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Robustness

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TECHNICAL PAPER

ROBUSTNESS

I. INTRODUCTION

A. Needs

The space shuttle vehicle is one of the great achievements of our times. Through the diligent effort of a large team, its performance has been superb. Yet it has not met all goals set for it. As a general statement, it is a performance-driven design; therefore, its robustness was not emphasized or optimized. This does not mean that high performance cannot be robust. At the time the shuttle was evolving, the national situation was such that, in all likelihood, only the performance-driven concept was salable. (Development cost was constrained, therefore, weight was restricted, which is what cost was primarily related to.) Several aspects of the system illustrate this point: (1) the assembly and processing (including checkout) of the vehicle require extensive touch labor and a staff of several thousand; (2) the launch constraints and problems result in many costly holds, not the least of which are the wind loads and dynamic pressure (which has resulted in three launch delays); (3) each launch has to be tailored, requiring detailed flight mechanics and loads analysis to be accomplished; and (4) many systems such as the space shuttle main engine (SSME) and the orbiter heat protection tiles are very sensitive, requiring maintenance and hardware replacement in order to meet safety requirements.

Quoting from *Aerospace America*, "A Second Look at Launch Systems Reliability," by Joseph Fragola:

"Current costs for a low Earth orbit payload are on the order of \$10,000/lb, with launch costs at about \$5,000/lb. This implies that for an average 10,000-lb payload, the launch is worth about \$150 million, \$100 million for payload and \$50 million for launch. The average success ratio of the current U.S. stable of launch vehicles, including upper stages, is about 92 percent (without upper stages it is close to 95 percent). The 8-percent failure probability implies an expected loss of \$12 million per flight, not including the lost opportunity costs.

"The new generation of launch vehicles proposed for the Advanced Launch Development Program (ALDP) has specified payload-to-orbit capabilities in the 100,000 lb range while holding launch cost constant. (In its latest incarnation, the launch vehicle system associated with this program is the National Launch System, or NLS.) Thus, an order of magnitude reduction in launch costs, or \$500/lb, would be required to keep each launch in the \$50 million range. Even if this ambitious goal were achieved, it is doubtful that a corresponding reduction in payload values would ensue. Holding payload values per pound constant would imply values approaching \$1 billion.

"While significant reductions in payload value are achievable, future payload cost will likely be a high percentage of the launch cost. Total launch values could exceed \$500 million, producing losses in excess of \$40 million per flight at historical launch success ratios. Increasing the success ratio to 99 percent would cut expected

losses to about \$5 million and could save as much as \$4 billion across even a modest 100-launch program—a considerable fraction of the overall launch vehicle development cost, even when present value considerations are included. Reducing launch cost to \$500/lb could create considerably increased launch demand and thus produce additional savings.”

The operational, maintenance, and refurbishment costs of the space shuttle vehicle, as well as the large overruns and problems with many other space projects (payloads, etc.) tax the NASA resources. It also precludes or limits starting much-needed new programs. There is, therefore, a mandatory requirement to design new products such that they circumvent the problems stated above by significant or dramatic changes. To accomplish this, new innovative approaches are needed. Business as usual will not meet the goals. Total quality management (TQM) principles applied in a program using concurrent engineering, up-front teaming, etc., hold great promise toward solving these problems, providing the innovative solution. These measures would focus on a low-cost system of high reliability versus high performance efficiency at the expense of a delicate product. A fundamental part of this process is accomplishing a total design that has robustness.

Robustness is not a well-understood concept. This lack of understanding or wrong perception raises several key questions. What is its definition? How do you achieve it? How do you measure/verify it? How do you design for it? If the design is to fulfill this goal, all these questions must be understood and answered.

The design for robustness is further complicated by the many types of space systems which require a diversity of materials, manufacturing, assembly, processing, checkout, facilities, operations, and so on. In a real sense, each type of system has a separate set of measurables and design requirements. Therefore, a specific definition of robustness and necessary design requirements is needed for each program or project. This eliminates or restricts the ability to be generic in approach (fig. 1).

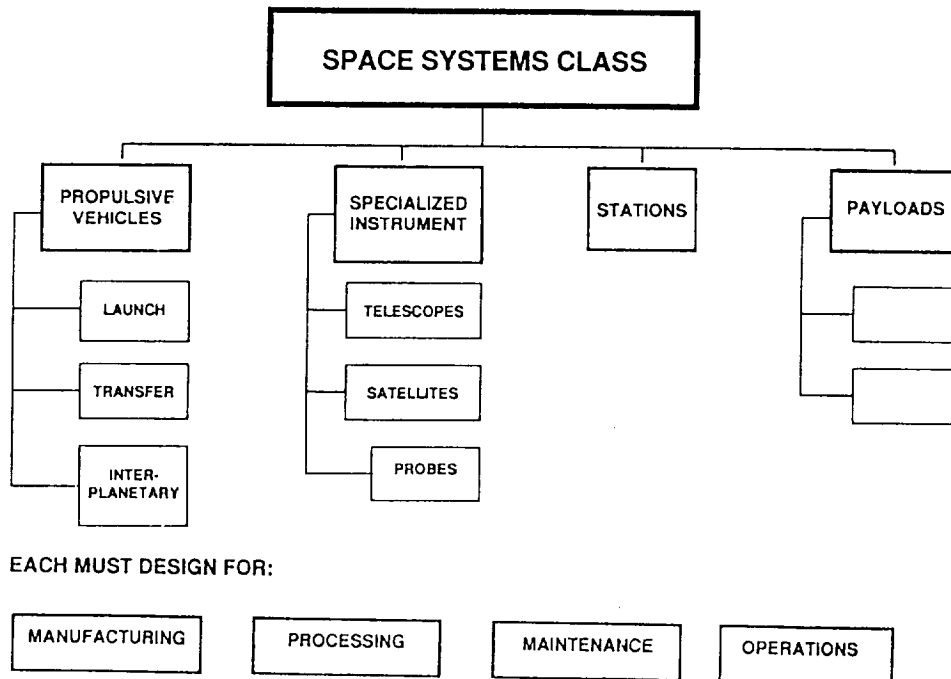


Figure 1. Space systems.

In "Robust Quality," Taguchi and Clausing say, "Quality is a virtue of design. The 'robustness' of products is more a function of good design than of on-line control however stringent the manufacturing process... An inherent lack of robustness in a product design is the primary driver of superfluous manufacturing expenses." This means that if we are to have robustness in a system, we must define what it is, the design requirements, the achievable functions (characteristics required to meet requirements), and measurables for verification, if the operating system has robustness.

This paper will develop an approach for designing in robustness as a means of reducing cost, while producing high reliability and meeting requirements. The approach will form around the items shown in figure 2, which shows the six options or their combination for achieving the desired robustness, the concept selection, the trades, and the design, all measured against the indexes. Obviously, the measurables contained in (1) cost, (2) reliability, and (3) performance are not uncorrelated even when they are shown independently. Their correlation or interrelationship must be understood as a part of the process. The approach starts with a definition of, or a determination of, where and to what degree robustness is to be included in the design of the system. A determination of the criteria to be used for the design follows along with the indexes (measurables) for evaluation of robust goodness. Using these criteria and indexes in conjunction with the various approaches available for achieving robustness, a series of trades is selected and conducted. After the concept is selected, the detailed design is accomplished. Many tools are available to augment this approach. These tools will be touched on in this paper but not discussed in depth; however, they play a key role in designing for robustness.

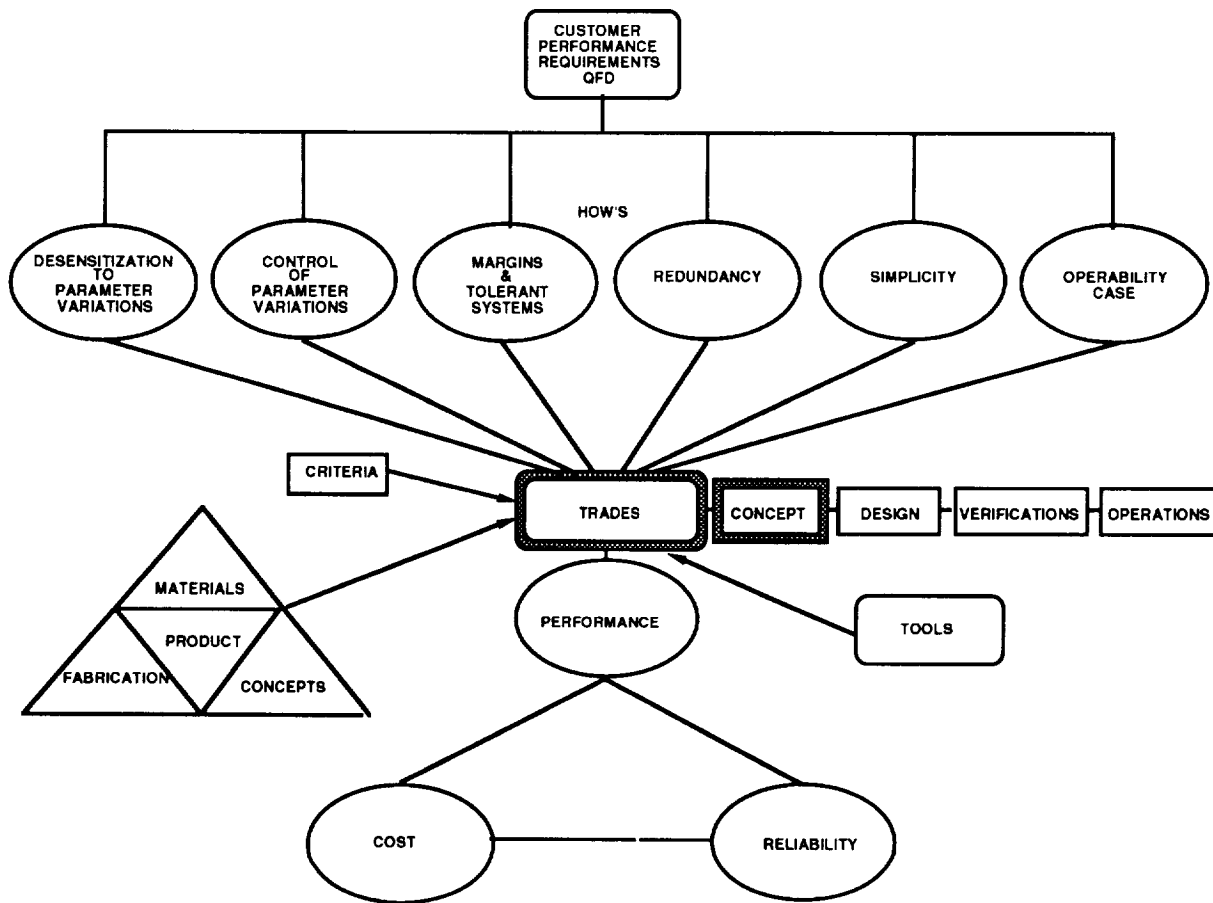


Figure 2. Robustness design approach.

A part of these trades involves concepts, materials, and fabrication approaches. Through these trades, measured against performance, cost, and reliability, the robustness of the design is driven. Testing to failure is a fundamental part of this process where the real margins (not analytical) are determined and used as part of operational flexibility. In addition, the paper will deal with a simple beam example and will show some typical factors and trades for various space systems such as a launch vehicle, propulsion systems, payloads, satellites, and the like.

B. General Approach

The task of designing for robustness starts with the visions of the program, project, or mission, and is finished only with successful operations. There are five major (top level) tasks in this design-to-operations sequence. They are:

- (1) Definition of the level of robustness required
- (2) Formulation of criteria required to ensure robustness level defined
- (3) Perform trade and sensitivity studies of potential concepts
- (4) Concept selection and design
- (5) Verification of robustness quality/level.

These steps are to some extent sequential, yet they are highly interactive, considering all areas as the tasks proceed. The focus must, therefore, be from the system viewpoint in order to achieve a balanced space vehicle, spacecraft, or space system.¹⁻⁴ Figure 3 shows these five steps and also includes the major subtasks of these areas. The following paragraphs discuss each of these tasks and subtasks.

1. Vision. Robust design starts with a vision which is translated into the original set of requirements. The initial set is generally a philosophy, some goals, and some guidelines on cost and schedule. As an earlier example indicates, space vehicle cost must be drastically reduced. This reduction must be accomplished for the launch vehicle, payload, operations, and so on. The big costs are the launch vehicle, payload, and operations. Robustness should reduce the cost associated with facility, rework, maintenance, operations, and so on; but not necessarily significantly reduce the development cost—particularly the up-front cost. To accomplish this, the second task must deal with the characteristics of the system that are necessary to achieve this objective, i.e., to reduce space vehicle cost.

2. Characteristics Required/Robustness Definition. Capturing part of these characteristics is the term, “robustness” or “robust design.” This means that the second step considers the system requirements and translates them into derived requirements (characteristics) called robustness (system focus). These can be in the form of functional statements of how to, or what to, achieve. Determining the characteristics or definition of robustness means that each of these areas must have a set of measurables identified so that the level of robustness can be determined. At the top level, this can be called the definition of robustness. All areas including design, manufacturing, and facilities must be captured in the requirements definition tasks. A part of defining robustness and

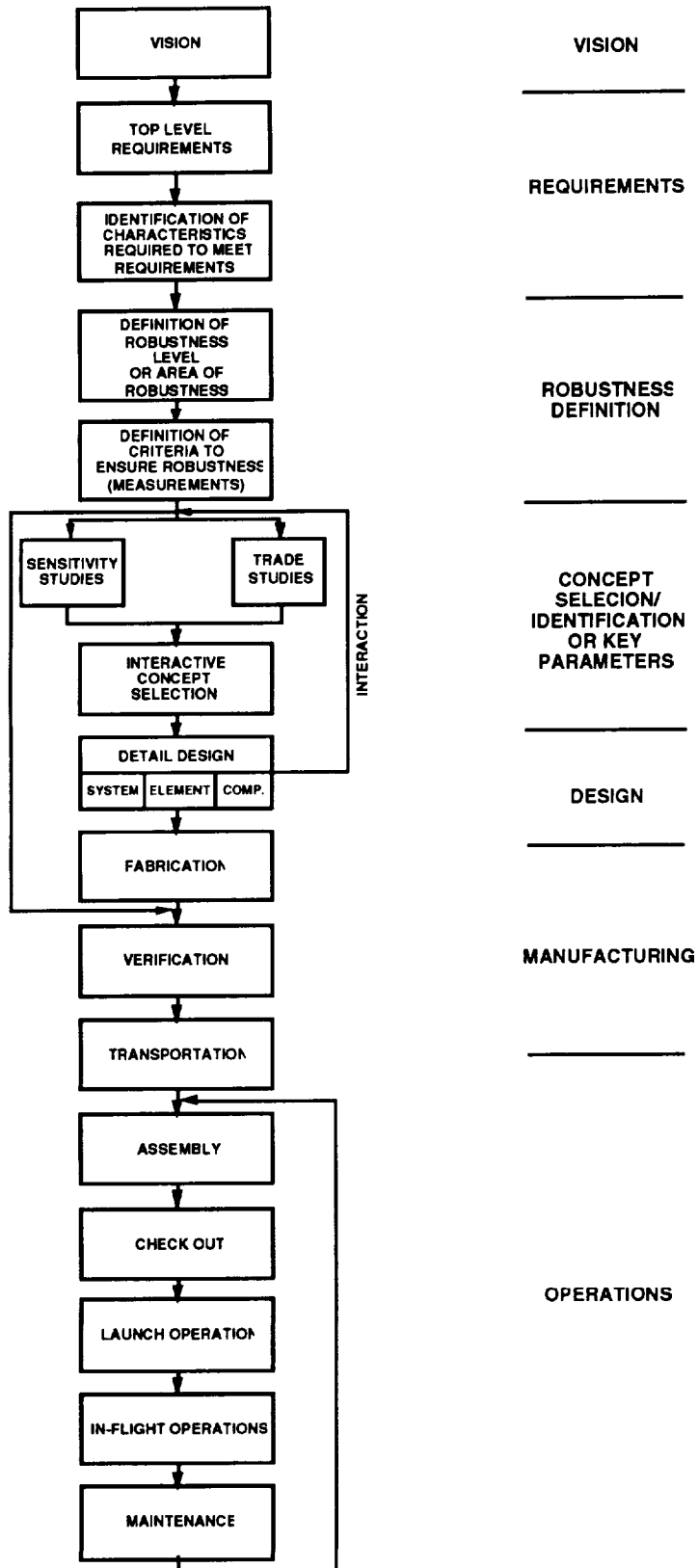


Figure 3. Robustness design flow chart.

capturing the characteristics is a listing and study of prior systems problems that increased cost, delayed operations, etc. This list will serve as a basis for describing characteristics, formulating definitions, and developing functional statements of how robustness is achieved and the requirements for it. Quality function deployment (QFD) works well in translating customer wants into characteristics leading to the definition of robustness for the system under consideration.

3. Robustness Criteria/Measurables. The next step derives and combines the generic criteria (specifications) and the requirements into a document for the project. To accomplish this, documented past experience must be brought together with the specific characteristics of this project in a way that tailors the total into a specific set for the project procedures and gives the needed control without introducing excessive cost, etc. These criteria are the key to achieving robustness. They must clearly define what it takes to ensure that the design is robust. Pugh calls this the product design specifications (PDS).⁴ QFD is one tool that translates customer needs into requirements.

4. Concept Selection/Trade and Sensitivity Studies. Next, concept selection is made by listing the functions required to meet the vision, requirements, and criteria. Using these functional statements, several viable options are formulated that can potentially fulfill the visions and meet the requirements. Three tasks are now performed: (1) conduct sensitivity analyses that identify the key areas and parameters that are important to achieving robustness; (2) conduct trade studies between the potential concepts using the sensitivities and the measurables; and (3) select a narrow set of concepts, and conduct a more indepth analysis of steps (1) and (2). These three tasks are repeated until a single concept is converged upon for design (system focus again). Tools available here include, but are not limited to, optimization programs, computer-aided designs (CAD's), and integrated analysis.

