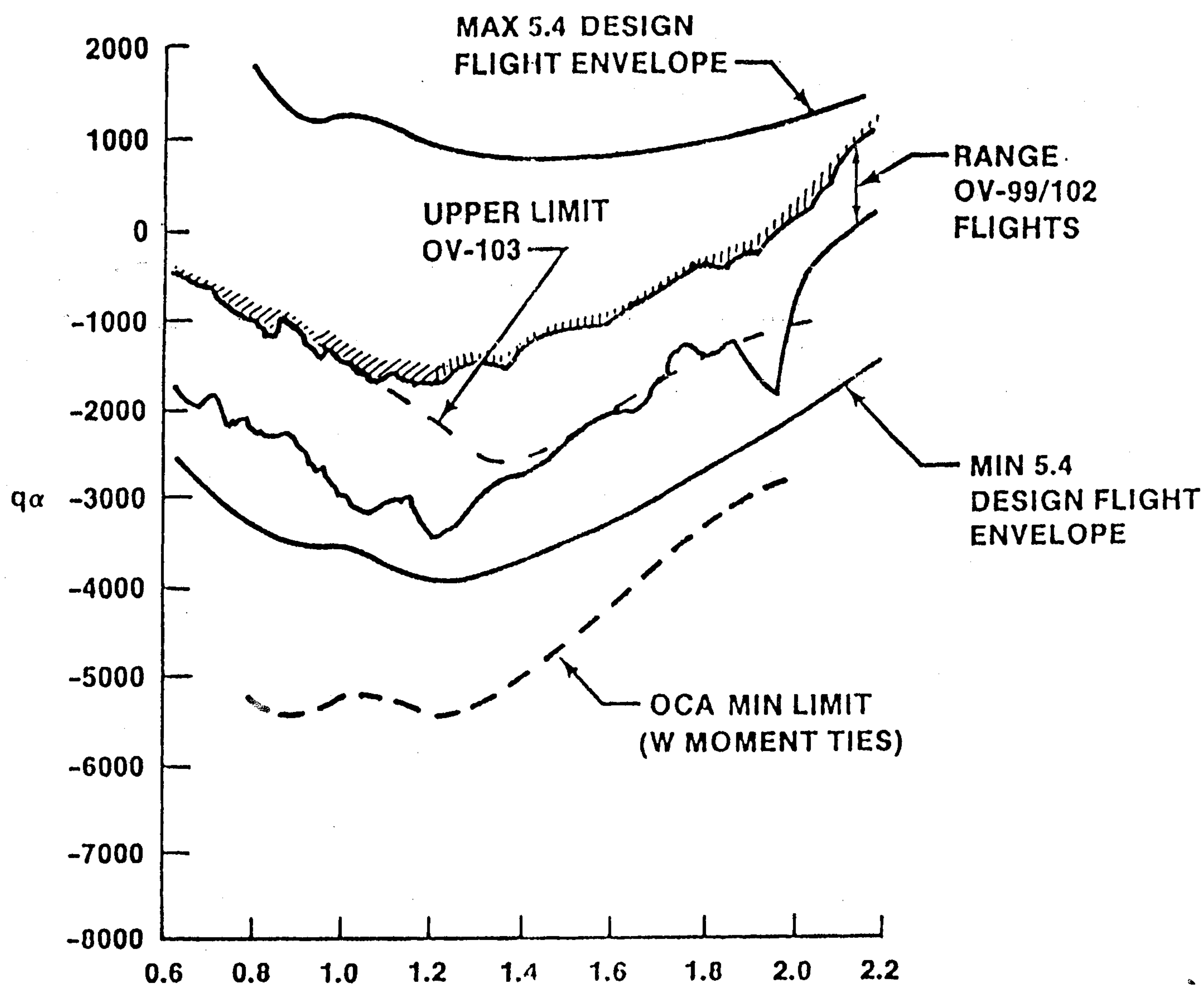


Figure 63. Ascent flight envelope limits.

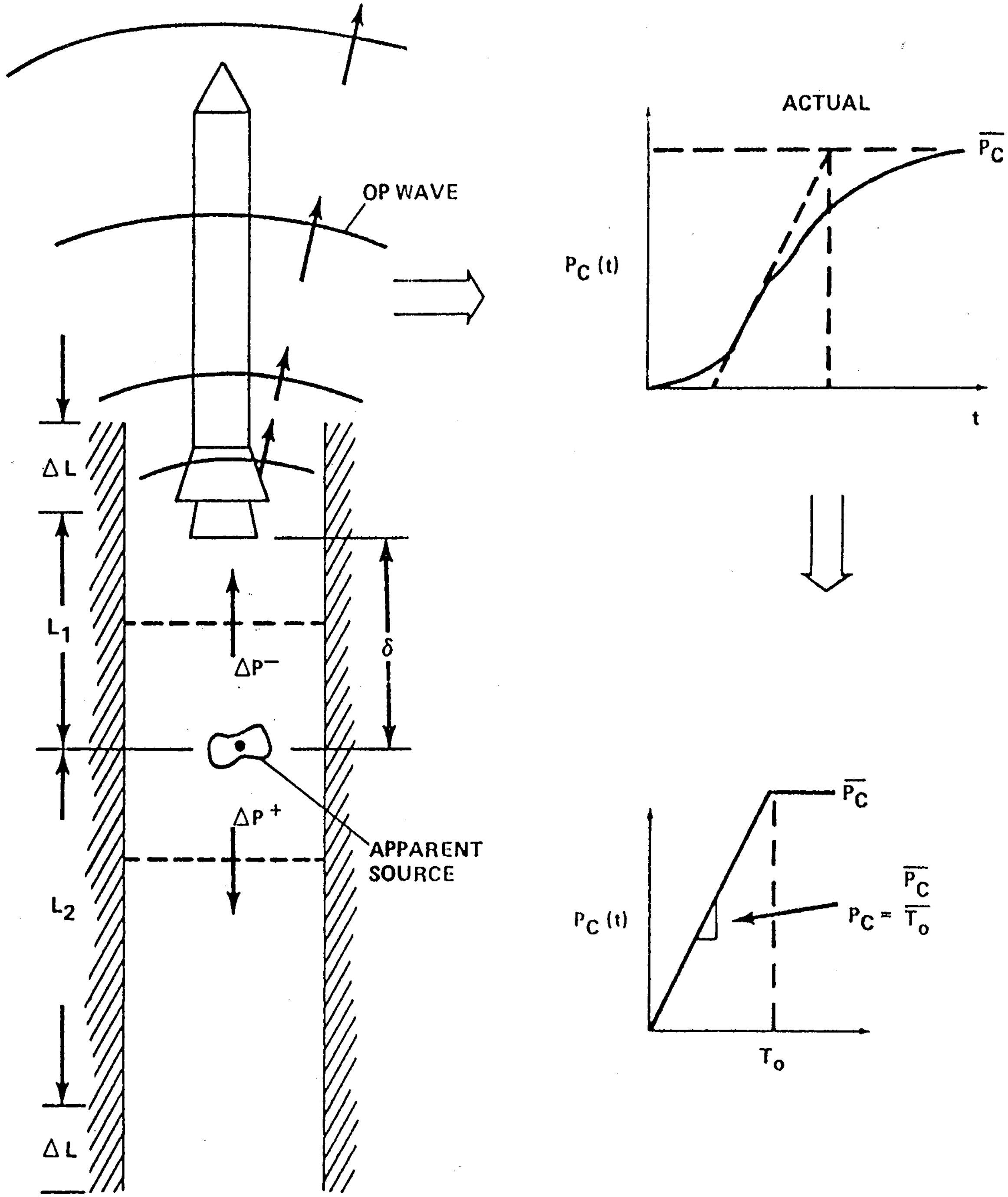


Figure 64. Overpressure model.

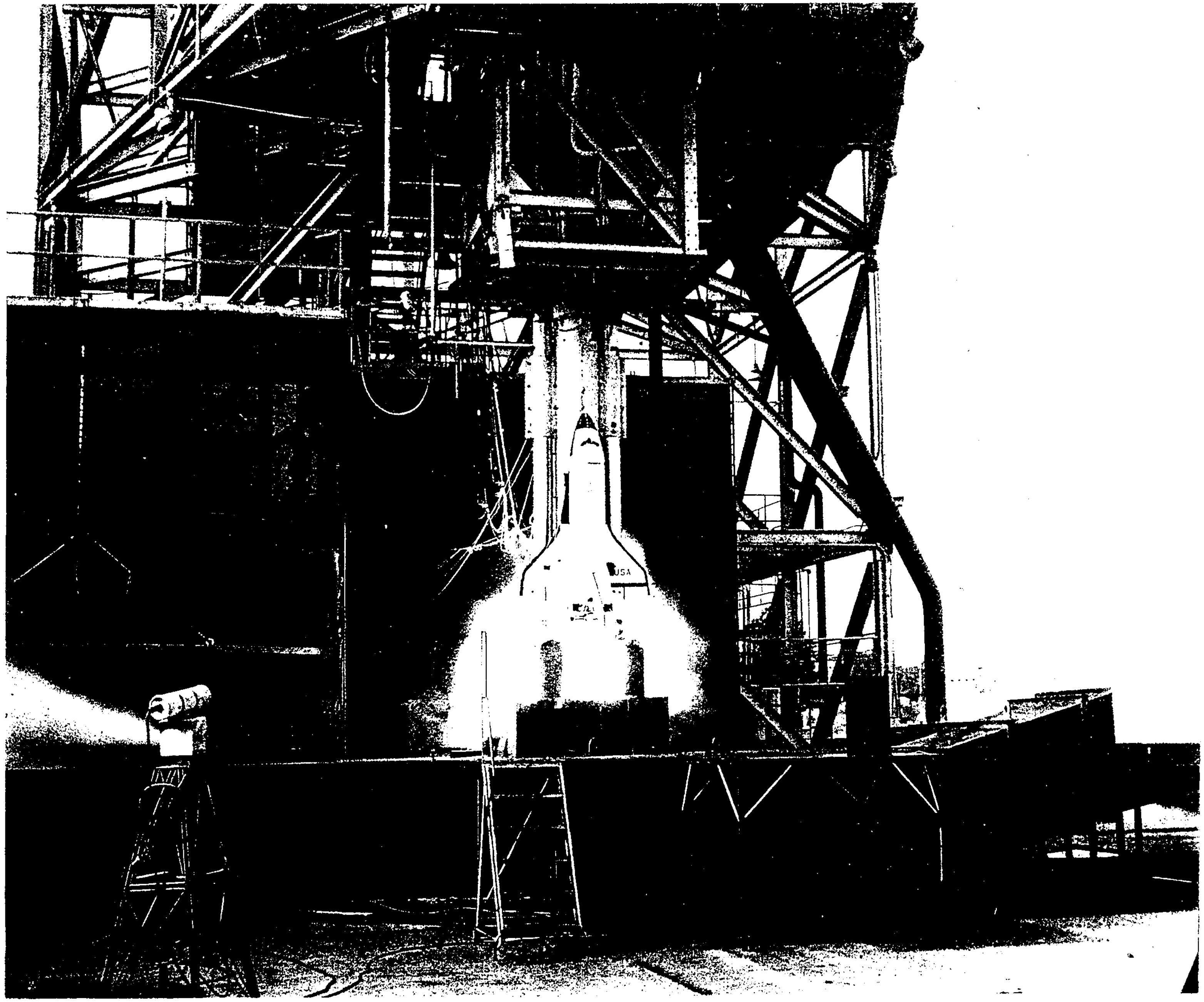


Figure 65. Shuttle acoustic at 6.4 percent and overpressure hot fire model.