5. Detail Design. The detail design is accomplished using the concept selection as a starting point and using concurrent engineering approaches, TQM tools, etc., through sensitivity analysis, trades, design, and verification—all against the set of measurables laid out from the requirements or derived during the design process. Both the concept selection and design are evolutionary in nature, requiring several iterations. In fact, in discrete areas during design, the originally selected concept has to be changed, due to added information starting the design process over in these areas. Tools available for design are numerous and are specific for many disciplines. The list is too long for this paper, but is generally accessible. Most exist as commercial codes available for lease.

6. Manufacturing/Verification. The next step is to build and verify the product; testing many times to failure to determine limits for use in operations. The product is built right using a robust manufacturing process ensured by concurrent engineering teams upfront during concept selection and design. The verification process must determine the goodness of robustness achieved, setting the operational procedures and identifying areas for improvement.

7. Operations. The last step is operations. Operational procedures, constraints, etc., are based on the information developed during development, design, and verification analysis and testing. Although operations appears at the end, it also must be part and parcel of the requirements, concept selection, and design—a true concurrent engineering approach. These procedures, assembly, checkout, and launch and flight operations, must be designed with the same degree of robustness as the vehicle payload.

The task then is how one deals with the parts and then rolls them up into the total system since everything is interactive. In the sections that follow, these steps will be explored as they apply

to robustness as one means of increasing reliability and reducing cost. Each of these steps applies not only to the system, but to the subsystem, elements, and components. Space systems are so complex that much of the design work must occur at element and component level. How this division is made and then reintegrated into the whole is a major challenge in designing for robustness.

II. GENERAL CHARACTERISTICS OF ROBUSTNESS (DEFINITION)

A. Definition

Establishing the desired characteristics of robustness is not an easy task, particularly because, in space system design, there is a requirement that the system be quantified against the design criteria and goals. The first avenue open to accomplish this is the easiest to state, but is very difficult to quantify. For example, the classical dictionary definition reads: "The state of being strong; having been strongly formed or constructed." *Business Week/Quality 1991* defined robust design as a discipline for making designs "production-proof" by building in tolerances for manufacturing variables that are known to be unavoidable. The trick is defining the measurables of being strong. It could be stated as the insensitivity of the product to requirements, environment, manufacturing, or operational variabilities. In space systems where so many requirements are in conflict, this is not a real possibility because all designs are a balancing act—a trade-off. Gordon⁵ in "Structures" says it like this, "All structures will be broken or destroyed in the end—just as all people will die in the end. It is the purpose of medicine and engineering to postpone these occurrences for a decent interval. The question is: what is to be regarded as a 'decent interval'?"

In trying to clarify the two previous statements, classical and insensitivity, a statement can be formulated that reads: "A robust system is one which is designed and verified to have features that accommodate variability (3σ) of parameters which affect performance and margins without unacceptable degradation, and achieves the optimum combination of operating costs, reliability, maintainability, and performance." This definition treats the total system from start to finish, but still has the difficulty of determining measurables. The other open definition avenue is a mathematical definition which uses deterministic and probabilistic approaches. Here, performance indexes must be formulated for each area of concern in mathematical terms, then the system verified to those values (fig. 2). For many of the areas, this is easy to formulate if they are treated separately; however, they interact with others leading to the requirement for a higher level index.

A possible mathematical definition is: a design that provides a sufficient ratio between "strength" (or capability or capacity) and "stress" (or loadstate environment or operating condition) to accommodate variability of the parameters affecting stress and strength without failure inducing overlap.

The essence of the above two statements is required to define robustness. The final result is a statement that is a combination of the generic statement and the multitude of mathematical indexes. The first can be generic, as stated above. The second is specific for each space system and requires much effort to define the sensitivities, conduct the trades, and then quantify the requirements indexes. Many times it is desirable to modify the statement such that robustness is defined only in terms of one area such as launch operations (cost, processing, turnaround, checkout). In this case, each component or subsystem is not optimized individually, but only to the extent it affects operations. The indexes are tailored to fit this special case. As has been stated previously, the

definition of robustness for a space system is always tailored to fit the needs and requirements of that particular product.

B. Measurables

Determining what are the measurables of robustness, how they are formulated and quantified, is a major and key task for achieving robustness in design. Bill Campbell of Aerojet provided figure 4 and the following statements as a way of determining measurables for evaluating robustness.

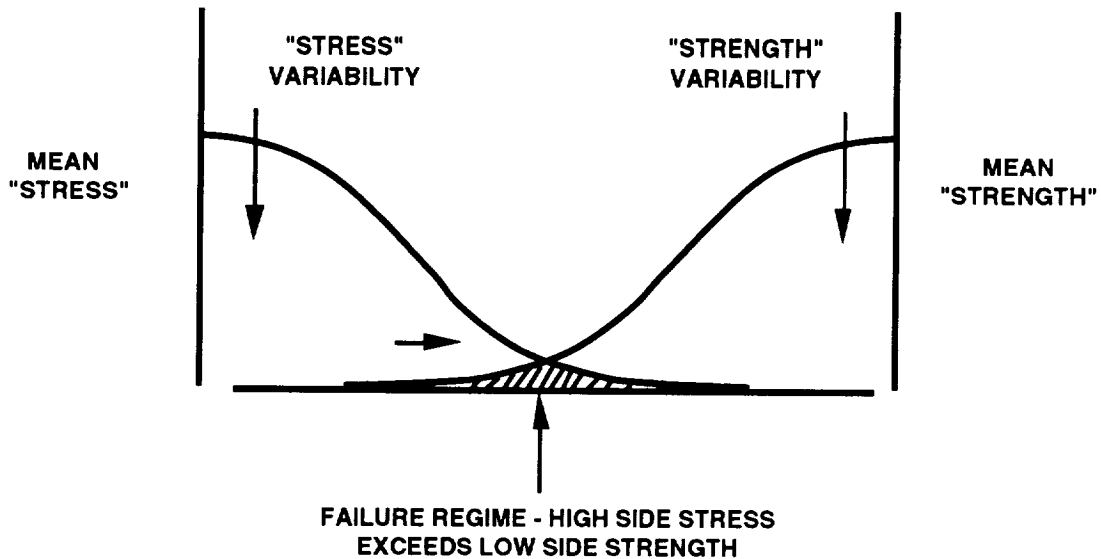


Figure 4. Failure definition/margins or capability.

“Capability or capacity” may be defined as that characteristic of a device which accommodates a given “stress” and is a function of its configuration, material, environment, manufacturing process, and prior operational history. Stress, in this case, is a prediction of any type of response, while strength is a quantified measurement of its capability. This should be expressed in statistical distributions where possible.

Therefore, “environments or load” may be defined as the characteristic of a device which infringes on the “strength” characteristic and is a function of the environments to which it is subjected.

Variability is a measure of the range of both “stress” and “strength” that a device experiences or possesses as a function of the range of conditions, process and properties, analysis, etc., involved in the design, analysis, manufacture, and operation of the device.

These indexes are typified by design margins (safety factors, stability margins, redundancy level, etc.); depletable margins (weight reserves, software reserves, etc.); performance margins (delta v, acceleration, propellant tankage, etc.); launch capability; payload processing and change out; assembly and checkout; launch processing; facilities; reliability; maintenance; dependability; and touch labor. All must be quantified in some measurable manner as requirements.

In dealing with the performance and reliability indexes for concept selection and design, many times mathematical or statistical formulations do not exist. Yet this is the most critical time for making decisions that involve materials, configuration, etc. Because the decision cannot be quantified (qualitative answer only) and is made by judgment, this judgment must be justified by developing check-off matrices, logic charts, and rationale statements as supporting evidence and historical records. These can include, but not be limited to:

- (1) Number of welds
- (2) Joints
- (3) Load paths
- (4) Margins
- (5) Number of elements/bodies
- (6) Manufacturing complexity
- (7) Technology maturity.

In some cases, these can be augmented by some statistical estimation that cannot produce an absolute value, but can verify trends, etc. The problem that always faces one is how to develop reliability data or statements in terms of the hardware design parameters. In avionics systems and materials characteristics, some of this work has been accomplished. In structural systems, there is much less data to deal with.

The bottom line is that the process under discussion works regardless of the degree of quantification achievable. However, the more quantification, the better the decision. Later sections will deal with the process for establishing and quantifying these indexes.

III. GENERIC/TOP LEVEL APPROACHES

A. Basic Approach

Using the generic definition as a base, the generic makeup, or top level, approach to robustness can be formulated. Figure 2 attempts to accomplish this task. As is shown on the top of the chart, there are many elements or ways of achieving robustness. In the case of certain components or subsystems, it is possible to design in a measure of robustness using only one element such as structural margins or redundancy; however, in general, some combination of the ones listed, or others, is required. One of these elements can be chosen to be the definition of robustness. In this case, it is move to the robustness block for example operations such as launch on time. Using this new definition, all the other elements are judged only as they affect that special definition. In general; however, to make a total system (such as a launch system) or an orbiting system (such as telescope) robust, a combination of all will be required. In complex launch systems, spacecraft, and orbiting instruments, a sensor failure during launch scrubs a mission, while failures in operations can lead to mission loss (possible loss of life, if manned). A breakdown in manufacturing tolerance

control may also lead to many problems. The same can be said for any part of the system, processing, facilities, assembly, communications, operations, etc. The old saying “for the want of a nail for shoeing the horse, the war was lost” is appropriate here. To have robustness in space systems, the total system must be robust. Each system must define what is meant by robustness for that system; an example would be the launch facility. In all cases, regardless of which area or definition is chosen for robustness, the sensitivities of the system to its parameter variations must be determined (quantified, if possible) against that definition so that robustness is *built in only where needed*. The goal for robustness, by its very nature, cuts across many disciplines—from fatigue and fracture control, to avionics hardware and software, and then manufacturing and operations. The basic question is: what do you design in up-front to preclude downstream problems? How far do you go? What is the balance? Otherwise, the cost and/or weight becomes prohibitive, or the performance is degraded.

Designing in robustness proceeds down two legs simultaneously. One is designing the product, the other is designing how to make the product (this includes manufacturing and assembly). Operations can be separated out of the product design function, thus creating three legs. It appears to the author that operations are such a fundamental part of the product that they must be involved in product design. In other words, the design must be compatible with the manufacturing, operations, and assembly capacity in order to be robust. It is of little value to design a system where manufacturing cannot meet the tolerance requirements, thus producing yield that is too low. Experience in manufacturing of high performance systems such as SSME has shown that these systems are very sensitive in manufacturing to such things as weld offsets, weld beads, etc., producing fatigue or fracture failures, and numerous reworks and material review discrepancies requiring extra effort to maintain operations. Even with these problems, the SSME is an example of the degree of craftsmanship that can be achieved in manufacturing a very complex, high-energy density system. However, sophisticated manufacturing capability is of little value unless the design requires it. The simpler the design, the simpler the manufacturing process required. Figure 5 attempts to show that this parallel, yet highly interactive, process is required to have an operational robust system.

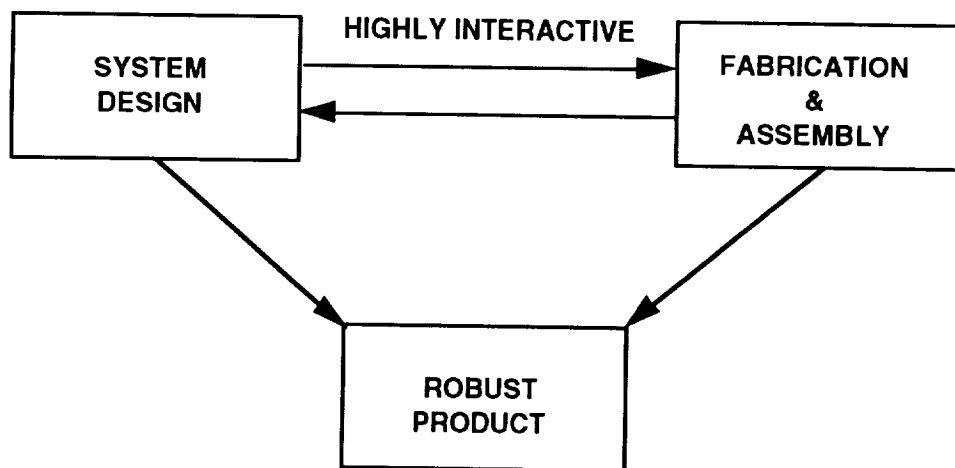


Figure 5. Legs of robust design.

Robustness in the manufacturing and assembly leg occurs in two ways. First, it must be able to achieve the characteristics the designer evolved within acceptable limits. Products are plagued with problems that arise because of the lack of manufacturing robustness. Part of the time this is due to poor communication, in that the designer asks for more than can be reasonably achieved. Then other times, the designer does not do the design job with consideration for manufacturing limitations. This clearly indicates the need for concurrent engineering in both legs. Second, manufacturing must be robust in delivering quality robust hardware on time. Robust products depend on both.

Figure 2, therefore, must be applicable to each; getting the same emphasis and focusing on the interaction. Obviously, the operational procedures, processing, and the like must have the same robustness as these two legs, but, as stated earlier, is included in the product design leg. In the following, it is assumed that this integration approach is followed in designing for robustness.

1. General Characteristics. In order to gain insight and understanding, it is necessary to first understand the definition, characteristics, and functions of each proposed way of achieving robustness (fig. 2). With this understanding of each potential candidate, the robust system can be achieved using various combinations of these broad areas. Designing for margins (tolerant system) is not straightforward. For example, increasing the structural safety factor adds weight that, in turn, can increase the inertial load, but not provide added margins. Also, if this increased safety factor margin in the design is not reduced (limit load safety factor) for operations, then no real gain occurs because the system cannot take advantage of this margin—except in an anomalous situation during operations. Stability margins for dynamic systems, including control, fall into this category because you cannot, by operational design, take advantage of extra margins unless it is specified differently for design and operations. Avionics, software, performance reserves, etc., all fall into this same category. However, extra margins judiciously placed early in design can be used as a hedge against environment creep—producing, in the end, an adequate system (based on the sensitivities). If this is not done, then the environment creep leads to either a redesign or a constrained operational system. One way of gaining margins is to take advantage of the inherent nonlinearities, not included in the linear design, for operations. This requires more accurate quantification of the response characteristics and is, therefore, more costly. One method for quantification is testing the product to failure; determining the limit that can be used to make up robust operational procedures and constraints.

Ideally, one would like to design the system so that it does not respond to variations in the parameters. (In the discussion that follows, the use of the word parameters is all-inclusive. It not only implies such things as flow, thermal, acoustics, and the like, but also includes manufacturing tolerances, processes, flaws, offsets, and so on, which affect the robust characteristics under consideration.) In most cases, this is not possible; however, when it can be accomplished, the gain is not free. For example, vibration isolation of a component (electrical, hydraulic, etc.) renders it insensitive to the vibration, but at the introduction of larger deflections from static and quasi-static loads. In other words, vibration absorbers can desensitize the component to the vibration by introducing large static deflections; however, complexity, including new failure modes, is added in addition to cost increases. Load relief and ride control add complexity and new failure modes, as does active thermal control. The same is true for controlling manufacturing tolerances, etc. However, in many cases, this added cost and complexity is more than balanced by the gain in robustness.

Control of parameter variations is another design tool for achieving robustness. Many examples for this approach exist: active flutter suppression of aircraft wings, POGO suppression, modal suppression, rigid-body load relief control, thermal control systems, day of launch I-loads update (real-time wind biasing), and statistical process control (SPC) in manufacturing, to name a

few. These techniques are used extensively and are the tools that allow a system to operate safely and meet its performance goals. Another approach to controlling the environment is to have a predictive scheme that results in no operational use during times of higher-than-predicted acceptable parameter variations. Prelaunch atmospheric wind monitoring for launch vehicles is in this category. In this case, the vehicle is not launched into atmospheric disturbances that are greater than its capability, or the I-Load (trajectory shape) is updated to reflect the effects of the wind measured 1 or 2 h prior to launch increasing the margins allowing a safe launch (day of launch I-Load update). Controlling the parameter variations is not free. Complexity and failure modes are introduced as well as added cost, assembly, limited operations, and so on. In some of these cases, one gives up robustness in launch flexibility, introducing operational complexities and increasing cost.

Redundancy, particularly on manned systems, is an acceptable way of achieving robustness. This approach is used extensively in electrical and hydraulic components, windows, fasteners for joints, load paths, etc., and such things as dual thermal insulation and debris shields. Again, one must deal with complexity, failure modes, cost, and weight. The design, in this case, must deal with how many layers of redundancy are required. The greater the redundancy level, the greater the complexity and cost.

Simplicity in design normally enhances robustness, as well as manufacturing, assembly, operations, and response. This design area for robustness is broad in scope, number of elements, load paths, geometrics, turnings, structural concepts, and the like. It also affects redundancy, margins, variations, and operability. The use of simplicity in design is a well-known approach. Pugh in "Total Design" discusses it in detail and has formulated some criteria for measuring its achievement.⁴ Design simplicity should always be a goal. The simpler the design, the easier it is to gain robustness.

Designing for operability leads to robustness in at least two ways. A complex operational procedure causes problems because it opens up more paths for errors. The second part of the definition of robustness, particularly for space vehicles and spacecraft, deals with launch on time, processing, checkout, etc., required for each mission. Ease of operations not only has a direct correlation with simplicity, but also with cost. As stated earlier, operation efficiency can be used as the total definition of robustness. Then the other elements are used as means of achieving this new goal.

A part of the design for robustness is the use of failure modes and effects analysis (FMEA) as augmentation to the normal design process.⁴ Minimum failure modes should be identified for each concept and evaluated in line with the other considerations to ensure a better quality of robustness.

As mentioned previously, part of the process of the "design for robustness" is the study of problems that have occurred in past systems.^{1 2} These problems have usually led to costly redesign, high maintenance costs, launch holds, etc. The process used in problem study must lead to an understanding of where the lack of robustness occurs in these systems and the resulting lessons learned. With this information, the project has the basis for deriving requirements and criteria, selecting concepts, and making them robust. Without this information, one is doomed to repeat the mistakes of the past.

2. Trades. So far, the six broad areas of designing for "robustness" have been discussed. There are additional factors required to deal with these areas in achieving robustness which are applied through engineering, trades, sensitivity studies, and design. First is the criteria that are imposed by the product that provides the mantle for the design. The criteria must be carefully tailored

to capture the characteristics of robustness desired (see later section), and must be accomplished by a combined Government and contractor team including all pertinent disciplines.⁶ Second, a key in the robustness trade is the concept selection, materials choice, and fabrication requirements approach. These three elements are correlated, presenting options from which the design engineer can choose to create robustness (fig. 6). For example, he picks a concept (ring/stringer/skin), then chooses between several materials (aluminum, steel, etc.), and the different fabrication processes (milling, welding, riveting, etc.). After repeating for other concepts, a set of trades is conducted to arrive at a concept selection. He must conduct these trades using the three measurables of performance, cost, and reliability as the judge or evaluation guide. The cost measurable is very difficult to define. Up-front cost loading, used effectively, lowers recurring cost. Which cost is the driver? Concept selection? Design? Recurring cost? What is the proper balance between them? Also, how does one estimate the cost of major design problems versus indepth up-front preventative design? Proper formulation of the balanced total cost indexes is the key to good system engineering and robust design. Here, various indexes must be developed for these three areas to provide measurables for evaluation. They can be probabilistic or deterministic in nature. Developing these measurables is a major task in itself and is fundamental to the process. In later sections, some typical indexes, concepts, materials, fabrication approaches, and trades are listed as guidelines. They must be used only in that light. If robustness for any system is to be achieved, these must be developed specifically for the product being designed. Intuition and innovation, as well as lessons learned, are needed. In most cases, new paradigms must be developed. In the early part of the program, much effort must be expended in order to determine the sensitivities and concept potentials.

In "Quality Engineering Using Robust Design," Phadke talks about exploiting the nonlinearities inherent in the system due to the different parameter combinations even for the same noise factors/variations used.³ He then deals with the classification of parameters into these classes:

(1) Signal Factors (M): The parameters set by the user to express the intended value for the response of the product (requirements for performance, settings to produce performance).

(2) Noise Factors (X): Factors that cannot be controlled by the designer. Only the statics (mean and variance), not specific values, can be known.

(3) Control Factors (Z): Factors that can be specified freely by the designer. He is responsible for determining the best values of these parameters.

The relationship between these parameters can only be known through experiments. Also, the magnitudes, costs, etc., are not well known during design, so a three-step strategy is proposed.

(1) Concept Design: The selection of architecture, from a variety, that will achieve the desired function of the product.

(2) Parameter Design: Determine best setting of control factors that minimize quality loss.

(3) Tolerance Design: This is the tradeoff between reduction in the quality loss function due to performance variation and increase in manufacturing cost. Tolerance design would bring in higher tech solutions and should only be done after sensitivity to noise has been minimized through parameter design.

CONCEPTS	MATERIALS		PLASTICS		FABRICATION				
	Metallcs	Alloys	Composites	Elastics	Welding	Milling/Machine	Casting	Fasting	Robotic
Integral									
Commonality									
Ring Stringer									
Milled									
Modules									
Smart Structures									
- Active									
- Passive									
Erectable									
Space Assembly									
Space Manufactured									
Manned									
Unmanned									

Some of the selection factors are:

- Consequence of faults
- In-service temperature
- Weldability
- Stress level
- Fractur toughness
- Detrimentation/Corrosion
- Maintenance
- Verifiability
- Manufacturing complexity

Figure 6. Materials, fabrication, and concepts trade matrix.

The approach presented by Phadke solves many design problems, particularly for mass-produced systems. It does not work well for all space system problems. Many other approaches exist such as "Total Design" by Pugh,⁴ the various Taguchi approaches,^{7,8} including the above from Phadke, QFD,³ concurrent engineering, and probabilistic design. Each must be explored and used to aid in robust design. Figure 7 illustrates the process discussed in previous sections along with their characteristics and a partial listing of the available tools.

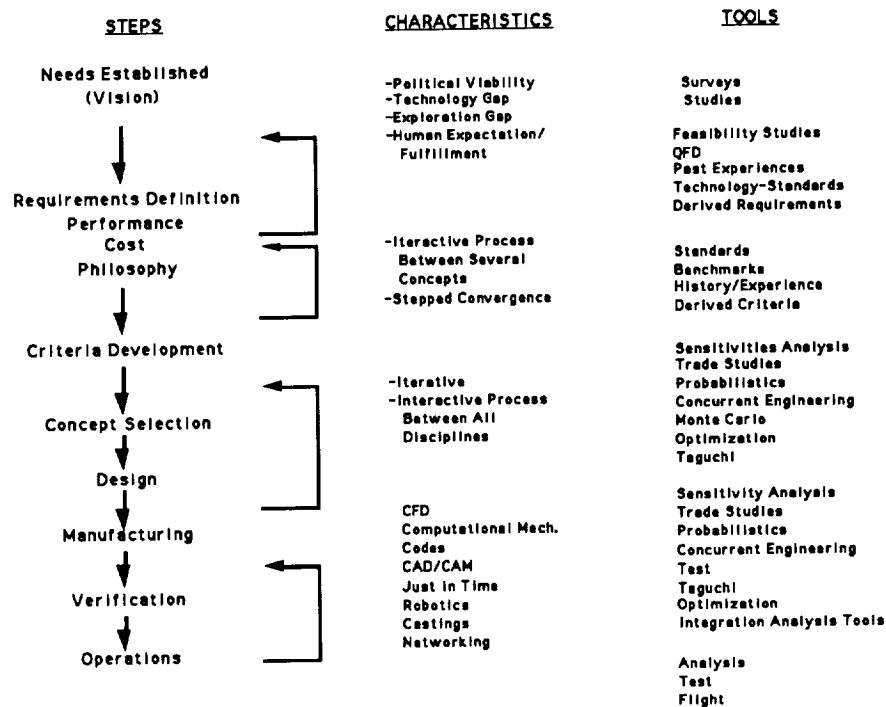


Figure 7. Steps in design.

The process is one of stepped convergence (fig. 8), initially involving several concepts which converge through proper trades and design analysis to the concept that can meet the criteria, performance, and reliability goals. Robustness is only one part of these measurables; many times being in conflict with other elements of the requirements. This leads to either a requirement redefinition or decision by the project to make certain compromises. All design involves compromises. In design for failure, as is so clearly stated by Gordon in "Structures," the success of the design depends on how well this "conflict of expectations" is managed and qualified. As stated above, figure 7 delineates these steps, their characteristics, and some of the tools available to augment the process of each step. This section has dealt with the design for robustness at a top level. In practice, the process becomes one of applying these principles to components, elements, systems, as well as functional areas, each involving very specific trades and criteria (requirements). Each of these then must be traded against the element and system interaction effects during the production of the final product. In the end, the total system must be evaluated using these subdivided robust parts to determine if the overall robustness goal has been met. TQM principles, with up-front teams composed of disciplines and functional areas involved, is the current approach espoused for achieving this goal. The following sections will deal with these more detailed trades and approaches as they apply to specific space system areas such as launch vehicles, propulsion systems, spacecraft, and satellites. Before pursuing investigating these areas, it seems prudent to illustrate the approach with an example.

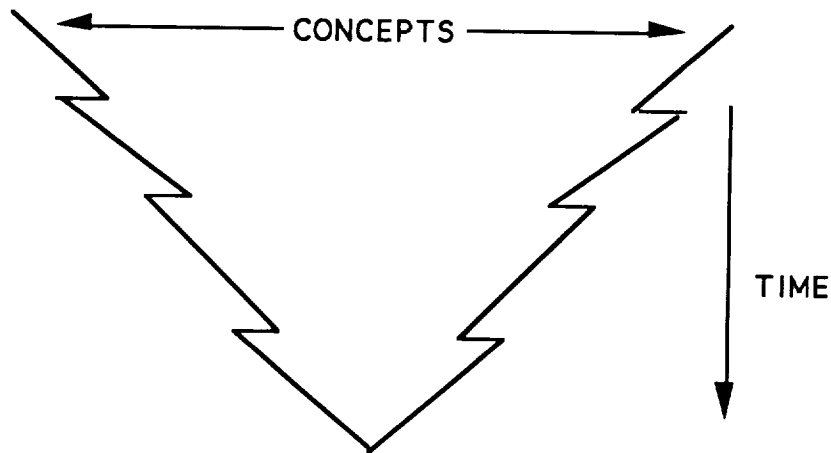
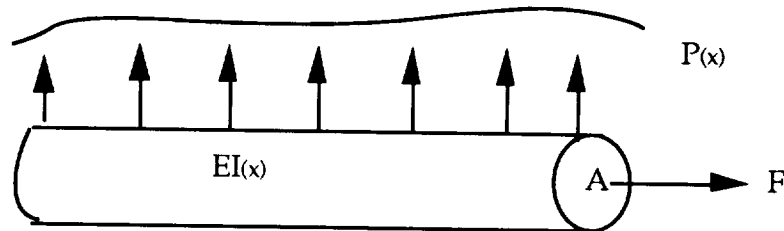


Figure 8. Concept selection.

3. Example. The generic approach just discussed is illustrated in the following with a so-called simple problem. A beam with lateral and axial forces:



The equation for the stress needed for design is:

$$\sigma = \frac{MC}{I} + \frac{F}{A} \quad \text{or} \quad \sigma = \frac{P(x) \left(\frac{X}{C} \right) C}{I} + \frac{F}{A} \quad (1)$$

$P(x)$ and F are forces that are both static and dynamic, containing both external forces and the induced inertial forces from the response.

Uncertainties exist in all parameters:

$$\bar{\sigma} = \sigma(1 + \varepsilon_1) = \left[\frac{P(x) \left(\frac{X}{C} \right) C}{I} + \frac{F}{A} \right] [1 + \varepsilon_P + \varepsilon_I + \varepsilon_F + \varepsilon_A], \quad (2)$$

where the ε_i are the variations in stress due to variations of the parameters.

This gives the basic equations for the stress of a beam performing a basic function. Now, let us see how it fits into the scheme of designing for robustness. The first step is to determine its use. Is it a seesaw, a lever, a simple support beam, etc.? The equations must be modified to account for the performance requirements. Given the usage (requirements), the criteria must be determined: strength, fatigue, ductility, buckling, thermal, moisture, deflections, vibration, corrosion, inspections,

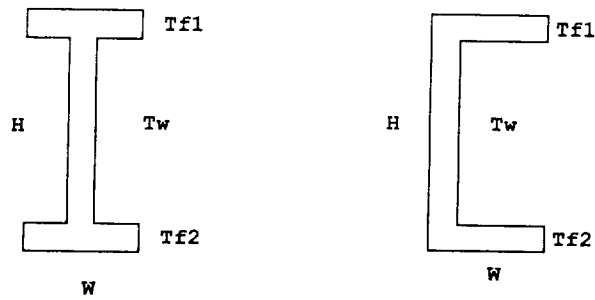
and so on. With requirements and criteria determined, the concepts and methods of redundancy must be selected for trades. A beam can be a truss, a continuous solid, laminated, etc. It can be made of wood, metals, plastics, or composites. The fabrication procedure also enters into the process; extruded, welded, laid up, glued, etc. The forces must be determined. They are, in general, both static and dynamic, distributed and point loads, mechanical, thermal, magnetic/electromagnetic, acoustical, etc. Some estimation of their magnitude and expected variations is needed, as well as the manufacturing variations and analysis errors. Given this type of information, a series of sensitivity studies can be made for the various concepts. These are traded against cost, reliability, and performance. This means that indexes must develop for each of these areas. Performance indexes include such things as dynamic response, deflection, stress, weight, and thermal. Cost includes complexity, design, manufacturing, facilities, and operations. Reliability covers the use items such as lifetime, failures, refurbishment, and operations.

To illustrate this part of the process, the simple beam, cantilevered, with a point force, is evaluated for three materials and two concepts. The two concepts are an I-beam and a C-beam. The materials are aluminum, titanium, and graphite/epoxy (fig. 9). The process is started by designing each beam concept using the three different materials to meet the same performance requirements using minimum dimensions. Figure 10 shows those dimensions as well as the corresponding design weight. Clearly, graphite epoxy has the lowest weight and total cost against the mean. Next, the sensitivity of the geometric dimensions (plus and minus), based on expected manufacturing variations, must be determined. The partials of the various performance parameters to the dimensional variations are then determined. Figure 11 is a matrix of these partials. Variations of other parameters such as the force, temperature, etc., must be included in a real decision case. Only manufacturing tolerances are used here to illustrate the approach. Also, these partials only deal with the sensitivity due to manufacturing variations, not the differences due to concept and materials effects on the mean value. These differences were discussed earlier and will be discussed again later. The key tolerance parameter is the web thickness variation. Graphite/epoxy, again, has the lowest sensitivity to variations in terms of the performance indicators. The matrix partials can be combined in equation form for each performance indicator for each system so that, in complex interactions, a quantitative evaluation can be made. For example:

$$\delta_i = \frac{\delta}{\delta\omega} \Delta\omega + \frac{\delta}{\delta H} \Delta H + \frac{\delta}{\delta T\omega} \Delta T\omega + \frac{\delta}{\delta T_A} \Delta T_A + \frac{\delta}{\delta T_{f2}} \Delta T_{f2} .$$

The same can be formulated for the other performance indicators. Graphical presentations of this performance indicator provide excellent visualization and help understanding.

A typical linear variation for one performance indicator, one material, and one concept is shown in figure 12. The effects of combining the variations (sensitivities) and the basic characteristics of the three materials and two configuration concepts on cost are illustrated by assuming that all five configurations were designed to the same performance indicators (for nominal conditions) for stress, deflection, and buckling. Assuming that this system is to fly on the space shuttle, then there is additional cost of \$10,000 per pound of payload assumed. This leads to a total cost value shown in the last column (fig. 10). The results are shown graphically on figure 13 for the manufacturing and materials cost, while figure 14 shows all the cost including payload. Based on cost, the graphite/epoxy is far and away the cheapest regardless of the concept. Because cost is, in general, not the only consideration, the deflection (stiffness) can now be evaluated in the same manner as cost. Putting all the indexes together using the matrix of partials allows the final evaluation. The key to the exercise is the linear partials that allow a quantified evaluation of the



Design Case: Cantilever Beam; point load located at free end
Cross Sections: I-Beam, C-Beam

Design Constraints:

- i) stiffness
- ii) material stress limits
- iii) torsional stability
- iv) frequency response

Materials Investigated:

- i) Aluminum
- ii) Titanium
- iii) Graphite/Epoxy

Figure 9. Design for minimum weight.

Material and Manufacturing Costs:

	Material	Manufacturing	Total Fabrication	Weight	Weight Penalty	Payload Penalty ***	Net Cost
Aluminum-I	140	720	860	3.11	1.59	15,900	16,760
Titanium-I	1,100	720	1,820	4.37	2.85	28,500	30,320
Gr/Ep-I	76	1,006	1,082	1.52	0.00	0	1,082 *
Aluminum-C	140	720	860	3.11	1.59	15,900	16,760
Titanium-C	1,100	720	1,820	4.37	2.85	28,500	30,320
Gr/Ep-C	88	757	845	1.76	0.24	2400	3245 **

* – Does not include one-time tooling cost of 3,240
 ** – Does not include one-time tooling cost of 1,620
 *** – Based on \$10,000 per pound of payload

Cost vs. Performance Evaluation:

- All three materials were designed to have equivalent performance characteristics
- The graphite/epoxy beams cost comparable to aluminum to fabricate (not including the one-time tooling cost)
- The weight savings (payload penalty) for the composite beam is the most favorable

Summary:

- Graphite/epoxy (unidirectional) I-beam is the optimum configuration for the design case studied

Figure 10. Material and manufacturing costs.

Dimension ?		W	H	T _W	T _{F1}	T _{F2}
AL-C	δ	0.420	0.300	5.850	1.835	1.835
	σ	0.420	0.190	5.850	2.665	1.000
	ω	0.190	0.950	8.110	0.850	0.850
TI-C	δ	0.465	0.360	5.345	2.045	2.040
	σ	0.465	0.220	5.345	3.010	1.075
	ω	0.220	0.110	7.790	0.990	0.990
GR-C	δ	0.445	0.420	4.340	1.875	1.875
	σ	0.445	0.260	4.360	2.740	0.995
	ω	0.215	0.130	6.215	0.890	0.890
AL-I	δ	0.415	0.300	5.775	1.875	1.875
	σ	0.415	0.190	5.775	2.730	1.020
	ω	0.190	0.095	8.060	0.875	0.875
TI-I	δ	0.465	0.360	5.345	2.045	2.045
	σ	0.465	0.220	5.345	3.010	1.075
	ω	0.220	0.110	7.790	0.995	0.995
GR-I	δ	0.490	0.390	5.100	2.145	2.145
	σ	0.490	0.240	5.100	3.185	1.110
	ω	0.240	0.120	7.620	1.070	1.070

Figure 11. Partials of deflection, stress, and weight due to geometrical tolerances.