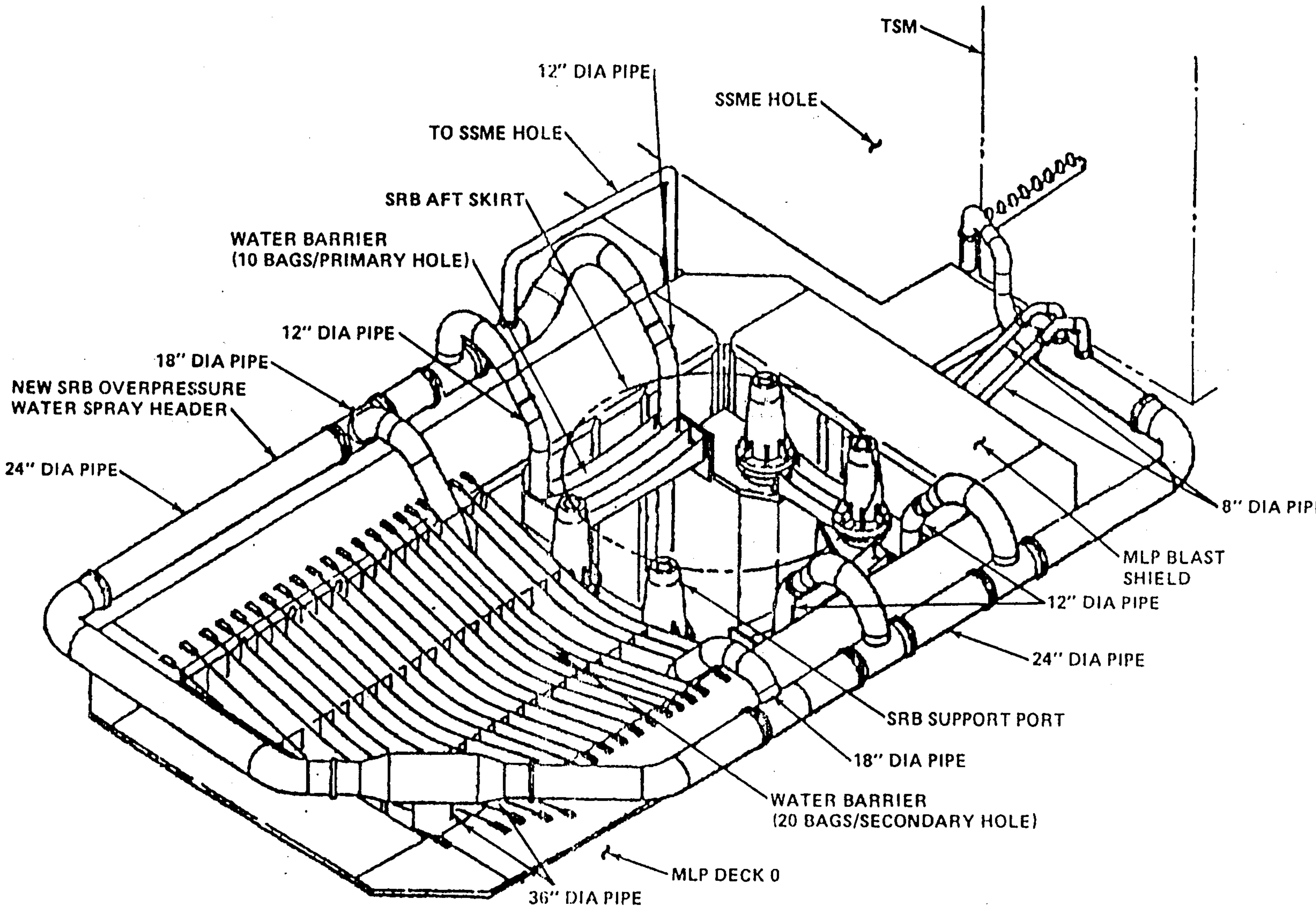
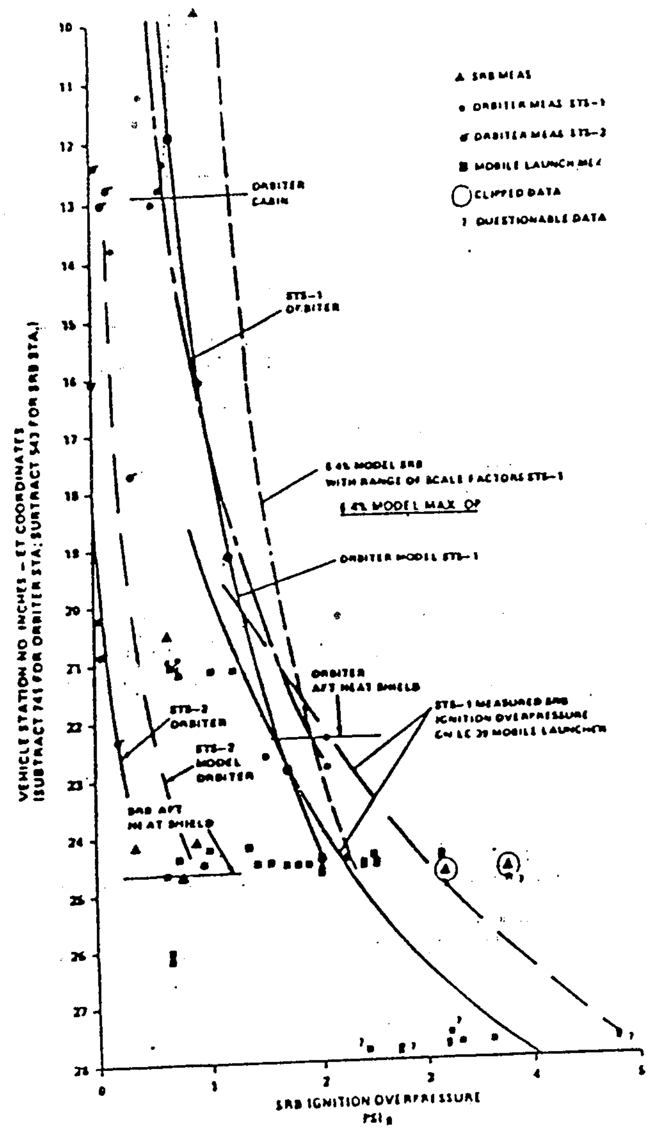


Figure 66. Overpressure suppression mods.



STS-1 measured SRB ignition overpressure versus vehicle station

Figure 67. STS-1 measure overpressure.