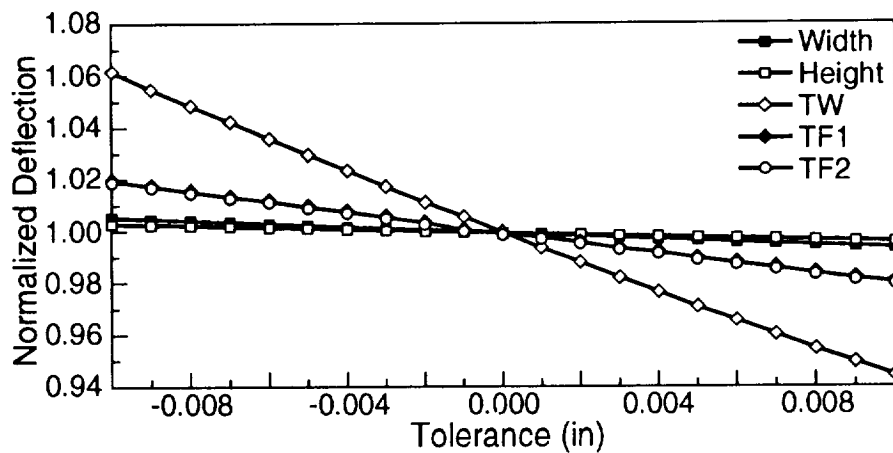


Figure 12. Tolerance sensitivity normalized deflection I-beam (aluminum).

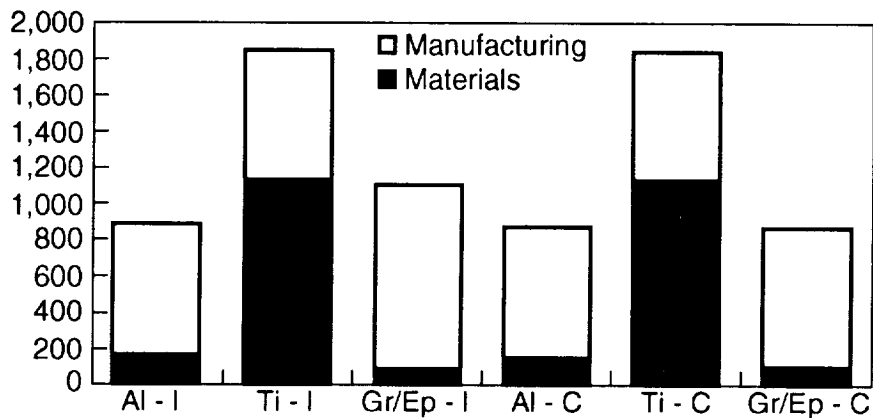


Figure 13. Design for minimum weight fabrication cost analysis.

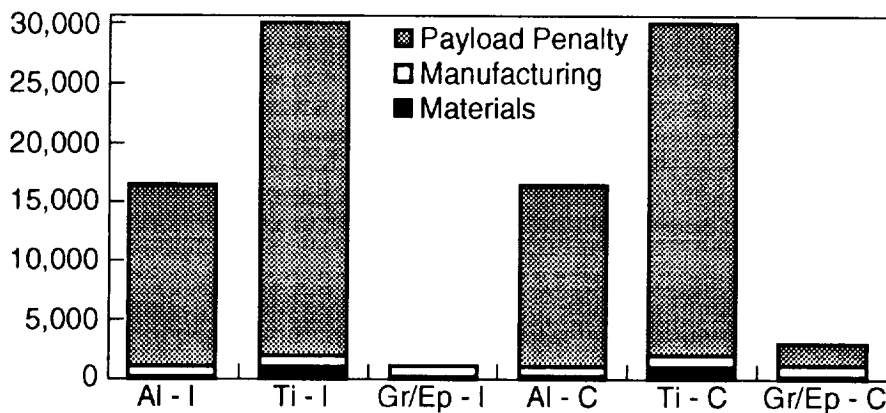


Figure 14. Design for minimum weight summary cost analysis.

sensitivities and performance of the concepts. Notice the matrix of partials where one parameter dominates the performance indicators, making it easy to evaluate the concepts in terms of manufacturing tolerances. In most design cases, several parameters have sensitivities large enough to be part of the evaluation. In most cases, several parameters can be eliminated through the process, reducing the problem complexity. It is prudent to eliminate as many parameters as possible to reduce analysis effort and concentrate the design effort on the highest payoff. As several scientists have pointed out, 20 percent of the parameters create 80 percent of the responses.

In summary, in the design for robustness, two basic areas have to be traded: (1) the variations in weight, cost, etc., due to basic concepts and material differences, and (2) sensitivities of the performance of the system to parameter variations such as the forces, manufacturing tolerance, and the like. These two areas must be combined to make the final selection. It should be very clear that in conducting these evaluations, it is prudent to simplify the models to the extent possible in order to reduce effort and gain insight. As the selection process converges, more and more details must be included in the models.

To illustrate further design options available to the designer, the simple beam configuration has added the concept of feedback control. As was discussed previously, the forces and, hence, the response of the beam is not only static but is dynamic as well. The control function is composed of both a sensing system and an actuation system, and the logic to correlate the changes in both the

static and dynamic response. This is accomplished at the expense of complexity and the introduction of additional failure modes. The concept can be illustrated by looking at the first bending mode response of the beam using attitude, attitude rate, and acceleration feedback. The equation for the first bending mode response without control is

$$\ddot{\eta} + 2\zeta_{\omega} \dot{\eta} + \omega^2 \eta = \bar{F}(t) . \quad (3)$$

Adding control for position, rate, and acceleration feedback produces

$$F_c = (a_0 \eta Y_p' + a_1 \dot{\eta} Y_R' + a_2 \ddot{\eta} Y_A) \bar{F}_c Y_c . \quad (4)$$

Introducing the control equation into the bending equation and renormalizing gives

$$\ddot{\eta} + 2\bar{\zeta}_{\omega} \dot{\eta} + \bar{\omega}^2 \eta = F(t) , \quad (5)$$

where

$$2\bar{\zeta}_{\omega} = \frac{2\zeta_{\omega} + a_1 Y_R' \bar{F}_c Y_c}{1 + a_2 Y_A \bar{F}_c Y_c} , \quad (6)$$

$$\bar{\omega}^2 = \frac{\omega^2 + a_0 Y_p' \bar{F}_c Y_c}{1 + a_2 Y_A \bar{F}_c Y_c} , \quad (7)$$

$$F(t) = \frac{\bar{F}(t)}{1 + a_2 Y_A \bar{F}_c Y_c} . \quad (8)$$

In actuality, the control function must be formulated for the total response of the system that includes rigid body as well as the complete elastic body response. The simplified mode equation illustrates the major characteristics under consideration for robustness.

Now the beam system not only responds due to its basic material characteristics (structural stiffness and damping), but has introduced control functions that augment the mass, damping, and stiffness of the system, providing the designers with means of adjusting the response in any manner he chooses by shifting the basic frequency, damping, and inertia through the choice of the control logic, control gains, and control forces and moments. This does not (as stated previously) come free. The control function requires application of a force or moment that is proportional to the control signals. This can be accomplished using thrusters, momentum wheels, actuators, and so on. This introduced force system has failure modes and uncertainties associated with it that also must be accounted for.

In addition, control sensors (position rate and acceleration) must be designed into the system along with the logic (software). These also introduce additional failure modes and uncertainties. All these uncertainties and failure modes must now become a part and partial to ϵ 's given in equation (2). The last set of terms now becomes

$$[1 + \epsilon p + \epsilon l + \epsilon F + \epsilon A + \epsilon c] , \quad (9)$$

where ϵc is composed of the uncertainties discussed above.

Now the simple beam design is not so simple in that many options are open to achieve robustness which must be properly evaluated and designed. Let us see how the process works. Let us say the performance is not adequate using the initial concepts. The vibration response is high; the deflections too large. We must now introduce some new concepts; different materials, for example, or the beam can be designed using adaptive structural concepts (smart structures). Damping is built into the material to reduce vibration response. Using the control function with sensors and actuators can reduce the static and dynamic deflection, etc.^{9 10} One could change the geometry and add material. All these things increase complexity and failure modes, but can add redundancy or produce flexibility. Environmental controls can be added. Thermal insulation can be shaped to reduce wind loads and so on. Structural margins can be added during design and reduced during use. Now cost may be unacceptable, so may the reliability. The process must be replicated for each case until a reasonable compromise is met against the criteria and requirements. Manufacturing tolerances fit into this group. The introduction of augmentation can attach many of the elements of robustness; however, it always increases complexity which is usually a negative to achieving robustness. This interaction greatly complicates the task, but can be very effective in meeting robustness goals. It should be pointed out that the elements introduced to augment the response (sensors and actuators) must be individually designed for robustness in order to have overall robustness. Remember, the reliability of the system is the product of each element's reliability. Through the process shown in figure 2, one can, therefore, step through the design of a beam that has robustness and meet the performance, reliability, and cost goals. The secret to accomplishing the task lies in clearly understanding the needs/requirements and criteria, performing adequate sensitivity analyses and trades with quantified variations using a reasonable set of concepts, fabrication methods, and materials all measured against the indexes associated with performance, cost, and reliability. Remember, performance, cost, and reliability are usually in conflict, requiring a compromise to be made. Clearly, there are no generic solutions for the simple beam design. It depends on the requirements and constraints set by the customer. Remember, this is a stepped convergence process as discussed by Pugh (fig. 8). It is a process of weeding out concepts and adding new ones based on more information until the best set is selected. In short, it is an iterative process that converges in steps using formal procedures.

In the discussion so far, the process has been defined in a very formal way, listing trades that are evaluated against a set of measurables call indexes. There is contained in any of these formalized approaches a methodology called intuition and judgment (experience) where people can measure the rightness of a new pattern, a new concept, or a new model, by simulating the concept's operation in their minds. These intuitive judgments can be made at a big savings in time. Somehow, using intuition, they can test out the alternatives without formalizing them. When conceiving the engineering of robust design, one must break out of the old paradigms occasionally and use intuition, the leap of faith of intuition. Yet our systems are so complex, so costly, even when the intuitive jump (judgment) is used to form the concepts, they must, in the final analysis, buy their way formally against the set of measurables (performance, cost, reliability). Barker discusses this intuition along with risk-taking as well as the need for the formalized in reference 11. He says intuition and innovation are only 10 percent of the job. The other 90 percent are the standard procedures, yet they are a balanced set if progress in the future is to be made. However, if the intuition judgment approach is used, it is mandatory to provide the logic as a checkoff matrix and supporting statements for future reference as the project matures.

What has been discussed using the simple beam is the same generic approach and technology available in designing a launch system, satellite, etc., and their subsystems and components. In the case of the simple beam, the basic trades dominate with the sensitivities to

manufacturing tolerances being a secondary consideration. In the more complex systems, the trades and sensitivity functions are not simple. The sensitivities can be very significant compared to the basic materials, fabrication, and concept differences, requiring clearly defined weight factors. The options available to the designer for achieving robustness are very large and challenging, bringing out the best in all of us. The appendix will deal with some of these characteristics and trades of the various elements of a space system.

IV. MANAGEMENT (LEADERSHIP)

Management is responsible for all aspects of the total design from communicating the vision, controlling (allocating) the resources, to engineer design, manufacturing, and operations. Two elements in management are fundamental to achieving robustness in design. These are: (1) determining the criteria and (2) instituting a management structure that is compatible with the overall mission robustness goal. Reference 6 discusses these two factors. A top-level discussion follows.

A. Criteria

The development of a set of design criteria is one of the prime steps to achieving robustness in design. Requirements and standards are used in two ways that are highly interrelated. First, they serve as the framework for managing technical and project aspects of a spacecraft or space vehicle (to be discussed later). Second, they provide formal control or direction (legal) to the concept selection, development, verification, and operation of these systems. In addition, there exist many good practices and lessons-learned guideline documents, including monographs, handbooks, test and analysis approaches, and parametric data which can guide the design. These, however, are not contractually binding. Figure 15 is a flowdown of these two criteria. The proper formulation and use of these criteria is the real path to robustness. This means that this set of criteria must be specially derived, based on past history (lessons learned), for the particular project using the robustness objective as the guide. Also, they must be measurable, hence, verifiable. These measurables can and should become part of the indexes used to determine robustness.

Further, the legal requirements must be simple, unambiguous, concise, and direct, providing order to the engineering process; but not overpowering to where they stifle creativity and remove responsibility. The balance between legal requirements (formal organizational structure) and creativity (informal organizational structure/leadership) is probably the most challenging, but important, task engineering faces. "Optimal performance needs administration for order and consistency (formal), and leadership (informal) so as to mitigate the efforts of administration on initiative and creativity 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. Greenleaf¹²). This is the challenge of the robustness criteria development tasks.

How one achieves this goal is an interesting study. Many approaches have been successful. There is no magic formula other than teamwork and dedication. Several have used the skunkwork approach where all disciplines are formed into a colocated special team to design the vehicle.

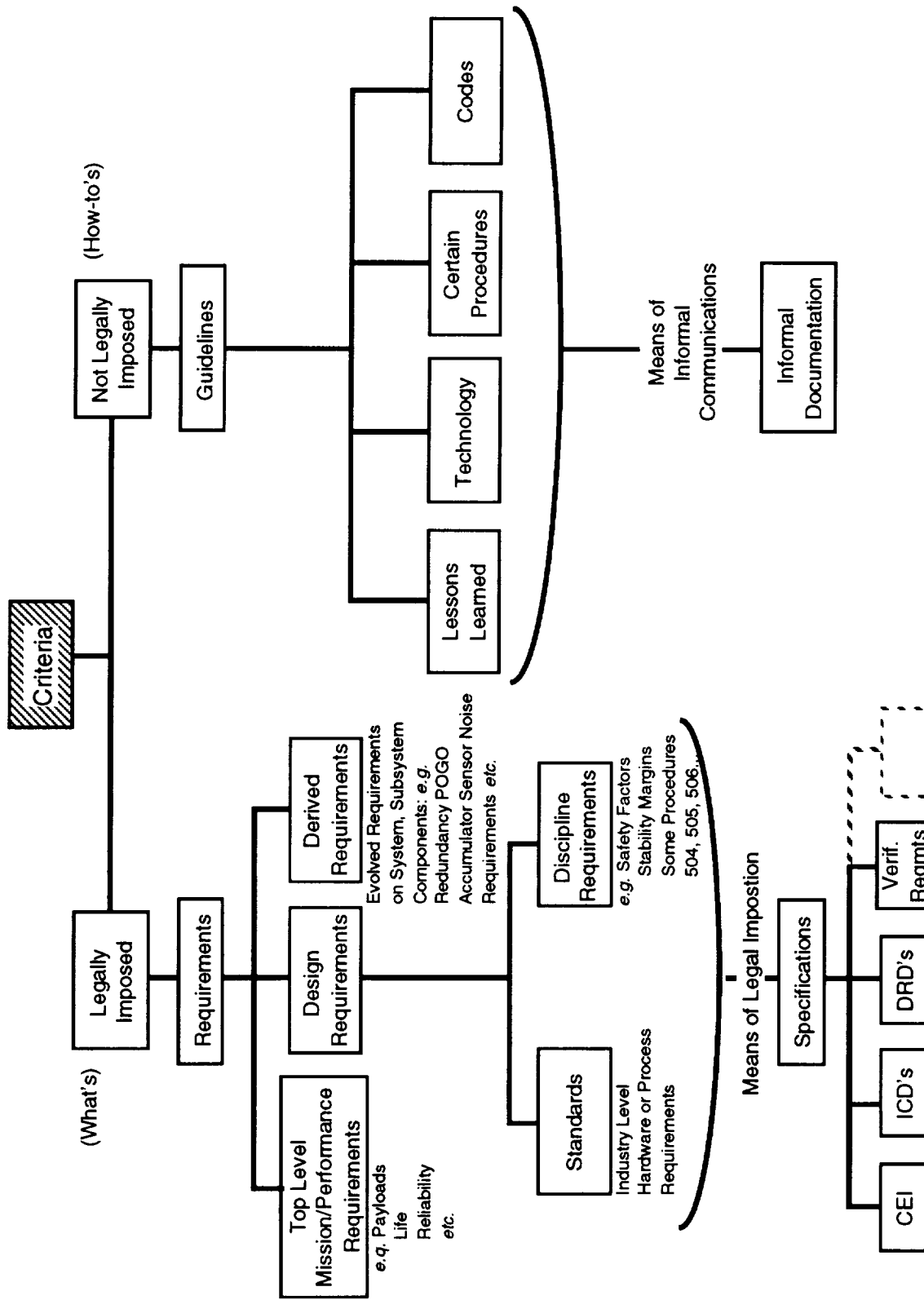


Figure 15. Role of requirements in product design.

Integrating working groups and panels consisting of key representatives of each discipline, as well as customer and contractor, has been successful. A different approach is being used by the new space transportation system main engine (STME) to formulate these criteria. This approach is based on a functional management approach (product and component development teams) for design. The criteria and documentation requirements are formulated using Government (customer) and contractor discipline-oriented teams. Maximum use is made of the contractor's documentation bases, criteria, and so on to formulate these requirements (fig. 16). Proper development of criteria focused on robustness as well as the physics of the systems involved. Regardless of the approach taken, criteria formulation requires teamwork focused on development of a low-cost, robust system. The results of the design rest on this (see "Total Design" by Pugh⁴).

B. Project Management Approach

Just as key to achieving robustness is the project management approach used. It is paramount that it also be conceived and formulated with a focus to achieving robustness. Again, there is not one approach. Skunkworks have been used successfully. Working groups and panels are successful. Line engineering organization can work well. Nearly all systems use design reviews and audits keyed to critical design progress points. With the current trend of applying the principles of TQM to improve quality has arisen the use of functional design teams composed of members from both the customer and the contractor. The aircraft industry has used this approach to develop several planes. Currently, the STME has opted for this approach. Two levels of functional development teams are baselined. The first level, called the product development team, focuses on the design of engine subsystems such as nozzles, injectors, turbomachinery, avionics, and systems. Because each of these subsystems is composed of various components, the product development team is subdivided into component development teams (figs. 16 and 17). They are staffed by engineers (all disciplines) from both the Government and contractor, using concurrent engineering along with all its intended tools to ensure robustness, cost, reliability, and performance. Because the STME is being designed and manufactured by a consortium of three contractors, the component design teams are housed at the individual contractor responsible for the development of that hardware.

Figure 7, mentioned previously, is an attempt to show the flow of a total design focused on robustness (flow is basically the same regardless of the focus). The arrows indicate interaction (iteration) and awareness of the various steps. The center column lists some of the characteristics while the right hand column provides a partial list of tools available to optimize the efforts of that step. These steps must be applied to at least four levels of the project (fig. 16). These are:

- (1) System
- (2) Subsystem
- (3) Element
- (4) Component.

These two figures clearly show the complexity of the management tasks and the need for integration. All interact. Also robustness must be achieved at end level, or the overall system goal of robustness is not achieved. Thus, we have both the challenge and the dilemma of the management effort.

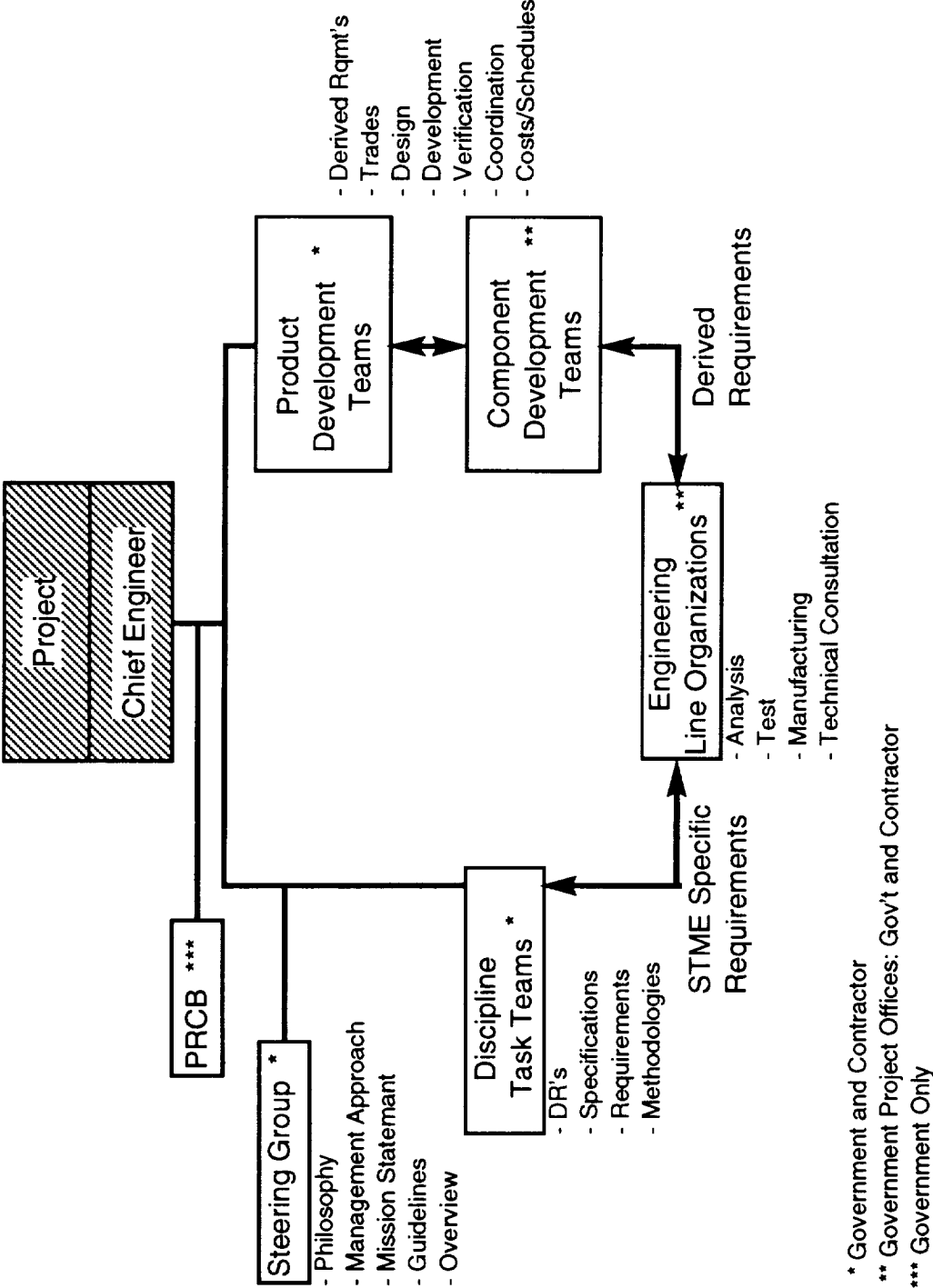


Figure 16. STME management and criteria development approach.

PDT/CDT RELATIONSHIPS

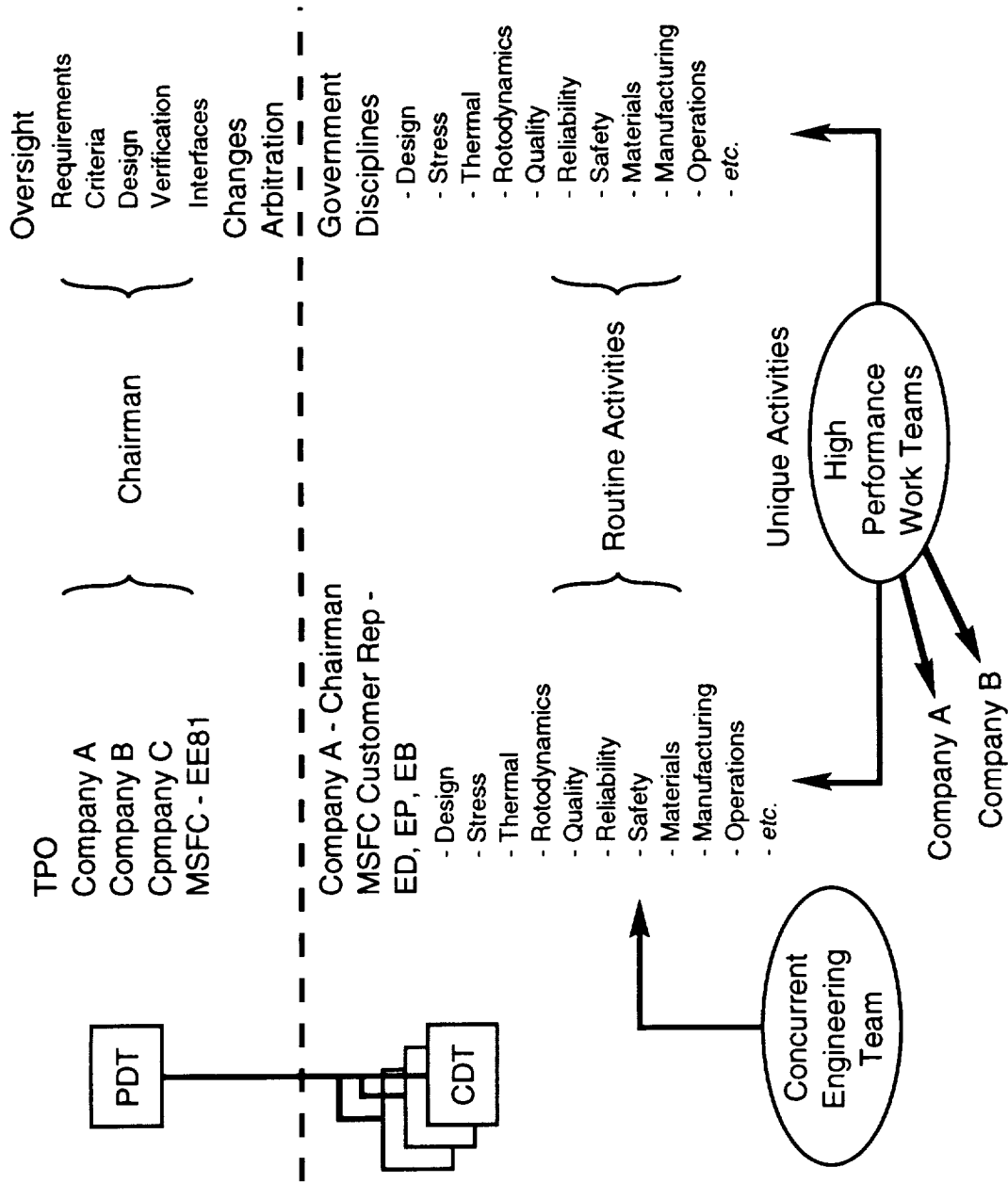


Figure 17. Functional design groups.

Regardless of the approach used for management, such characteristics are mandatory if robustness is to be achieved. It must:

- (1) Focus on the customers and their requirements for robustness
- (2) Spend up-front money to drive out the key parameters and develop the requirements flow down as well as selection of a proper concept
- (3) Utilize concurrent engineering through teamwork and open communications (lateral and vertical)
- (4) Have a well-laid set of formal requirements and a verification plan for achieving (meeting) them
- (5) Delegate authority to the lowest level possible (empowerment)
- (6) Have well-defined formal reviews and audits at critical design points to eliminate or reduce surprises during verification. This includes objectives and scope
- (7) Properly assure total systems integration.

In the final analysis, the key factors are communication, empowerment, and up-front concurrent engineering. To be successful, all approaches must include these and be focused on robustness. Otherwise robustness will not occur, or when it does, it will be too costly.

V. SUMMARY

A vision, conceptualization, designing, building, and operating a space system is like a great symphony. The symphony starts with a composer who has a vision of a great orchestra playing the great piece of music by harmonizing the strings, brass, woodwinds, bass fiddles, percussion instruments, French horns, tuba, trombones, clarinets, trumpets, bassoons, oboes, flutes, piccolo, cellos, violas, first and second violins, and pianos into a series of movements emphasizing, at various times, the various sections united by combining the elements. When heard and seen, the general working of the parts, originating in the composition, flow into a concept from which the music was composed; all the time being held together and harmonized. Once the music is written, it must be arranged to fit a given orchestra and situation. This is done by the arranger and the conductor. Practice starts with the different sections fine tuning the arrangement and the orchestra. When all is ready (after much time in practice and preparation), the production is carried out to please the audience.

Prior to the orchestra playing together, each instrumentalist must have spent years perfecting his knowledge and skills in music and his instrument. Each must coordinate and blend with all the others in concert with the music score and the conductor. What a great experience to be present for a great symphony!

A space system also starts with a vision, moves to a concept, is designed and manufactured, and then the great performance occurs. As with the symphony, each engineer, technician, scientist, secretary, welder, millwright, etc., must have honed knowledge and skills that are harmonized

together to make the whole. This first happens in terms of conception and design. The system is not built by one discipline, but all playing together, each fitting his piece into the vision, the concept. This requires leadership, dedication, and servanthood for this process to happen as a team. Not only must the musical team harmonize together to make a symphony, but so must the space system. It is composed of its many parts, avionics, structures, propulsion, materials, etc., that must all play together to form the operating system which is another symphony in itself. First, the team (design and manufacturing) must have a full vision and understanding of how the system plays together including how to manufacture and operate it. As with the orchestra and the music score, it must be fine-tuned as it is developed to fit the constraints that always occur, as well as the changes that must be made to produce operating systems (harmony).

This process is complicated by the fact that space exploration requires several different systems that must work together: launch vehicle (transportation); spacecraft, which is, in reality, two systems if it is manned; payloads; orbiting systems; transfer vehicles; planetary systems; manufacturing including the facilities; and operational systems composed of launch, communications, checkout, real-time operations—all requiring special facilities and equipment. Not all of these parts would be present on every space system.

In the case of the symphony, the conductor usually makes the decision as to when and to what level a section participates in the music. He may consult the various sections, but generally, it is his decision. In space systems design, the various disciplines are not only the conscience of the project by continuously raising issues and judging the design, but are a part of the decision process. Clearly, the project can override, call the shots, but only after understanding the issues and risks. In other words, someone must have the final say.

The total process is called system design, or according to Pugh,⁴ “total design.” The major source of problems and failures in space systems is not due to the lack of technology (individual skills also), but the neglect of the process of system design.¹ The requirement for harmony is as great as for the symphony—one sour note can spoil the whole performance.

As an orchestra is broken into sections, so is a space vehicle or spacecraft. The components and subsystems must be a whole as the first violin section, but must also play with all the other parts of the vehicle. This further breakdown or rolldown of each system into subsystems, elements, and components complicates the problem further. Integration of all the rolled down pieces into a whole is required to make a successful system. Someone, or several persons, must be able to see the system. All must capture the vision, the objectives of the system. Honing the individual skills, interplaying them together in harmony in terms of a clear vision makes great music and a great space system. Robustness is achieved using this team process.

It should be pointed out that the systems design for space exploration has several additional complicating factors not generally present in normal product design, manufacturing, and operations. These are:

- (1) Very complex needs and requirements
 - Politically driven, must be politically viable
 - Technology pushing, high performance required
 - One or few of a kind
 - Not generally perceived by the public as a need, more a toy or fantasy
 - In general Government controlled, budget and regulations

- (2) Costly
- (3) Long development time, high risk
- (4) Limited historical database
- (5) Multioperational control
 - Scientists
 - Government
 - Contractors
 - Technical disciplines
 - Manufacturing disciplines
 - International.

When all the factors discussed are added together, it provides not only an overarching challenge, but one of the great opportunities man has faced. This paper addresses how this is accomplished starting with the vision, the marketing of the vision (requirements derivation), concept selection, design, manufacturing, and operations. It discusses the processes, tools, and emphasizes how TQM philosophies, principles, and tools fit into the subject.

VI. CONCLUSIONS

Robustness is the pivotal design philosophy for achieving low-cost, reliable space missions. The earlier in the program it is incorporated, the greater is its impact; manufacturing cost will be reduced. Costly failures during development and operations will be greatly reduced, if not eliminated. For space systems, which is what this paper is about, operational complexities and constraints are reduced as well as costly launch delays. Increased life is apparent along with flexibility. Companion to these increases are lower refurbishment and maintenance, assembly, processing, and checkout efforts and cost. Paramount also are increased reliability and safety. The following points are conclusions that were embedded in this paper.

- (1) Robustness, in general, cannot be designed in a global sense. It can and should only be used where the biggest payoff occurs.
- (2) The areas of biggest payoff can only be determined using sensitivity analysis and trades in terms of the project's objectives, philosophy, and requirements.
- (3) The degree of and definition of robustness must be defined specifically for each project.
- (4) Robustness must be the guiding star throughout the whole life cycle of the project: concept, design, development, manufacturing, verification, and operation.
- (5) Designing for "robustness" is a process that utilizes established TQM techniques starting with concurrent engineering, and incorporates Taguchi Quality Method, design of experiments, sensitivity analysis, Taguchi tolerance versus cost, QFD, other available techniques, and new TQM techniques as they evolve.

(6) Designing for robustness implies that one avoids, where possible, designing to the edge of technology.

(7) Robust systems have the general characteristics of simplicity such as load paths, symmetry, configuration, number of welds, number of parts, etc.

(8) The basic trades involve the triangular relationship between concept, materials, and fabrication evaluated against cost, reliability, and performance.

(9) There are many options for achieving robustness. The six basic ones are: (1) desensitization, (2) control of parameters, (3) margins, (4) redundancy, (5) simplicity, and (6) operability. Most robust systems employ various combinations of the set.

(10) Quality is a virtue of the design rather than of the on-line control, however stringent the manufacturing process.

(11) Concept selection and project definition basically determine the degree of robustness. All else is fine-tuning. The best design engineering cannot right a poor concept selection.

(12) Verifiable measurables (performance indexes) are required to judge the merits of robust concepts, etc.

(13) All concept selections and designs are a stepped convergence process, incurring more and more details as the convergence occurs.

(14) Histories of prior programs (lessons learned) are key to identifying robustness requirements, design approaches, etc., and should be collected and studied prior to concept selection and design initiation.

(15) Statistical significance of the sensitivities is key to evaluating robust characteristics and making correct trades for configuration selection and design (concept, materials, fabrication).

(16) Management/leadership is a key factor in achieving robust systems. It must focus on the customers and their requirement for "robustness;" be willing to empower teams (concurrent engineering) and ensure vertical and horizontal communications; and lead the development of project tailored requirements and specifications and allocate up-front resources to drive out key parameters where the payoff is the greatest. The key factors are leadership, communication, empowerment, and up-front concurrent engineering.

(17) Designing space systems to be robust is complicated by complex needs and requirements:

- Politically driven, must be politically viable
- Technology pushing, high performance required
- One or few of a kind
- Not generally perceived by the public as a need, more a toy or fantasy
- In general, Government controlled, budget and regulations
- Long development time, high risk
- Limited historical database
- Multicustomer controlled, scientist, Government etc.

Designing for “robustness” is the great challenge facing the aerospace industry. Its achievement will make access to space achievable and affordable. It is the task we all must accept with dedication to ensure the future of exploration.

APPENDIX

The characteristics of robustness vary for various space systems, as do the critical trades involved. This appendix is provided for more completeness and insight into what these trades and characteristics are for launch vehicles, their propulsion, avionics, materials and structure subsystems, payloads and satellites, orbiting platforms, stations, interplanetary tugs, and transfer and reentry vehicles. Each designer should use this list as a point of departure for developing his own complete list of the project being designed.