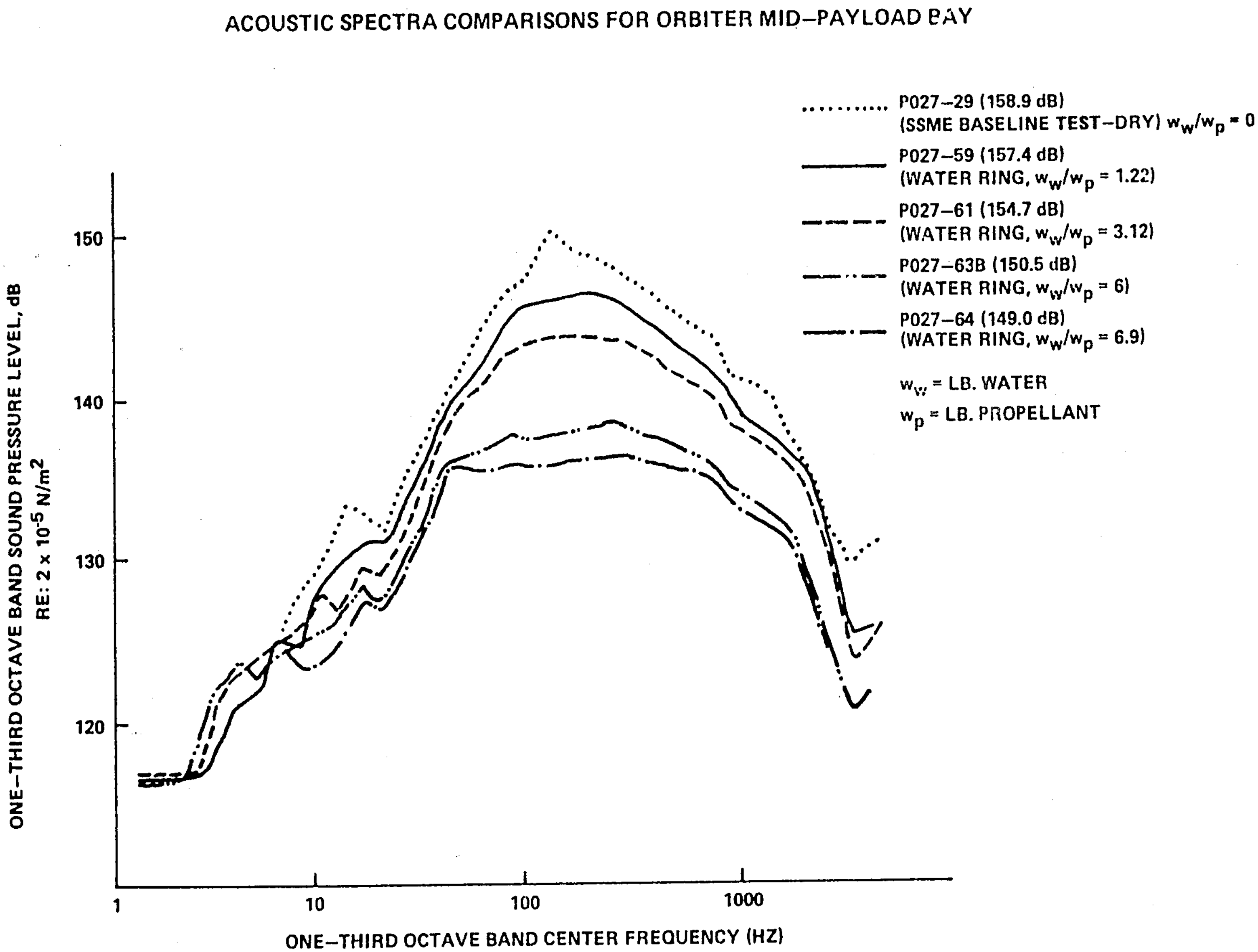
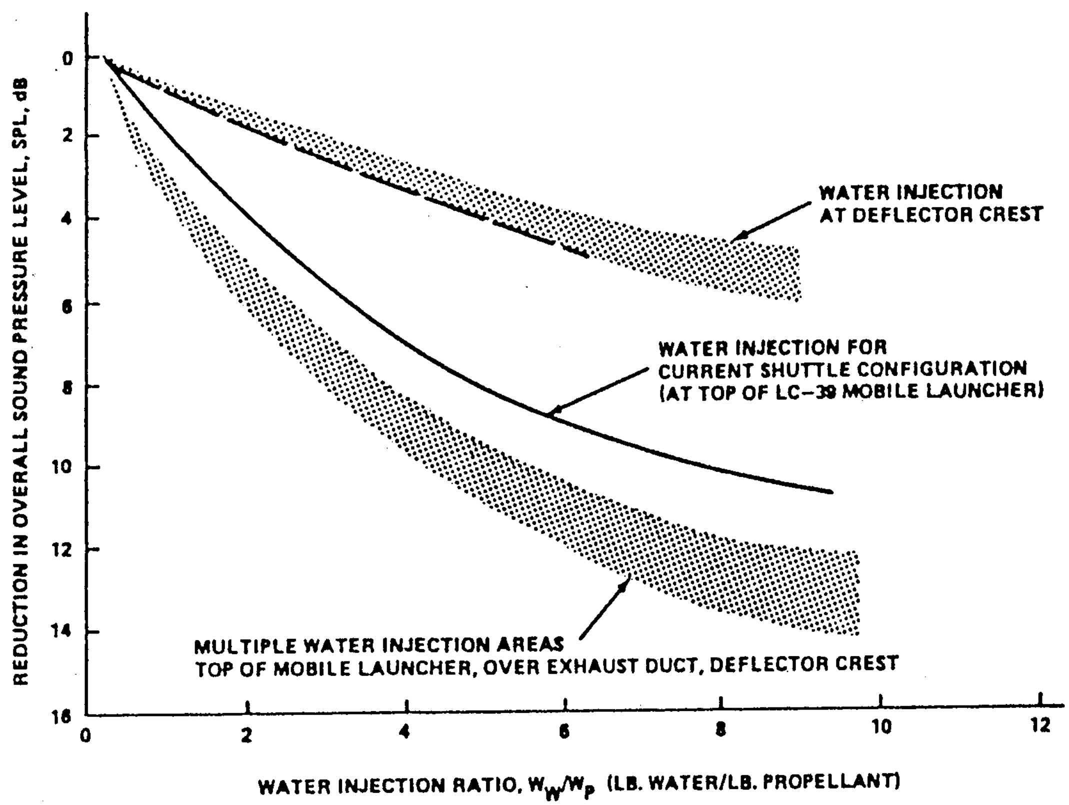


Figure 68. Acoustic levels with and without suppression.



Acoustic levels with and without suppression

Figure 69. Overall sound pressure levels with and without suppression.

Pre STS-26 Containment System

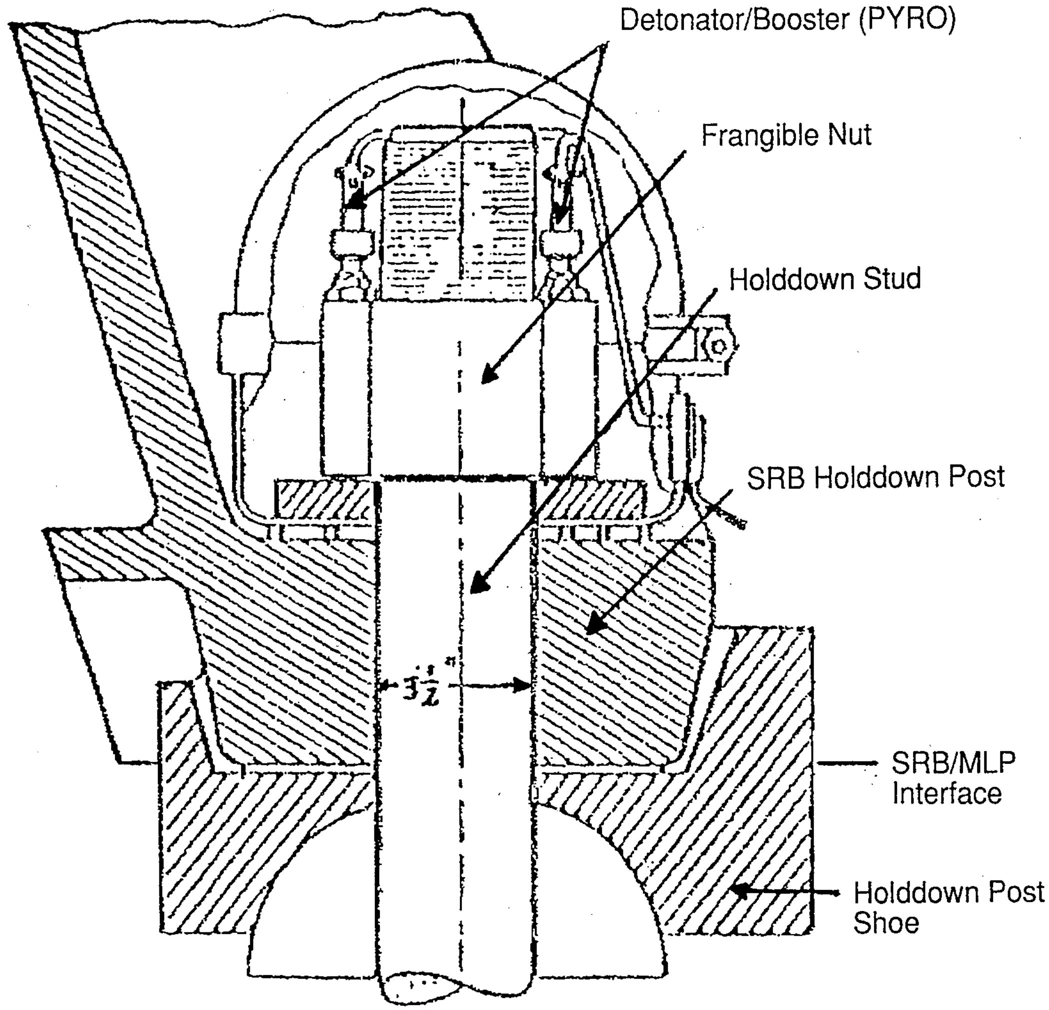


Figure 70. SRB holddown bolt configuration.