Launch Vehicles

There are several ways to separate the design functional areas for a launch vehicle. At the top level, one must deal with the vehicle, manufacturing, facilities, transportation, processing, and operations. The payload, although a part of the vehicle during operations, is a design area in itself. Each of these major functional areas is usually broken down into subelements in order to make the design task more manageable; for example, vehicles/facilities which includes manufacturing, storage, processing, assembly, launch, and operations. A fundamental part of these is the ground support equipment (GSE) or ground handling equipment. In this paper, emphasis will be placed on the vehicle, even though its design must be totally correlated and traded with the other areas such as facilities and manufacturing. The vehicle itself must be subdivided into subsystems, elements, and components in order to have manageable design tasks. The following paragraphs will address the design of a launch vehicle from the standpoint of propulsion systems (liquid and solid), avionics system, structural system, materials, carrier component, and, for manned vehicles, crew quarters. Before dealing with the subsystems, a discussion will take place on the integration of the subsystems into the total system; in other words, on the system's robustness and design.

1. Vehicle Systems

a. **Factors:** What are some of the factors or characteristics of a launch vehicle that most would agree makes it robust? Are there some general answers to this question? Probably. Before answering this, it is prudent to look at the space shuttle and delineate those characteristics that are undesirable. A history of the problems encountered during shuttle operations is a good starting point.¹³ The first shuttle launch was held for several days due to a glitch in the avionics system. Sensors have failed, creating launch holds. Three launches have been delayed due to excessive winds aloft. Hydrogen leaks have held several launches—one for several months. Other problems can be studied in the above cited reference. In addition to these problems, there are several standard procedures required for each launch. Each launch is unique, requiring a specially shaped trajectory and extensive data (loads, performance, thermal) for launch operations. Day of launch I-loads update (wind biasing), based on wind sounding balloons sent up periodically, is used on each flight. Along with this wind biasing, a launch constraint system is in place to hold the launch if winds aloft, with the wind biasing, create excessive loads, dynamic pressure excesses, or performance degradation.^{2 7 14} The orbiter heat tiles must be protected from ice forming on the external tank. After each flight, damaged tiles must be replaced. Heaters are in place on the RSRM joints to ensure proper sealing. The vehicle must be protected from propulsion-system-induced overpressure using a water spray system and water troughs. Some of these approaches ensure robustness by controlling the environment, but are costly to launch operations. The vehicle was designed using load relief in pitch and yaw as well as the use of monthly mean wind biasing. Additional conservatism was taken out in formulating the wind criteria. Why this was necessary is clear if it is understood how influential the

aerodynamic surfaces (orbiter wing and tail), coupled with the unsymmetrical configuration, are on loads.

There are many costly items in the assembly that the writer is aware of, but he does not have hands-on experience with, such as launch, processing, checkout, and launch operations. These should be identified and studied to identify factors or characteristics to design out, or in, whichever produces robustness. The problems associated with the engine will appear in another section.

The Saturn/Apollo vehicle, being a three-stage configuration, allowed certain conservative approaches that paid off in operations. It was designed without wind biasing using nondirectional 95-percent wind speed, 99-percent wind shear, and gust RSS providing margins. As the vehicle evolved into the operational configuration, wind biasing could and would be used to gain launch flexibility. This was of particular importance for successfully launching Skylab where margins were lower. Load relief was not used. While it (load relief) reduced the rigid body loads, it increased the response of the first bending mode to wind gust, canceling out the rigid body load reductions on the front third of the vehicle. Much of the rest of the vehicle was not designed by aerodynamic loads. Also, the vehicle had performance margin or flexibility that allowed launching the Lunar Rover and the Skylab vehicle.^{1 2 14} Being an expendable vehicle (only launch pad and facilities were reused), it did not have the reuse problems and cost of the space shuttle. An obvious trade between reuse and expendables was throw-away cost versus maintenance, inspection, refuel, etc.

b. Candidates for Characteristics of Robustness: First, a robust launch vehicle is one that can meet orbit on demand for the range of missions specified in the requirements. There are many facets to this characteristic, from avionics functioning, engines functioning, margins on temperature, winds, and performance (propellant reserves) to minimum operational procedures, processing, checkout, assembly, and payload substitution (fig. 18, taken from an NLS study task performed by Martin Marietta).

Second, a robust vehicle has flexibility. It is a given fact of space exploration that, in the design phases, one cannot specify all the missions, payload, and so on that a system will be needed to perform. The Saturn V Apollo was designed to send man to the Moon and safely return him. Early on, it became clear that not only did he need the means of landing on the Moon and returning to Earth, but that he also could explore the Moon's surface much more efficiently if a Moon buggy could be carried along. Through some clever innovations in design of the Lunar Rover, this was possible within the performance inherent in the design. At the end of the Moon voyages, the same launch vehicle was called upon to put Skylab in orbit by replacing the CSM, LEM, and SIVB with the Skylab (modified SIVB), ATM, and MDA. This changed the nose geometry and produced larger bending moments in the first and second stages which could be handled without redesign. The space shuttle has flown more than 45 various missions by modifying the ASE, life support, and operation procedures (constraints). The penalty on the shuttle has been launch holds and high costs.

Third, the system is insensitive to manufacturing tolerances, among other things, which eliminates excessive inspection and complex manufacturing procedures. History has shown that high performance systems have a problem in meeting this goal. The SSME has experienced many problems due to weld offsets, lack of weld penetration, and stress corrosion, to name a few. This has added to inspection complexity, redesign, numerous MR's, etc.¹⁴

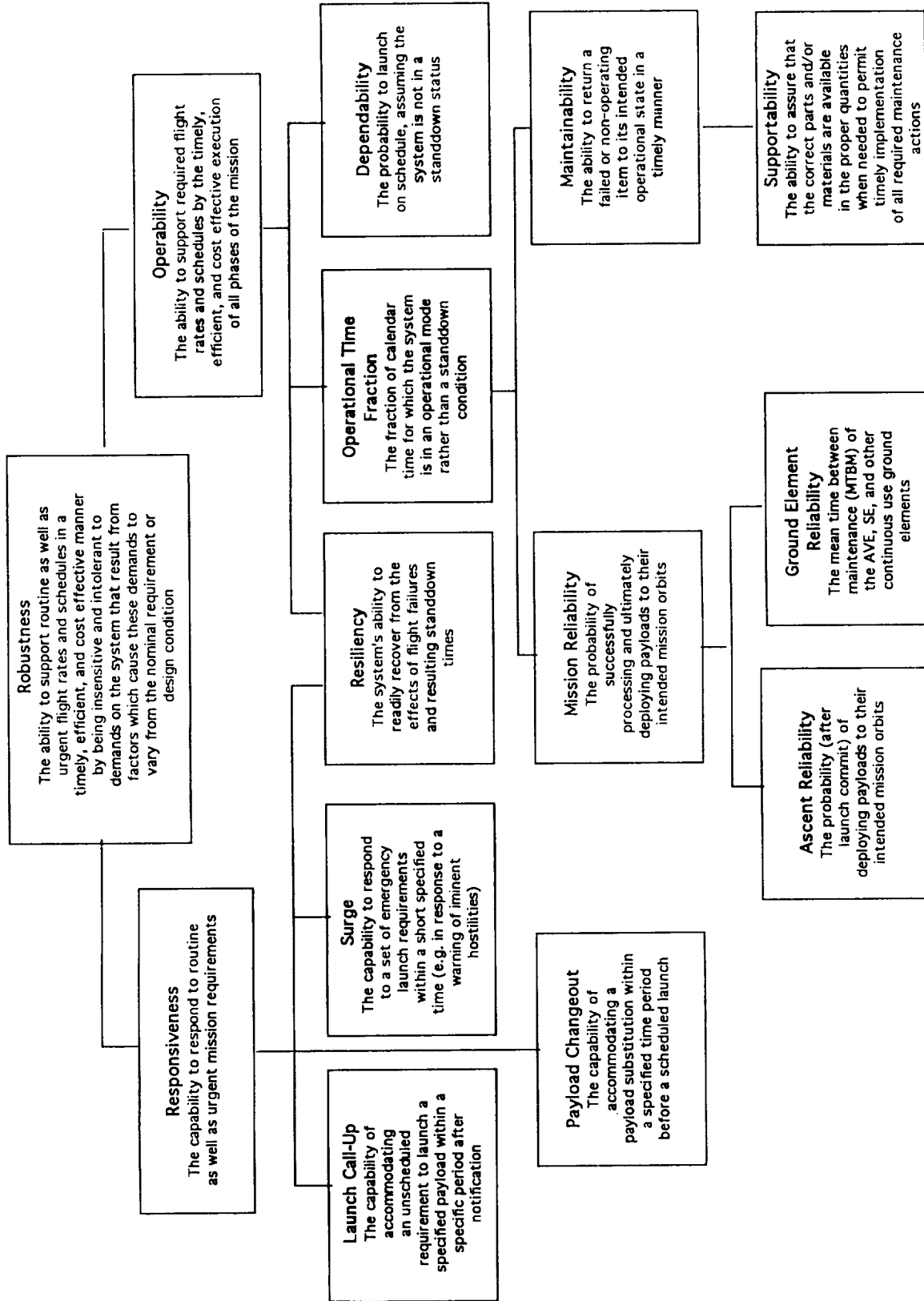


Figure 18. National Launch System robustness tree.

Fourth, the system is tolerant to the unexpected. This can be in the environments, handling, assembly, processing, and manufacturing. The detailed list of the unexpected or unpredicted is too long for this report, but they vary from banging and dropping parts to lightning, winds, and corrosive materials.

As mentioned previously, a study of failures and problems of current and past systems, as well as all the processes involved in these systems, provides the information to define these desired characteristics, select the needed trades, and determine the requirements and criteria for robustness. Each new system should always start out from this vantage point. Lessons learned are fundamental to achieving robustness.

The process whereby one builds in these characteristics is through performing a system of trades weighed against the various indexes involved in performance, cost, and reliability (fig. 2). These trades have to be performed at all levels, systems through components, then integrated involving all disciplines to arrive at the right answer. The next section addresses some of these trades.

c. Trades: In order to design in these characteristics, many systems trades must be accomplished using the process outlined in figure 2. This means writing various performance indexes for cost, reliability, and performance, to determine the best options. Taguchi's method and Design of Experiments are good tools to help identify the optimum number of cases to run. The first set of studies determines the concept selection. As Pugh so adeptly said, "A poor concept selection cannot be righted with excellent design, neither can an excellent selection produce quality products without good design." From a total vehicle standpoint, the concept selection determines to a great extent the degree of robustness. It should be pointed out that, in accomplishing the concept selection, things will be missed. Also, the total integration does not, in general, take place. This results in a configuration that requires developing some high technology in order to make up the delta and meet the performance goals. For example, one may have to go to a higher performance/lower material weight to reduce weight (mass fraction). Fabrication techniques may become exotic. This means that the engine and the propulsion system are not independent of the vehicle system. The SSME, due to lower than required vehicle performance (orbiter weight growth), operates at 104 to 109 percent of design thrust in order to make up part of this performance delta. This higher operating performance requirement for the engine has led to numerous low- and high-cycle fatigue problems.¹⁴ Placing the wrong requirements on the engine can lead to a high-performance, minimum robustness. Conversely, too optimistic an engine system will drive the vehicle to low robustness. This occurs in all areas from structures and manufacturing to avionics. It is, therefore, highly desirable to wring out the sensitivities and issues as thoroughly as possible during the concept selection and, through PRR, to minimize these high-tech work-arounds during design.

The following trades are some of the basic ones open for design considerations: (Optimize these trades using "Design of Experiments," etc.)

(1) Thrust, Isp, propellant, and performance (structural weight and payload): Isp deals with propulsive efficiency versus complexity. The higher the Isp, the less propellant and structural weight are required, but the more complex the engine or motor and its propellant must be. Thrust can be traded for Isp, but at the increase of propellant and structural weight. This system trade, therefore, must have some indexes from the engine area to properly make the trade. Mixture ratio of the propellant also enters this trade. Figure 19 shows the effect of thrust, mixture ratio, and propellant capability on payload to orbit. Notice that, for a given thrust and mixture ratio beyond a certain point,

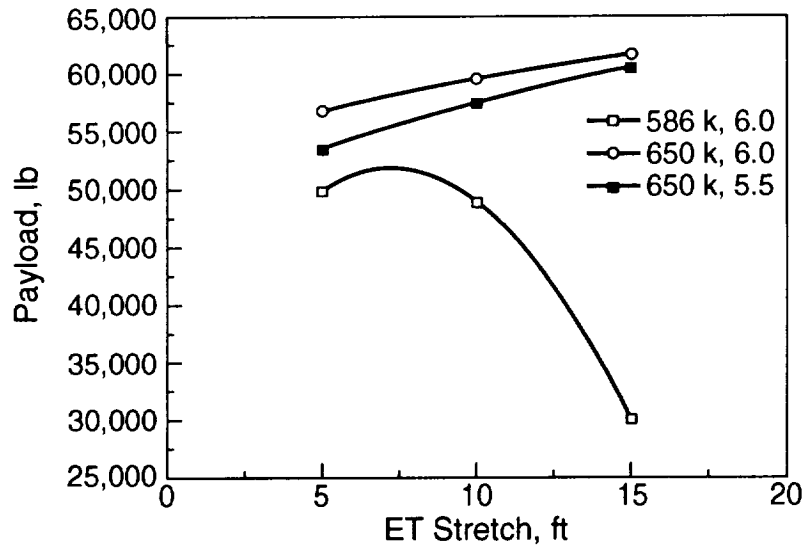


Figure 19. NLS stage 1.5 tank stretch/thrust/mixture ratio study payload capability.

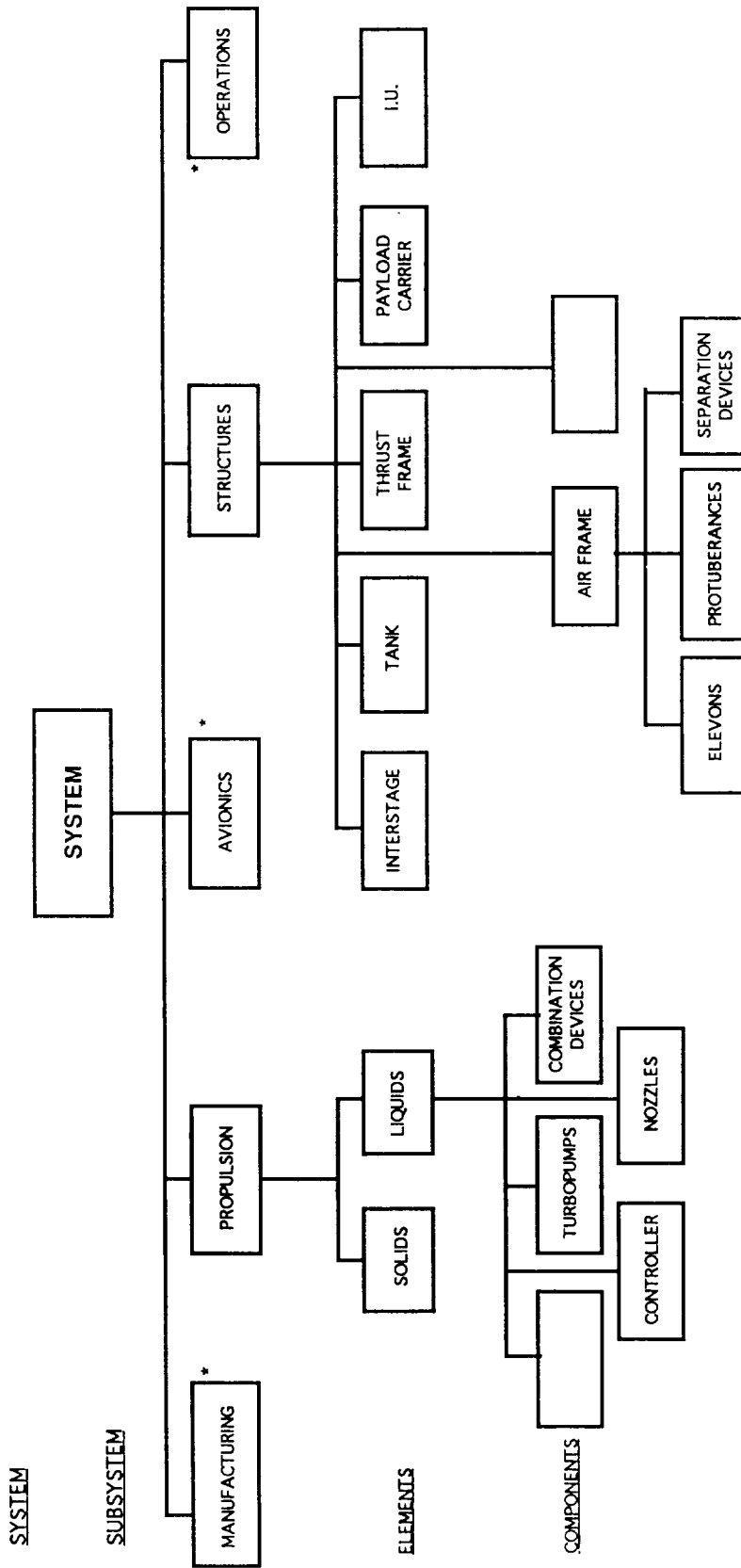
payload capability is lost by adding additional propellant. In figure 20, four levels of concept selection illustrate how far down these type trades could impact. The chart is not complete in that it breaks down only two of the many systems into their various levels.

(2) Staging: The more stages selected, the less sensitive the vehicle is to variations (higher performance); yet it is, by nature, somewhat heavier and more complex (separations, altitude engine start, disposal or recovery). Adequate performance, reliability, and cost indexes are required to make this set of trades. See figure 21 for various concepts available for trades.

(3) Propulsion system liquids, solids, pressure feed, hybrids: It is not easy to decide which type propulsion system to use. Liquids can be ground-tested before use. Solids are easier to handle among other things. This is a trade paramount to a robust system requiring well-thought-out and quantified indexes.

(4) Reuse versus expendable: Prior to, and during, the development of the shuttle, it was generally thought that a reusable vehicle was the answer to the cost and reliability issues. Current thinking says that a mixed fleet is better. This is a crucial task trade that can have major impacts on the robustness question. How do we recover? How do you inspect and maintain for reuse? What do we save by not reusing? What is the throwaway cost?