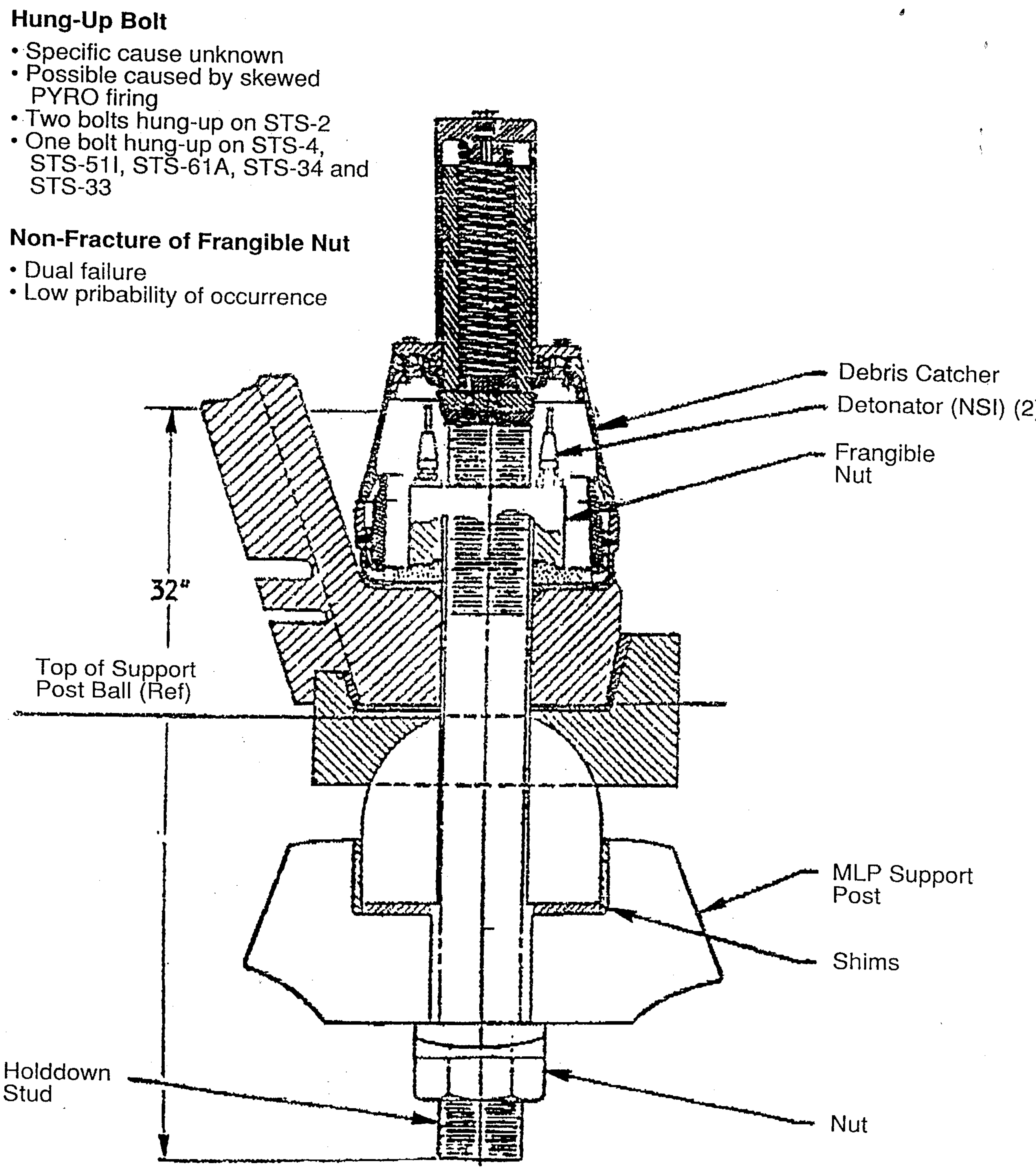
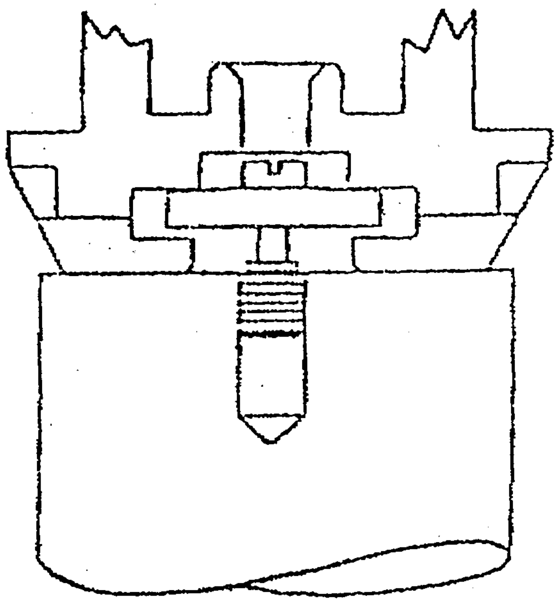


Figure 71. Debris containment system.

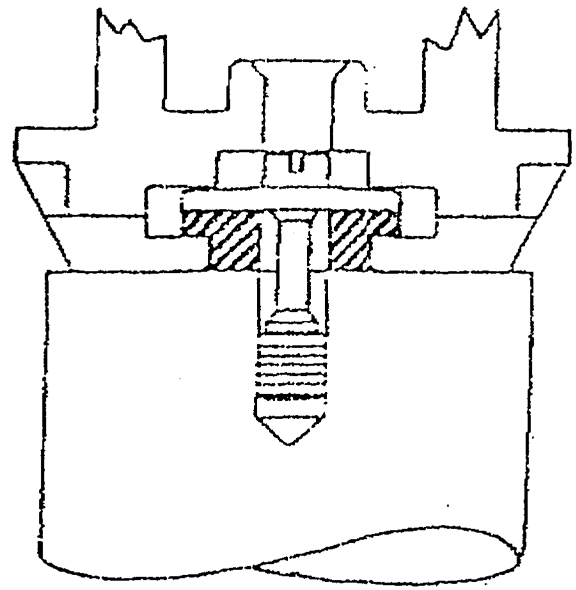
Old Design

STS-26, 27, 29, 30



New Design

STS-28, 34, 33



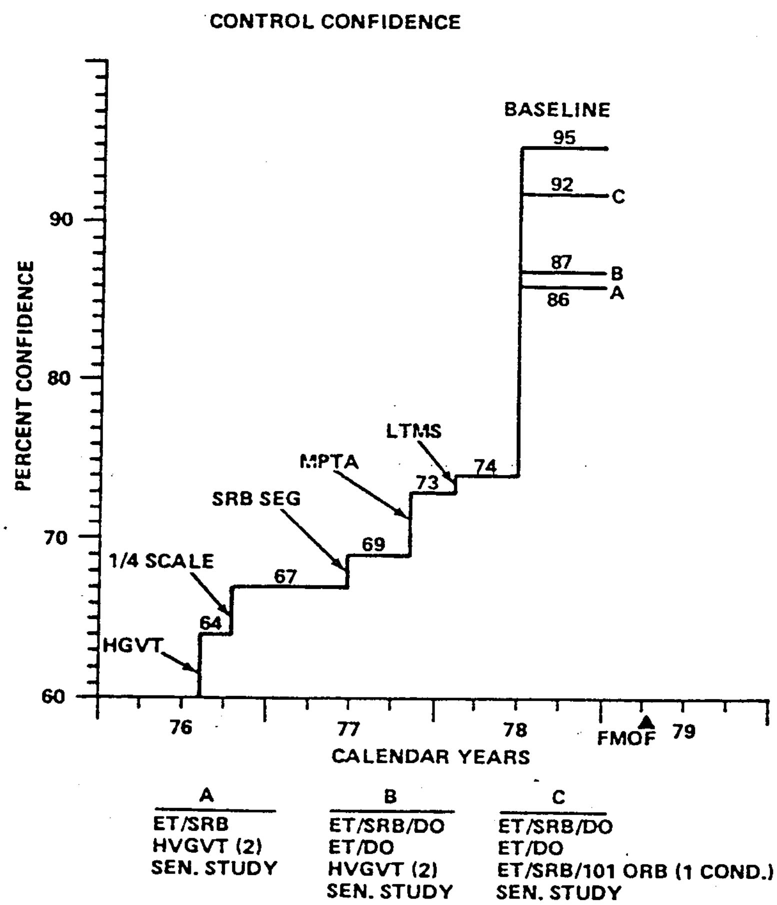
Old

Property	A - 286
UTS (KSI)	140.0
YTS (KSI)	95.0
Elong (%)	12.0
Toughness	14.1

New

Annealed MP35N
132.0
53.0
68.0
62.9

Figure 72. Attach link material changes after STS-30.



Confidence factor versus test combination (control).

Figure 73. Dynamic test option risks.

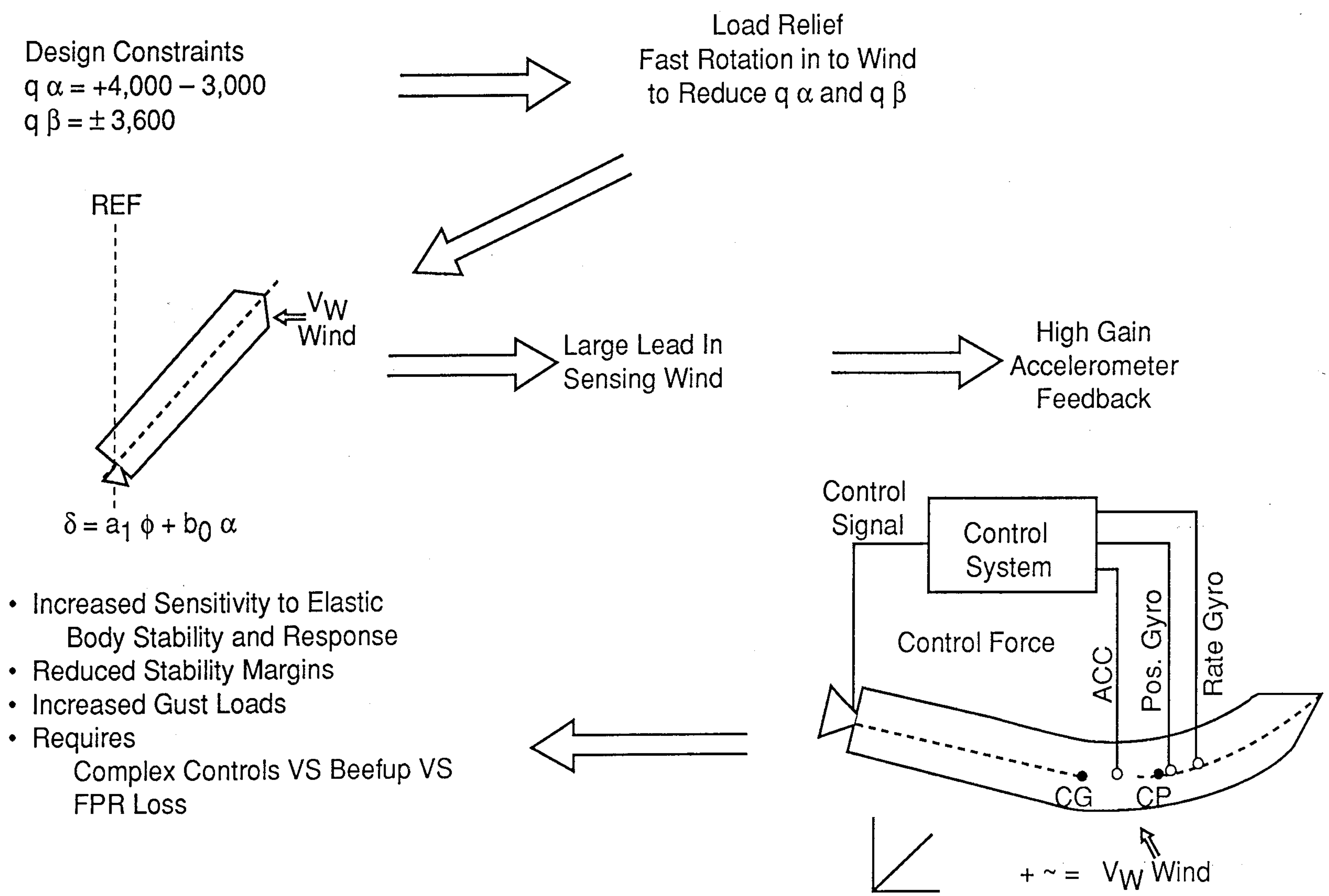


Figure 74. Control system complexity versus dynamic test.

1. Performance Requirements Drive Design.
2. Philosophy Sets the Course and is Fundamental to Approach.
3. Interfaces are Compatible and Well Defined.
4. Configuration Complexity Determines Penetration.
5. The Sum of Parts is Not Equal to the Whole. (System)
6. Statistical Significance Determines Design Adequacy.
7. Design for Robustness, Growth, and Flexibility.
8. People are the Prime Source. The Secret of an Organization (Quality) is the Development of People, All People, Not Only in Skills But Totally.
9. Analysis and Test Are Limited. Bracketing Hand Analysis is Key to Understanding.
10. All. Data Must be Characterized, Justified, and Understood: Environments, Materials, Propulsion, etc.
11. Read and Understand What the Hardware is Telling You. It has the Real Message.
12. Good Engineers Must Touch Hardware. It is Better if They Have Done Manufacturing, Run a Lathe, Built a Cabinet, Struck a Weld, Shot an Alignment, etc.
13. Proper Relationship Between Project Management and Science and Engineering With Clearly Defined Roles and Mission Between Government and Contractor.
14. Open Communications Mandatory for Quality.
15. Criteria or Legal Requirements Must Be Simple, Concise, Direct, Providing Order to the Engineering Process; But Not Overpowering to Where it Stifles Creativity and Removes Responsibility. Aerospace Engineering Requires the Best Answer.

Figure 75. Underlying design principles.

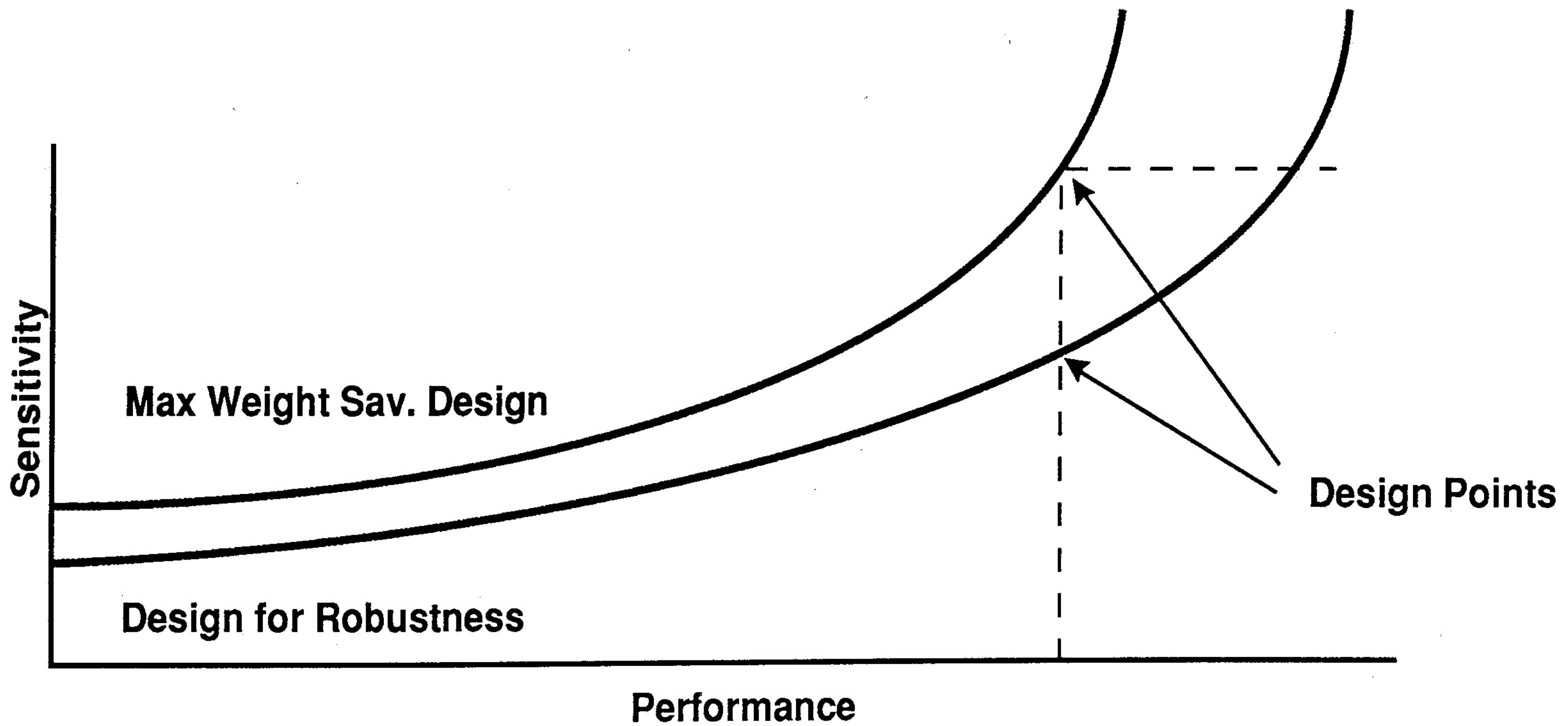


Figure 76. Sensitivity versus performance.

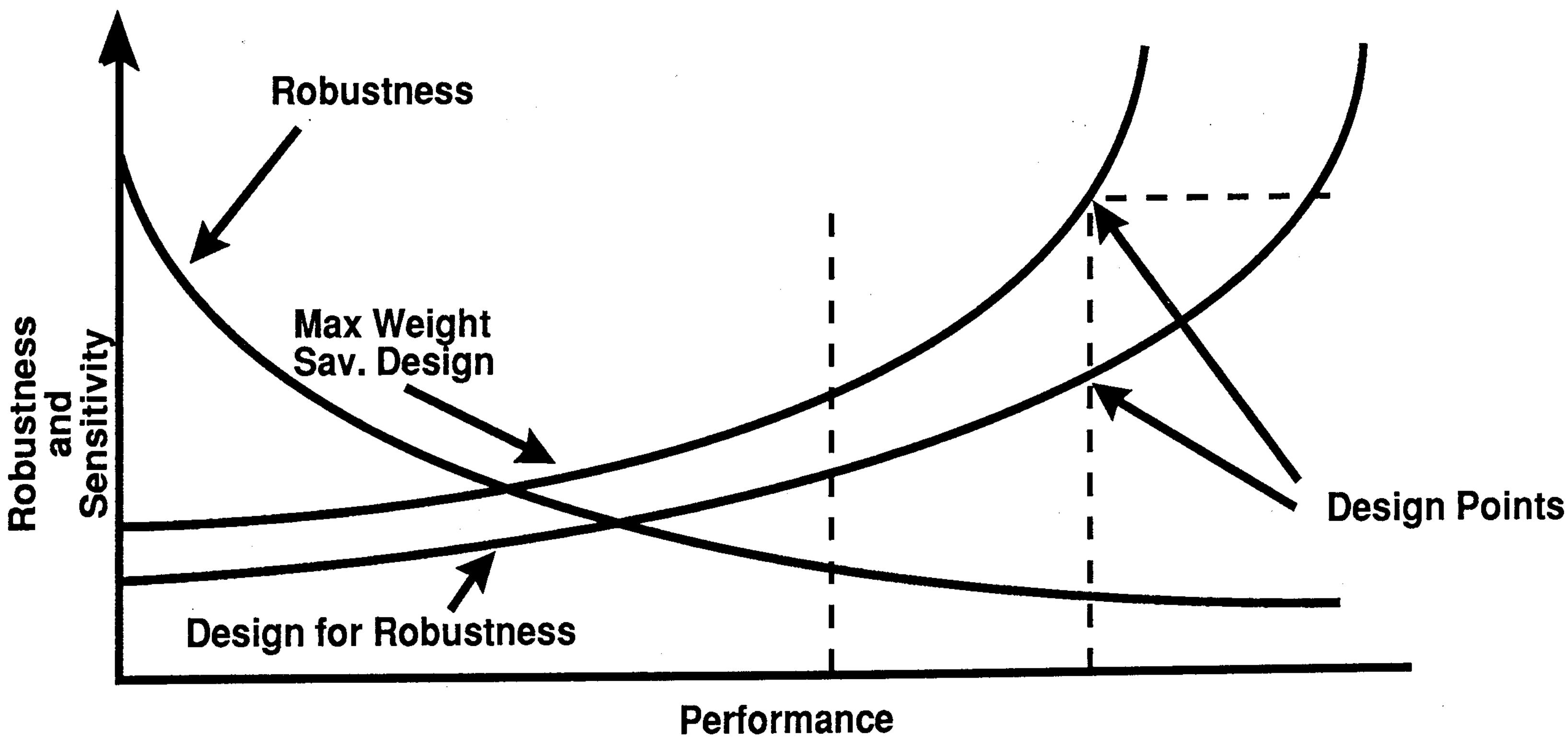


Figure 77. Robustness, sensitivity versus performance.