(5) There are several ways of producing forces to provide means of achieving guidance, navigation, and control of launch systems. Figure 22 shows some of these options for both liquid and solid propulsion systems. For the solids, thrust vector control devices, merits and demerits are given. By being aware of the characteristics and sensitivities of the various approaches, trades can be conducted to arrive at a best solution.



*The breakout of these subsystems to elements and components is left to the reader.

Figure 20. Four levels of concept selection and detail design for launch vehicles.

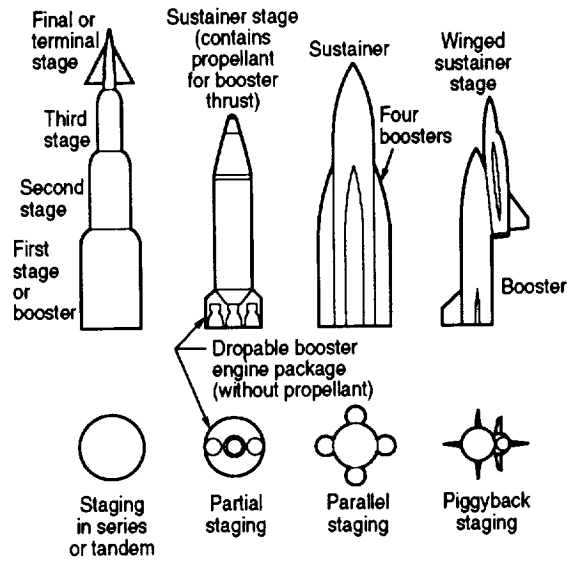


Figure 21. Staging configurations.

Gimbal or hinge	Jet vanes	Small control thrust chambers	Turbine exhaust gas control	Movable nozzle center plug	Side injection
Universal joint suspension	Four rotating heat resistant aerodynamic vanes in jet	Two or more gimbaled auxiliary thrust chambers	Gimbal on turbine exhaust nozzle	Nozzle throat is made unsymmetrical by gimbaled center plug	Secondary fluid injection on one side only

	Jet Vanes	Jetvator	Hinges or Gimballed Nozzle	Secondary Gas Injection
Description	Two or four aerodynamic heat resistant vanes inside exhaust stream	Rotation, airfoil shaped collar near nozzle exit	Rotary universal type joint at nozzle (hinge or gimbal)	Liquid or gas injection on side of nozzle
Merits	Can get high side forces	Low drag losses - erosion less than jet vane - low torque	Very low drag losses linear control characteristics	Light weight nozzle - rapid response
Disadvantages	High drag even at 0° deflection, vane erosion, nonlinear variable shaft torque	Heavy	Difficult to seal, high actuation torques	Large side forces require excessive amount of secondary fluid, complex system

Figure 22. Several thrust vector control devices or solid propellant rocket engines.

Many other system trades enter into the question of robustness which should be addressed up front instead of using them as add-ons or fixes. It is not the purpose of this paper to discuss each, but merely provide examples and a process. However, for completeness, the following is a partial list of others that might apply to the robustness question from a vehicle standpoint.

- (1) Active versus passive vibration modal or dynamic damping. Smart structures fall into this area
- (2) Central versus decentralized control and to what degree
- (3) Adaptive versus proportional control
- (4) Testing versus margins versus analysis
- (5) Manned versus unmanned
- (6) Thermal protection add or integral part of structure
- (7) Active versus passive thermal control
- (8) Health monitoring versus margins
- (9) Pyros versus mechanical devices
- (10) Load paths/number of elements
- (11) Number of engines versus reliability and cost (given vehicle thrust)
- (12) Fracture control versus fatigue design
- (13) Margins versus operational procedures
- (14) Manufacturing versus launch site assembly and processing.

The next section will deal with propulsion systems.

2. Propulsion Systems. The propulsion system is composed of the propulsive elements (solid or liquid), the propellant storage or containers (tanks), control (avionics, valving, actuators, etc.), lines and ducts, structural load carrying elements (intertanks, links, etc.), and thermal systems. All these must be integrated into a vehicle that carries out some mission, usually delivering some cargo (manned or unmanned) into some specific place in space. Let us examine some of these elements in order to better understand the process and its complexity.

a. Liquid Propulsion Engines: Liquid rocket engines are composed of several parts: Propellant pumps (rotary machinery), combustion devices, lines, valves, ducts, nozzles, and controls (avionics, software, actuators). Each of these components is composed of parts integrated to make the whole just as the components are integrated to make the engine.

As was done for the launch vehicle, it is prudent to look at the problems associated with the SSME to serve as a basis for robustness characteristics desired for future systems. References 1, 2, 14, 15, 16, and 17 discuss many of the problems.

There have been 36 major failures of the SSME in the ground test program. They include lox post failures due to vortex shedding (fatigue), propellant pump bearing failure, whirl, turbine blade failures, steerhorns (nozzle coolant tube tee's), valves, gimbal ducts, splitters, and so on. Many other problems have occurred but did not lead to major failures. Today, one-third of the high-pressure lox and fuel flight pumps do not pass green run and acceptance tests and are returned to the factory for rework. There are approximately 6,000 welds on the engine, several of which cannot be inspected for critical flaws, hence, must be accepted on risk assessment implying strict process control. High-pressure pump bearings and turbine blades are life-limited, requiring the pumps to be disassembled and refurbished, for example: lox pump bearings after two flights, and blades after six flights. The sheet metal in the pump turbines crack and must be inspected and repaired if required. Weld offsets in lines and ducts are a major problem, requiring detailed inspection criteria. The problems that have occurred can be classified in at least the following categories:

- (1) Fatigue (low- and high-cycle)
- (2) Manufacturing
 - Tolerances
 - Weld offsets
 - Corrosion
- (3) Acoustic excitation
- (4) Flow-induced vibration
- (5) Rotary dynamics
 - Stability
 - Vibration
 - Bearing life
 - Damping
- (6) Fracture control (inspectability)
- (7) Dynamic tuning.

(Again, the writer does not have hands-on experience, particularly at the launch site, with some of the processes that need study before finalizing robustness factors.)

In spite of these problems, the SSME is the epitome of the art of designing and manufacturing a very high-performance machine. It is truly a great high-energy density machine, although it is costly. The question that arises is: How do you design for robustness in light of these problems?

(1) **Factors.** There are many concepts available for design of a liquid engine. They range from a pressure-fed system to a staged combustion cycle. Reference 18 is an excellent article on various engine concepts (see summary from ref. 16 on figs. 23 through 25). Figures 23 through 25 show top-level trends between Isp versus chamber pressure, engine weight versus chamber

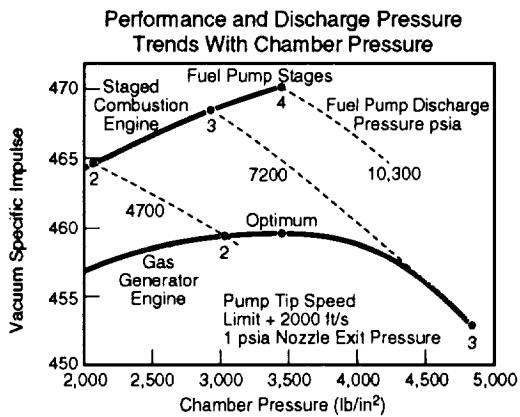
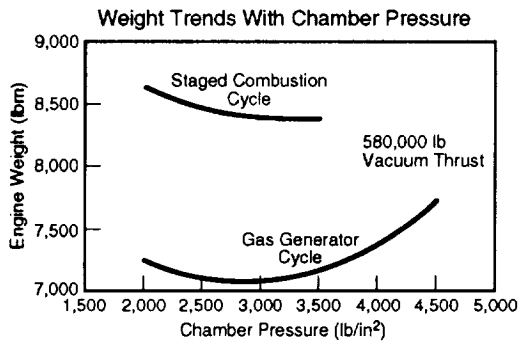
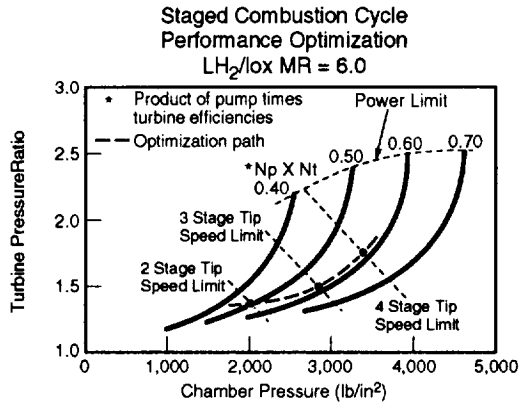


Figure 23. Top level trends.

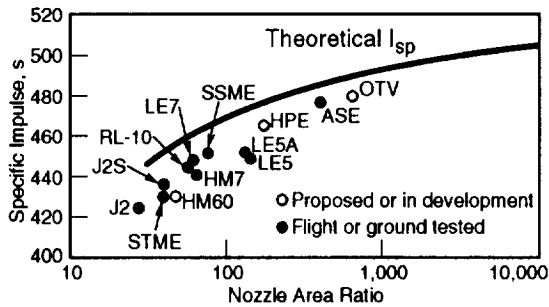
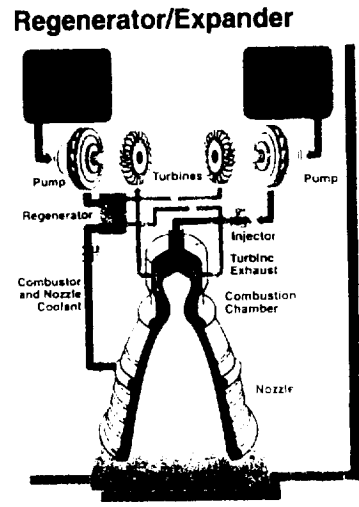
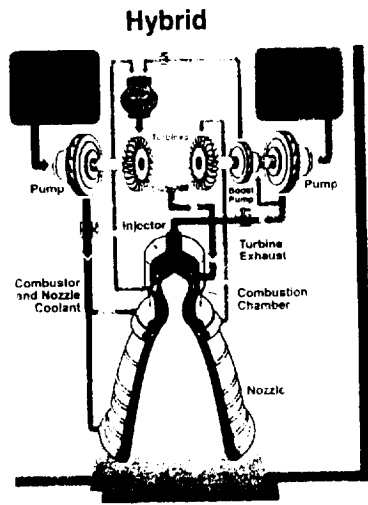
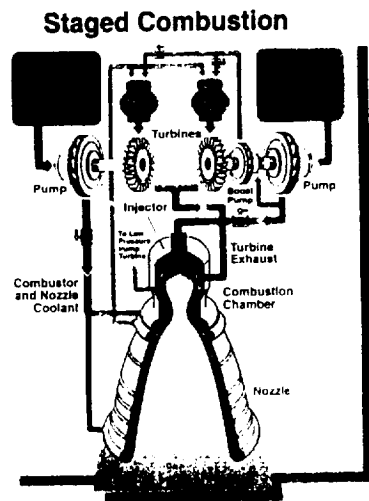


Figure 24. Performance evolution of liquid oxygen/liquid hydrogen engines.



Gas Generator (Typical of J-2)

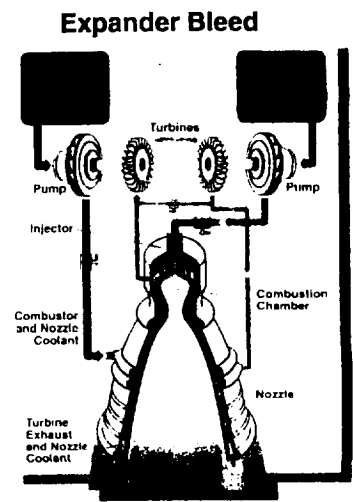
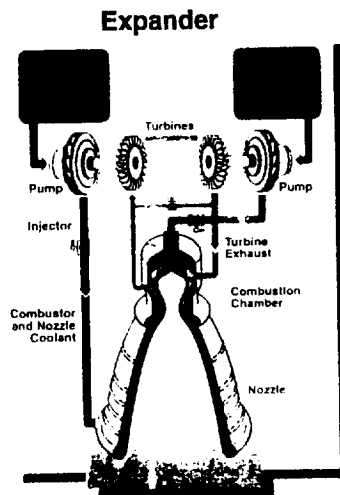
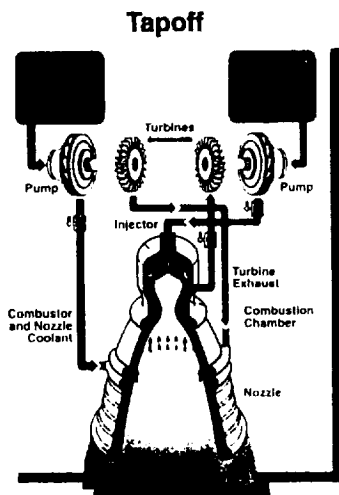
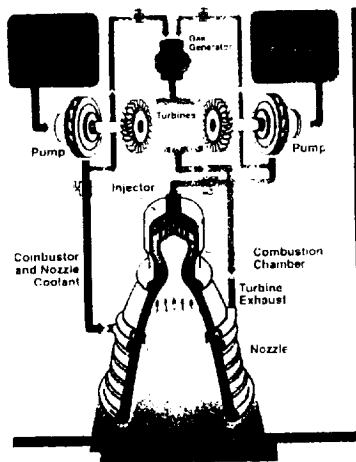


Figure 25. Sample engines.

pressure, and turbine pressure ratio versus chamber pressure. The two bracketing or extreme systems for Isp and chamber pressure are the staged combustion and the gas generator. The staged combustion produces the highest Isp, but is limited by the power increasing turbine ratios. The gas generator is not as efficient because of the low-energy turbine flow which hurts performance. For example, specific impulse drops after the optimum point as chamber pressure increases.

There are two areas of consideration in choosing the combustion cycle. The first deals with the vehicle system (performance, weight, reliability, and cost) due to the integral correlation of the propulsion system with the vehicle. The second deals with the engine system itself, such as the technology development required (turbines, turbomachinery, combustion devices, materials, etc.) as well as how they drive cost, reliability, and performance. If one chooses the gas generator cycle, the vehicle must be able to handle the gas turbine exhaust dump, the added propellant required, and so on to produce a robust system. The engine system itself is much less complex. The staged combustion drives technology pushing the margins but requires no exhaust dump and less propellant. Choosing which system is best is based on the requirements and performance indexes in conjunction with a set of trades. For example, a single stage to orbit drives the technology (high-performance) indicating the need for staged combustion or some hybrid system. The sensitivity of the single stage to orbit coupled with the payload to orbit requirements dictates a very high efficiency. A staged launch vehicle can lower the efficiency requirements. All these things do not only affect engine robustness, but the vehicle as well. The bottom line is that both the engine design and the vehicle design must be well integrated.

The next section deals with some of the trades involved in engine design.

(2) Liquid Engine Trades: Obviously, the first set of trades associated with a liquid propulsion engine is the propulsion power cycle discussed above. It should be pointed out, however, that this power cycle selection involves some indexes for the components as well as the engine system since they are not independent of the selection. The turbine power, pumps, pressure, temperature, and so on are good examples.

These trades are very interesting in that they not only involve the component, but also all the design disciplines. Again, the trade involves indexes on weight, performance, reliability, cost, operability, and so forth. The trades are formed for each of the indexes such that an improvement is noted for a given index. Many times, the indexes are highly interactive in that an improvement in one will be a detriment to the other. Robustness can generally be significantly improved at some cost to other indexes. Keen judgment must be exercised in order to design and build the robust system. Matrices designed to check off these complexities, either with quantified data or judgment factors, can be very helpful in this process. That judgment must be applied against the performance in terms of the robustness definition chosen. There is no universal answer.

Some other examples of technical trades might include:

- (1) Chamber cyclic life increase at reduced ERE by reduced wall temperature by film cooling-lower chamber Isp due to reduced core fuel flow, peripheral element mixture ration (MR) bias, lower chamber ERE due to core MR increase beyond optimum; more wall cooling due to higher channel velocity; lower engine Isp due to increased pressure drop effect on pump power and GG flow

- (2) Injector types are one set of trades available to the designer. Figure 26 shows some of the typical injector types that can be traded.
- (3) The choice of nozzle configuration is dependent upon when (the atmospheric range) the engine functions as well as all other considerations of weight, cost, induced environments, etc. Figures 27 and 28 are schematics of some of these configurations and their basic characteristics.