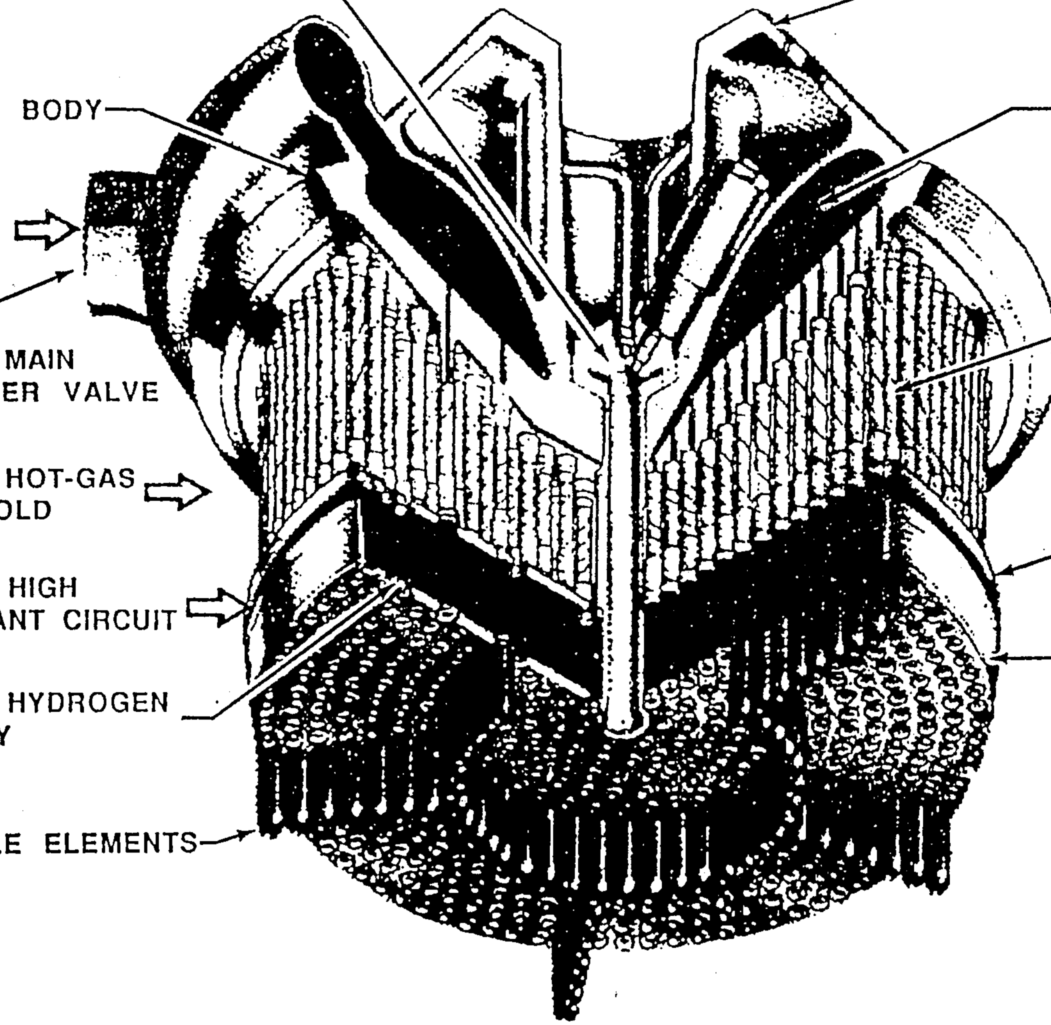


Figure 78a. SSME lox dome and splitter.

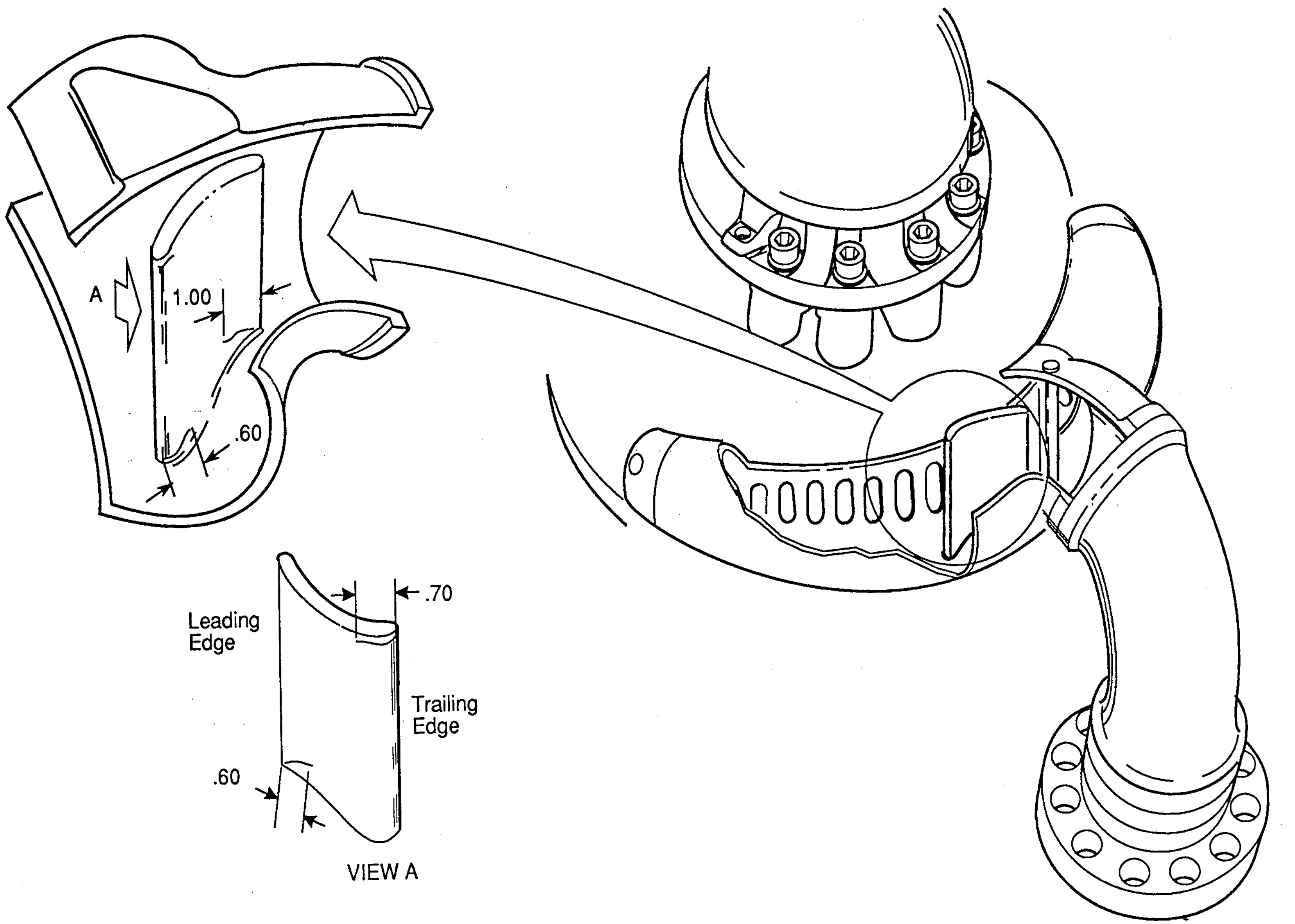


Figure 78b. SSME lox dome and splitter.

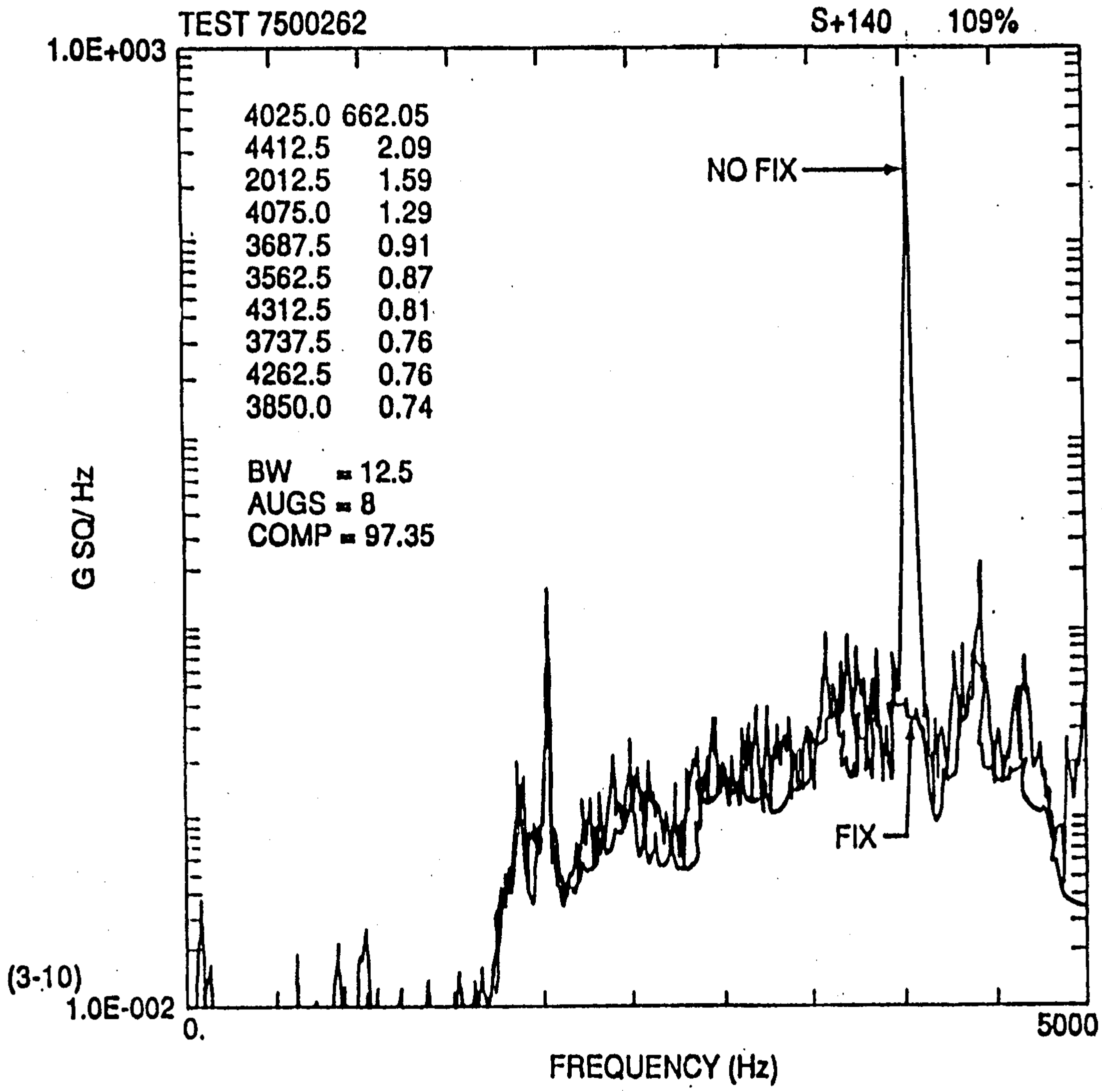


Figure 79. Spectrum of gimbal bearing acceleration.

- Load Sensitivities
- Aft Skirt
- Payload Loads
- Performance Loss
- Debris
- Pad and Tower Clearances
- Overpressure
- Acoustics (Payloads at Source)

Figure 80. Liftoff problems.

COMPONENT	DIR	MAXIMUM ACCELERATION (G's) LIFT-OFF LOADS			
		DESIGN VALUE	P.L.C.	I.L.C.	C.D.R.
PRIMARY MIRROR	X	3.7	3.1	3.5	4.5
	Y	2.4	1.1	1.2	0.9
	Z	3.7	2.6	2.0	3.2
SECONDARY MIRROR	X	3.8	3.1	3.4	4.5
	Y	3.5	2.3	2.6	2.3
	Z	6.7	5.0	3.3	12.9

P.L.C. = PRELIMINARY LOAD CYCLE, USED 5.4 SHUTTLE DATA
I.L.C. = INTERMEDIATE LOAD CYCLE, USED 5.7 SHUTTLE DATA
C.D.R. = CRITICAL DESIGN REVIEW LOAD CYCLE, USED 5.8 SHUTTLE DATA

Figure 81. Design values and analysis cycle values.

Holddown Assembly

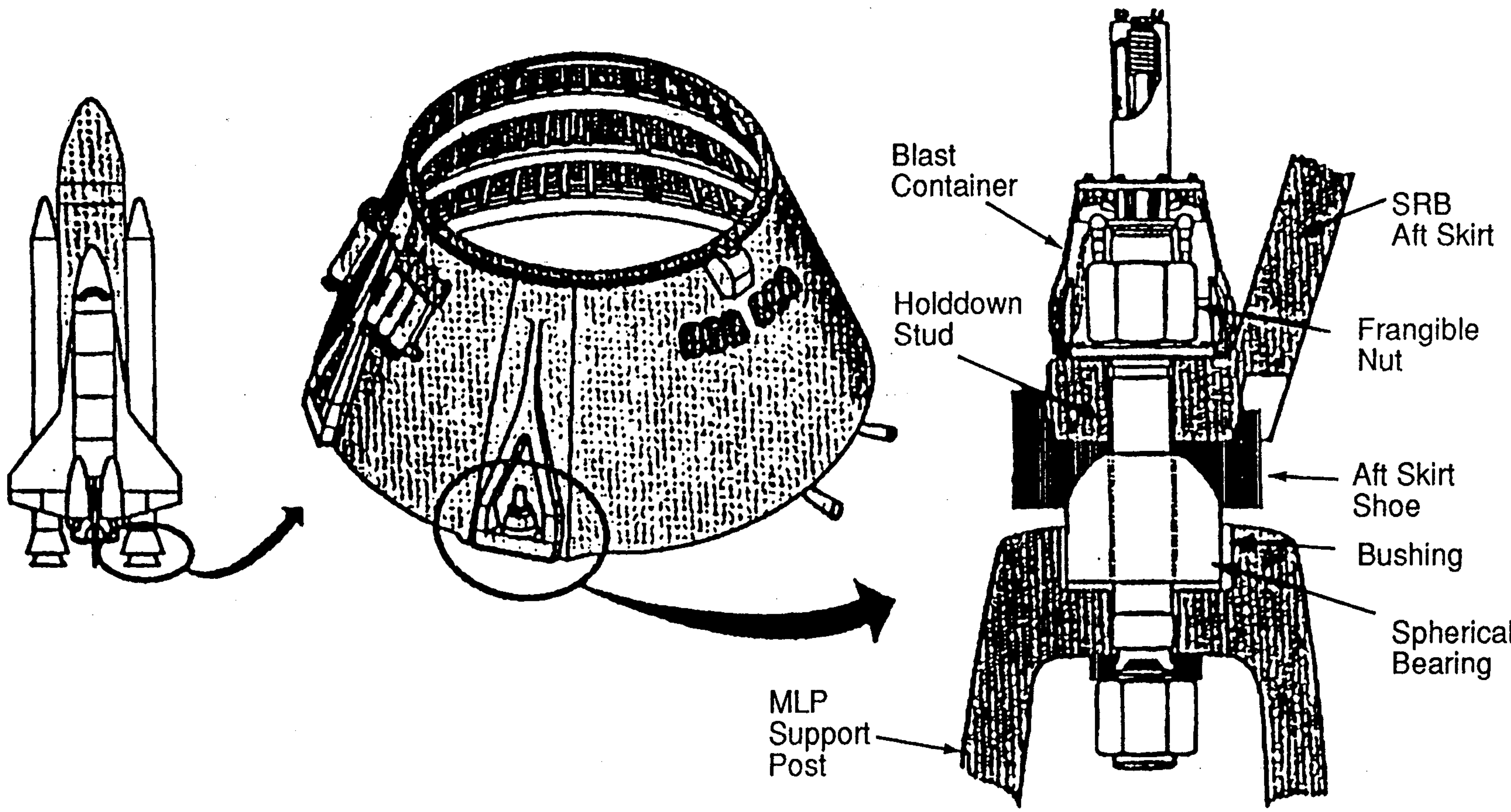


Figure 82. MLP bushing rotation anomaly.

Holddown Assembly

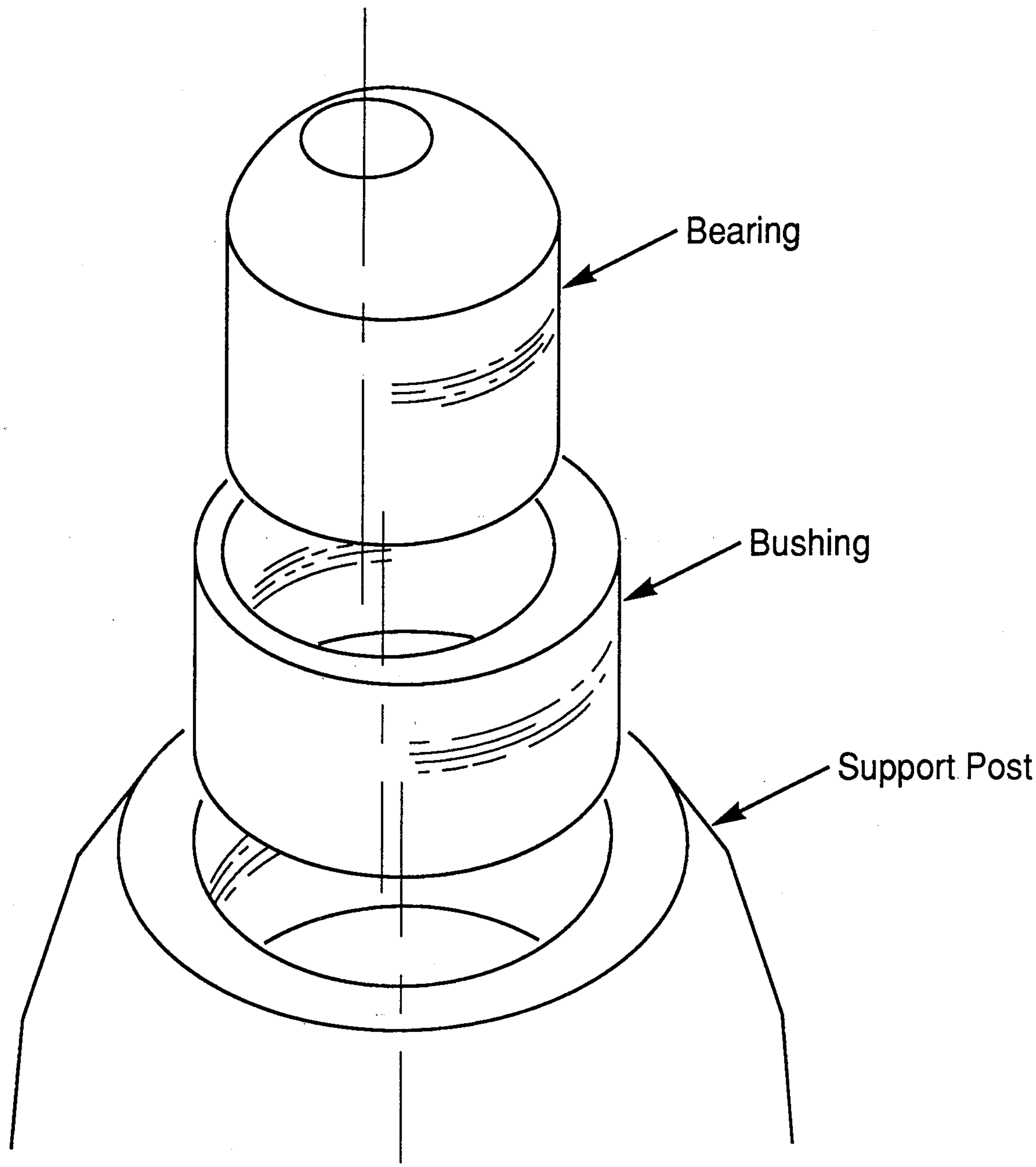


Figure 83. MLP bushing blowup.