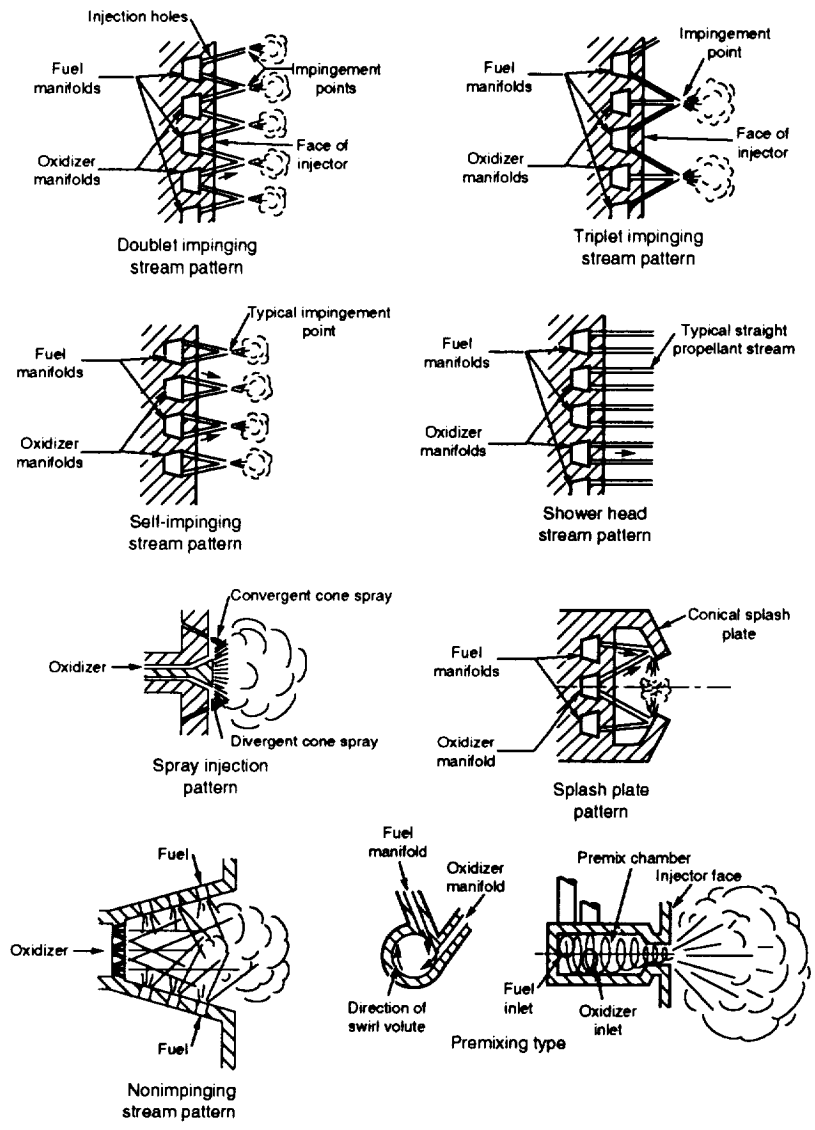


Figure 26. Schematic diagrams of several injector types.

	Cone	Contoured or Bell-Shaped	Plug	Expansion Deflection
Shape				
Flow with under expansion, altitude				
Flow with over expansion, (Sea level)				
Mass flow distribution at exit				

Figure 27. Aerospike/Bell nozzle exhaust plume comparisons.

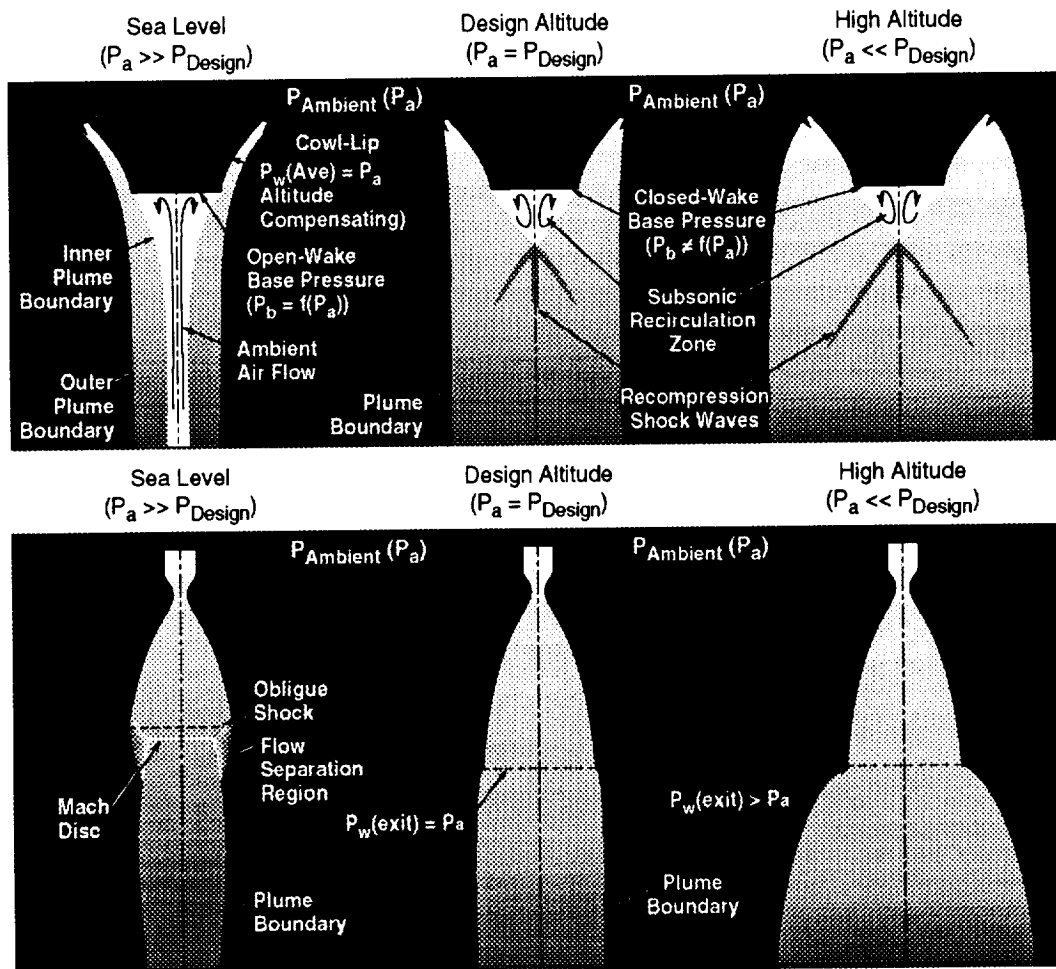


Figure 28. Four different nozzle configurations and their flow effects.

- (4) Turbine structural margin increased (at reduced Isp) by reduced turbine temperature, lower engine Isp due to increased GG flow; reduced turbine tip speed (and stress); lower engine Isp due to increased GG flow.

Note: Both of these changes may be partially offset by increased blade heights due to higher flow, therefore, the net effect on margin may be less than expected. A side benefit of improved nozzle cooling (increased margin) due to higher rate of lower temperature coolant gas may be available.

- (5) Pump suction performance margin increase (at increased engine weight) by reduced shaft speed; larger, heavier (perhaps lower pump efficiency) turbopumps
- (6) Injector chug stability margin increase (at reduced Isp) by increased injector pressure drop, lower Isp due to increased pump power and GG flow
- (7) Injector high frequency stability margin increase (at reduced Isp) by reduced vaporization/combustion efficiency with coarser injector pattern; lower Isp due to reduced ERE
- (8) Weight reduction (at increased operations cost by welded joints etc.)
- (9) Weight reduction (at increased unit cost) by wrought/welded rather than cast construction
- (10) Number of turbine and size of turbine stages, also pump stages
- (11) Blisks versus bladed discs
- (12) Roller versus ball versus hydrostatic bearings
- (13) Thrust chamber options, tubes, casting, welds, VPS, materials
- (14) Fatigue versus fracture control design
- (15) Propellant
- (16) Mixture ratio
- (17) Expansion ratio
- (18) Actuators, electrical, hydraulic, mechanical
- (19) Central versus decentralized control
- (20) Programmed versus closed loop control
- (21) Impeller stages

The merits and demerits of each are left to the reader. The list is not exhaustive. A new list should be formed for each project.

b. Solid Propulsion Systems. The solid propulsion system has advantages and disadvantages for a vehicle propulsion system. These should be traded up front in deciding the overall vehicle

concept. Once this choice has been made, the solid propulsion system is broken down into its key elements such as motor (including propellants, ignitor, insulation, skirts, nozzle, proturbance, and attach mechanisms). Using these breakdowns, a series of trades ensues to make the system robust. These include, but are not limited to: thrust vector control approach such as thrust vectoring, secondary injection, and vanes; actively cooled versus ablative nozzles; segmented versus continuous motor, propellant mix, propellant core shape. The thrust vector options were shown in figure 19. Figure 29 shows schematics of various propellant core shapes. The factors and trades for solid propulsive systems are left to the reader.

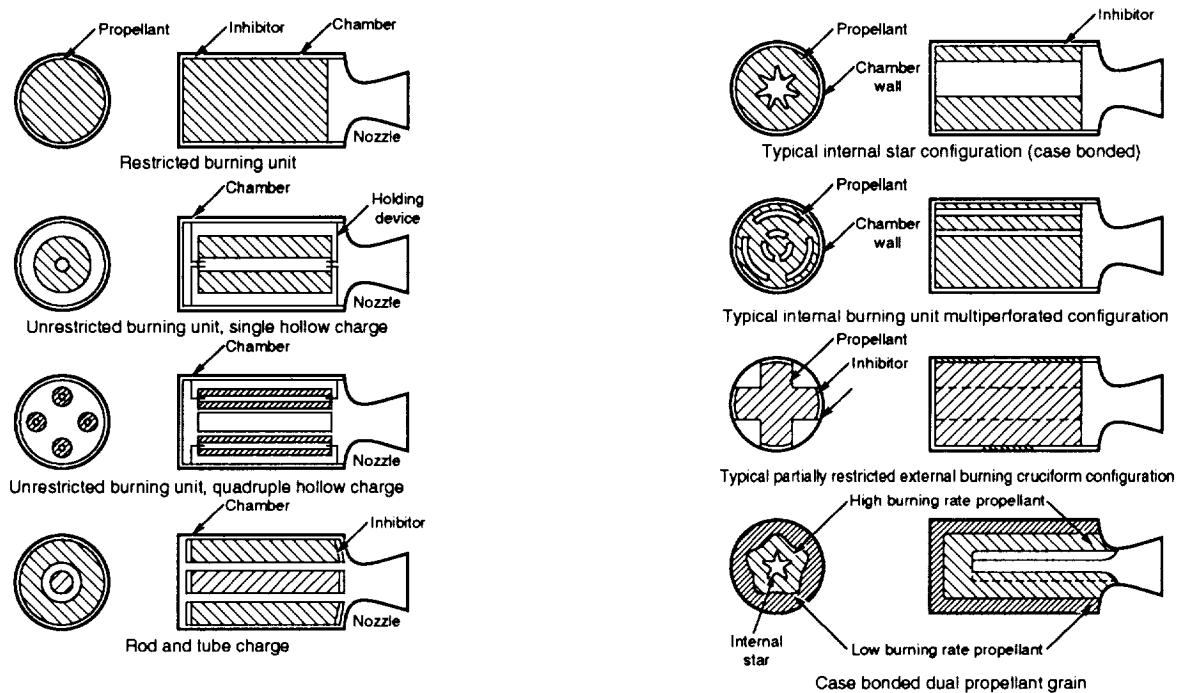


Figure 29. Typical solid propellant grain configurations.

3. Avionics. The avionics system is responsible for the control of all vehicle systems as well as the vehicle guidance and navigation. It is the brains of the system. In addition, it handles all communication between the vehicle and operations (ground, etc.). Evaluation of operational problems (holds, etc.) shows that approximately 50 percent of these are due to avionics problems. Therefore, the avionics system is a key to robustness.

a. Factors. This system can be conceived of as being sensors, actuators (integral to, but not necessarily a part of, avionics), hardware (computers, processors, etc.), wires and harness, and software. All must play together to produce the system. Key elements in the robustness of this system are:

- (1) Redundancy
- (2) Checkout
- (3) Quality and acceptance

- (4) Standards
- (5) Commonality
- (6) Changeout/turnaround
- (7) Flexibility.

In general, redundancy is a hedge against failures during operations and is not used until launch. Therefore, it does not improve the launch on time or turnaround time. In fact, the added systems increase checkout and processing. Clearly, it could be used at launch commit, then launching with a failure and taking the risks.

b. Trades. There are many trades associated with the avionics system. The first one deals with the degree of autonomy between the colocated elements. Or to say it differently: What is the degree of centralized versus decentralized control? What functions do you keep at central? What do you relegate to the subsystem?

The second trade is the level of redundancy required to meet performance, reliability, and cost. Do you build more reliability on part or make it redundant? How do you allocate redundancy into operational procedures? This is a very key trade that has a big impact on robustness. The space shuttle has three main computers in the redundancy mode plus a fourth as backup in order to assure safe return of the crew from orbit.

The third trade has to do with part standardization versus part uniques. Said another way, some loss in efficiency versus cost.

Other trades are:

- (1) Digital versus analog
- (2) Hardware versus software
- (3) Semiconductors
- (4) Superconductors
- (5) Parallel processing
- (6) Integrated versus nonintegrated electronics
- (7) Commonality of parts
- (8) Fault tolerance
- (9) Fiberoptics components and sensors
- (10) Artificial intelligence

- (11) Sensor fusion
- (12) Three-dimensional displays
- (13) Worldwide data and voice
- (14) Fly-by-wire
- (15) Remote sensing.

4. Structures, Materials, and Concepts.

a. Factors. As shown in figure 2, the triangle of materials, concepts, and fabrication is a set of the trades on design of all elements as well as for the system. This is not only true of structures, but all other systems such as avionics as well. These trades involve all aspects of robustness from components to systems, from structures to avionics. As mentioned earlier, one can design from the viewpoint of high technology and exotic materials to established technology and basic materials. In general, the characteristics of these systems involve ease of manufacturing, minimum parts, established materials, minimum number of load paths (lines), load paths not complex, adequate margins, simple processing, flexibility, minimum inspections, simplified checkout, minimum weight, and low cost. The choice is again arrived at through a series of trades using the indexes of performance, cost, and reliability. The next section lists some of these trades.

b. Trades. There are many choices in materials depending on the requirements for strength, ductility, yield, fracture toughness, stiffness, and such. Also important in these choices are the manufacturing and inspection options as well as the concepts. Some of these choices and the trades involved, as a minimum, were those shown on figure 6.

The designer must, therefore, try different combinations between concepts, fabrication approaches, and materials in order to achieve robustness. The key is the adequate formulation of indexes that fully capture all the requirements as well as sensitivities. These include performance, strength, fracture, stability, response, etc. See the simple beam example for the basic idea.

5. Payloads/Satellites

a. Characteristics. Payloads can be classified as those that stay with the system, such as the shuttle orbiter, and are returned versus those that are placed in orbit or on a planetary path. The first type can be reusable and simple, to the complex pointing systems such as ASTRO or tethered systems, such as tethered satellite system (TSS-1). Their lifetimes in space environments are short. The other type has, in general, long exposure time in space as well as being complex in requirements (pointing, docking, maintenance, health monitoring, redundancy, thermal control, etc.). These systems are usually one of a kind with a special mission to accomplish. The characteristics of these systems that describe robustness are: (1) adequate performance margins, (2) insensitivity to environments, (3) processing and checkout simplicity, (4) redundancy/reliability (key to long-term, on-orbit use), (5) low cost, and (6) flexibility.

b. Trades. All the payloads and satellite systems have the same trades listed previously for materials, concepts, and fabrication, as well as some special trades needed to meet the unique characteristics/requirements of these special systems. They include, but are not limited to:

- (1) Active versus passive thermal control versus CTE
- (2) Smart structures active and passive
- (3) Meteoroid protection layers versus thermal
- (4) Various control techniques (can also be part of same structures)
 - Momentum wheels
 - Reaction jets
 - Control moment gyros
 - Pizo electric
- (5) Manned versus unmanned
- (6) Expendable versus close-loop environmental systems
- (7) Power approaches
 - Solar
 - Storable/expendable
 - Chemical
 - Propulsion.

6. Orbiting Platforms and Stations

a. Characteristics. Orbiting platforms and stations have many characteristics that are unique. They also include many of those already discussed. The unique ones include: (1) long operating time in orbit, (2) can be manned or unmanned (permanent or tended), (3) cannot be fully verified on the ground (size, zero g, space environments), and (4) manufactured and assembled in space.

b. Trades. These systems obviously include many of those listed in figure 6 or previously discussed; however, some unique ones arise. These include at least the following:

- (1) Manufacturing in space versus erectable versus assemblage
- (2) Health monitoring
- (3) Adaptive/smart structures
- (4) On-orbit verification versus margins versus flexibility
- (5) Active versus passive thermal control versus CTE
- (6) Expendables versus close-loop
- (7) Power (solar versus propulsive versus chemical)
- (8) Stiffness versus strength.

7. Interplanetary Tugs, Transfer and Reentry Vehicles

a. Characteristics. Vehicles of this class have most of the same characteristics as those discussed previously; however, they have many unique differences. In general, they require low thrust rating over all long periods of time. This means various propulsion concepts as well as docking and capturing payloads, separation, shielding, etc. Reentry of the Earth's atmosphere from space and what braking is required is a review question. Weight is critical on these vehicles, complicated by the fact that they must withstand the launch vehicle environments.

b. Trades. There are many trades/options open for facilities at the top level of the "ship and shoot" philosophy versus processing, assembly, checkout, and the like at the launch site that influence the facilities and are a major trade for both the launch facility, manufacturing, and transportation. Vertical versus horizontal assembly, on pad versus processing building assembly, etc., are some of the other facility trades. Obviously there are many additional trades that must be put on the list and evaluated.

- (1) On-orbit maintenance and refurbishment versus expendable versus Earth returnable
- (2) Health monitoring
- (3) Propellant management (electric versus nuclear versus chemical versus solar)
- (4) Expandable versus close-loop life support
- (5) Automatic versus manual versus robotic docking
- (6) Redundancy
- (7) Seals
- (8) Meteoroid protection
- (9) Active versus passive thermal control.

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13. ABSTRACT (Maximum 200 words) Robustness is a buzz word common to all newly proposed space systems design as well as many new commercial products. The image that one conjures up when the word appears is a "Paul Bunyon" (lumberjack design), strong and hearty; healthy with margins in all aspects of the design. In actuality, robustness is much broader in scope than margins, including such factors as simplicity, redundancy, desensitization to parameter variations, control of parameter variations (environments fluctuation), and operational approaches. These must be traded with concepts, materials, and fabrication approaches against the criteria of performance, cost, and reliability. This includes manufacturing, assembly, processing, checkout, and operations. The design engineer or project chief is faced with finding ways and means to inculcate robustness into an operational design. First, however, he must be sure he understands the definition and goals of robustness. This paper will deal with these issues as well as the need for the requirement for robustness.				
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