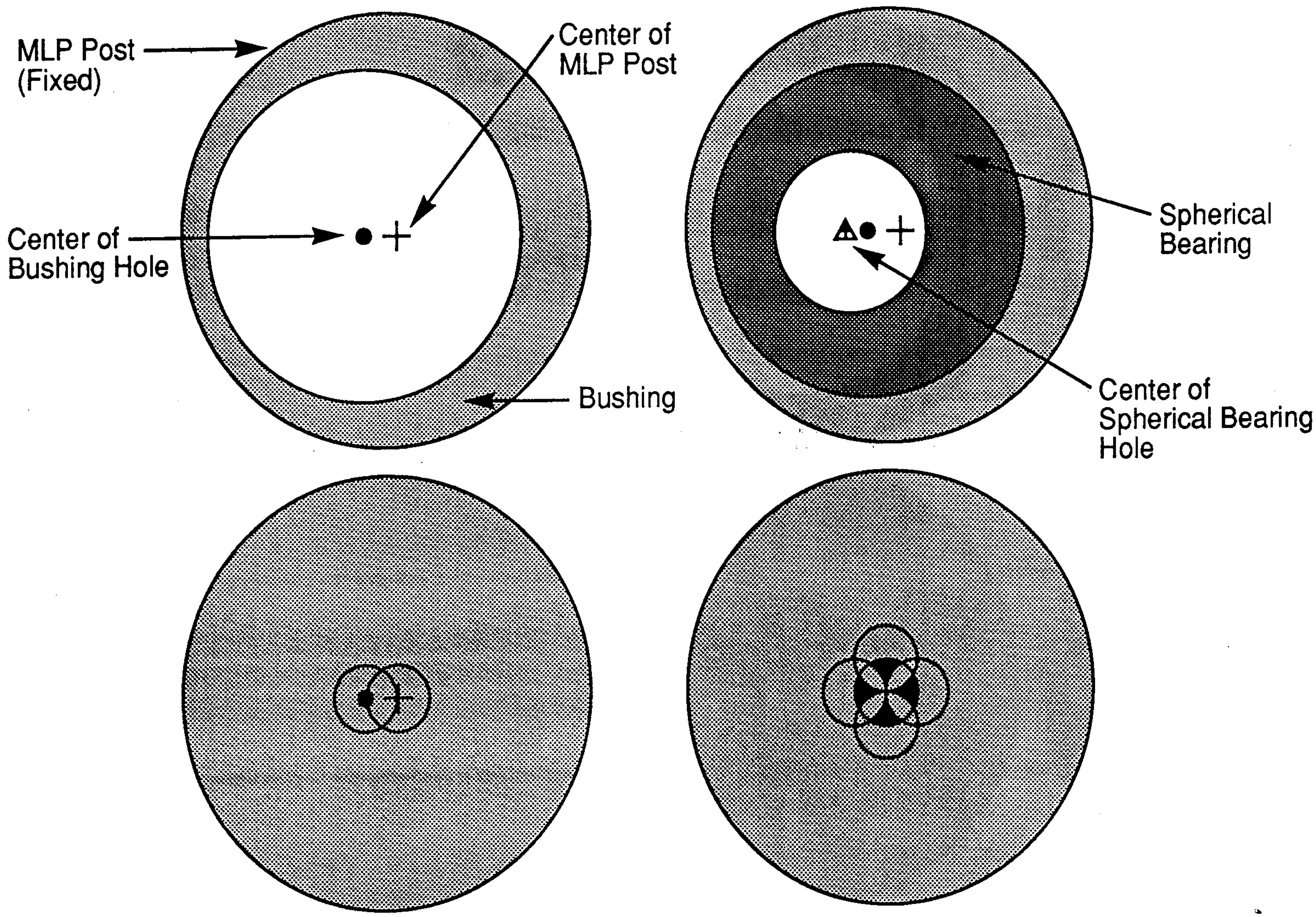


Figure 84. MLP bushing schematic of biasing.

- Constraints Imposed Early Create a Suboptimized System Which Transfers and Increases the Cost, etc., in Operations.
- Communication is Mandatory for Quality.
- Must Work as a Team Composed of all Areas.
- All Great People Make Company With Good People, Not Necessarily Agreeable People but Good People.
- Extreme Environment Variations (Cycles) Are Hard to Deal With in Long-Life Machines.
- System Analysis is the Key to Good Design.
- Sensitivities Must be Quantified and Understood.
- Dynamic Systems with Large Energy Sources are Very Susceptible to Problems.
- Elimination of Subsystem (Element) Testing and Analysis Leads to Trouble.
- Start All Complex Analysis with Basic Hand Estimation.
- Dynamic Tuning Should be Avoided.
- Never Neglect the Potential Coupling Between Structures, Acoustics, Flow, Control, etc.
- Models are Only as Good as the Assumptions Made and the Experimental Data Input.
- All Testing Must be Preceded by Pretest Analysis Giving Procedures and Instrumentation, Followed by Model Correlation and Updating.

Figure 85a. Lessons learned.

- Very Accurate Definition of the System is Required if it Must Operate Near a Stability Boundary or Margin Limit.
- Know What is Critical to the System; Model, Analyze, and Test That Area Accurately.
- Adequate Instrumentation is Required on All Tests and Flights and is Mandatory for All Critical Areas During Development Flights. Instrumentation Should be a Part of the Design.
- Multi-Body Dynamic Systems with Low Damping are Susceptible to Problems.
- Phases A and B of a Program Must Uncover Critical Technologies and Develop Approaches and Capabilities for Their Solutions.
- Read the Hardware; it has the Answers.
- Use Non-Linear Margins, etc., Only as Last Resort. Avoid During Design.
- People Determine the Design, the Hardware.
- Requirements, Constraints, etc., Leveled Early, Determine the Basic Hardware. Changes Made Later Are Only Tuning of the Original. It Is Nearly Impossible to Start Over With a Clean Sheet of Paper.

Figure 85b. Lessons learned.

1. Design Hardware for Inspectability and Manufacturability.

2. Eliminate Welds or Design Peak Stress in Parent Material Not Welds.

3. Design and Manufacture in Quality. Inspect for Insurance.

4. Eliminate Static and Dynamic 3-D Coupling Where Possible.

5. When Possible, Design in the Linear Range. Achieve Robustness. Employ Nonlinearities as the Last Resort.

6. Match Methodology to the Problem.

7. Margins Must be Specified and Validated.

8. Procedure/Criteria/Philosophy are the Backbone of Design.

9. Design Against Deterministic Criteria. Invoke Probabilities to Determine Sensitivities and Reliability.

10. Limitations of Analysis and Test Must be Well Understood and Documented.

11. Design Against Total Cost With System Optimization.

12. Design for Flexibility. What is Not Put in the Design Must be Made Safe by Operational Constraints, Maintenance, etc.

13. Institute Early Automated Data Basing.

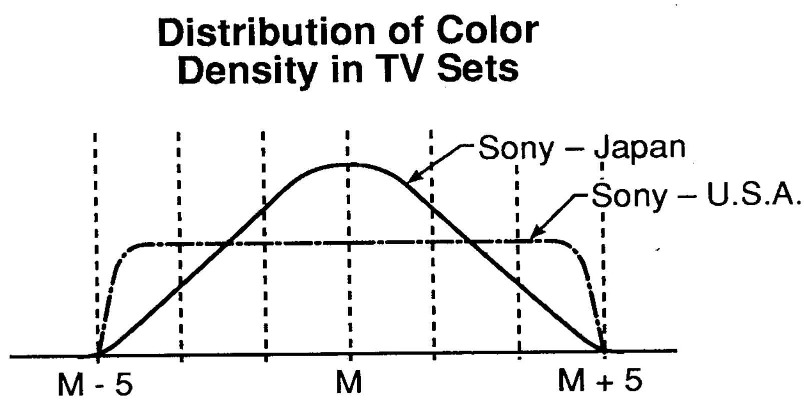
14. Design for Insensitivity to Environments (Natural, Induced, Corrosion, etc.) or Control Their Variation and Accurately Define.

15. Hydrostatic Damping Bearings Have Promise for High-Performance Turbo Pumps.

Figure 86. Design guidelines.

- Design for and Implement Fracture Control
  - Linear Elastic Fracture Mechanics
  - Plastic Fracture Mechanics
  - Materials Characterization
  - NDE
- Interdisciplinary Analysis
  - Thermal/Structural
  - Fluid/Structural
  - Structural Control Interaction
  - Aero Tailoring
  - Etc.
- System Focus/Total Cost
- Nonlinear Analysis
  - Geometric
  - Materials
- Combined Testing
- Statistical/Reliability Applied Mechanics
- Extend Technologies
- Robustness/Sensitivities
- Customer Interaction, Feedback for Requirements
- TQM

Figure 87. Envisioned tasks.



Source: "The Asahi", April 17, 1979

Factory Location	Approx. Type of Distribution	Percent Defective
San Diego	Uniform	Almost NIL
Japan	Normal	0.3%

Figure 88. Distribution of color density in TV sets.

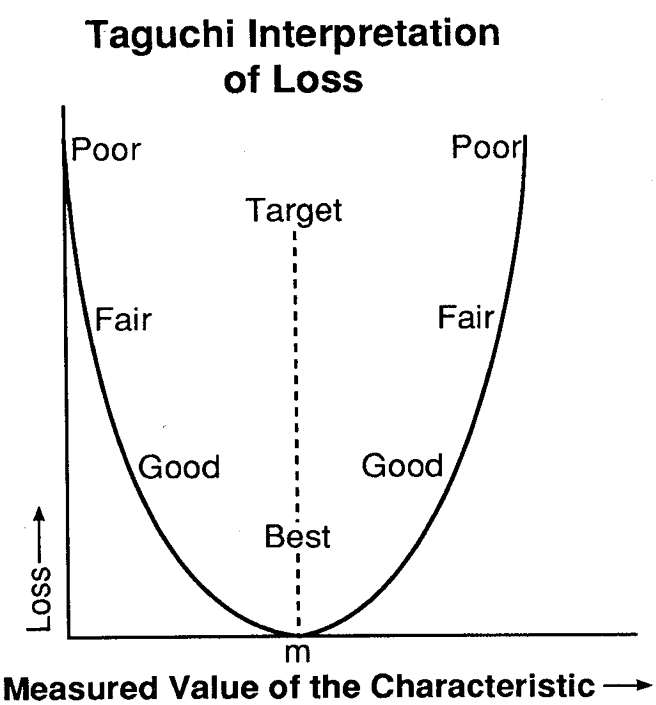


Figure 89. Taguchi interpretation of loss.

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13. ABSTRACT *(Maximum 200 words)*

This report presents the written version of a series of seminars given to several aerospace companies and three National Aeronautics and Space Administration (NASA) Centers. The results are lessons learned through a study of the problems experienced in 35 years of engineering. The basic conclusion is that the primary cause of problems has not been missing technologies, as important as technology is, but the neglect of basic principles. Undergirding this is the lack of a systems focus from determining requirements through design, verification, and operations phases. Many of the concepts discussed are fundamental to total quality management (TQM) and can be used to augment this product enhancement philosophy. Fourteen principles are addressed in this report with problems experienced used as examples. Included is a discussion of the implication of constraints, poorly defined requirements, and schedules. Design guidelines, lessons learned, and future tasks are listed. Two additional sections are included that deal with personal lessons learned and thoughts on future thrusts (TQM). A separate report, to be published later, will contain synopses of the problems experienced. They will be documented by project and cause. Approximately 175 problems have been treated to date.

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