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Role of Criteria in Design and Management of Space Systems

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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. Second, they provide formal control or direction (legal) to the development, verification, and operations of these systems. There exist in addition many good practices and lessons-learned guideline documents that can guide the design. These, however, are not contractually binding. The legal requirements usually consist of the basic performance requirements for the system and the design requirements that provide verifiable requirements such as structural safety factors, stability margins, process control, materials selection, etc. As the project develops, additional requirements are derived peculiar to the system under development. These are labeled derived requirements and are fundamental to program success. The assurance of low-cost, reliable space systems occurs when a proper balance exists between the formal and the informal and uses the proper development of derived requirements to anchor the informal. This paper will deal with this balance, the guidelines for the management approach, and the development of the criteria consistent with the basic philosophy developed. Total Quality Management (TQM) will be the guiding star used.

I. Criteria: Definition and Scope

THE design, verification, and operation of space systems are extremely challenging, emphasizing, on one side, manned flight safety and, on the other, long duration spacecraft, many with very stringent pointing accuracy or other specific requirements. Requirements specifications and standards must be developed to accomplish these many-faceted programs that technologically push the state of the art in all aspects of the project. In general, these vehicles/crafts are one-time items driving toward a unique craftsmanship vs routine design and manufacturing, greatly complicating the process. The philosophy, definitions, and scope of these technical legally binding requirements are the key to quality products.

A companion set of documents, designated "guidelines," that provide the lessons learned are very important to project development but are not legally binding. Figure 1 is an attempt to flow down these two different types of criteria essential to project design and operation. (Note: We have used the term "criteria" to designate the combined set of both formal requirements and informal guidelines. Sometimes the term criteria is used in a more narrow sense to mean what we have called "discipline requirements." In this paper, it will be used in the broad sense.) The left-hand side encompasses all of the legally binding requirements (whats), whereas the right-hand side shows the nonlegally binding information (hows). The legal requirements separate initially into three categories. First is performance requirements (mission peculiar). They are the whats that spell out such things as manned/unmanned, reliability, payload, orbits (mission profiles), lifetime, reusability, etc. These drive the configuration selection, size, thrust, etc. The second set is classified as design requirements. Design requirements have two categories: standards (industry-approved hardware or processes) and discipline requirements that include special processes, margins (stability, safety factors), redundancy, fracture control, and response limits. The third group of requirements are normally called derived requirements. These are the requirements that evolve during design and operations that are necessary for the system to meet the performance requirements. Load relief control is one example of this group. All of these requirements flow down into the contract controlling documents: contract end items (CEIs), interface control documents (ICDs), data requirements documents (DRDs), certificate of qualifications (COQs), and verification requirements. Because the final product must meet all of these requirements, they must be verifiable. They become the basis for the design reviews (audits) and operations. The right-hand side contains all of the lessons-learned documentation, which contains technology, databases, handbooks, procedures, tools, etc., that greatly enhances communication and knowledge transfer that is so important to space project success. These informational documents are not legally binding but serve as guidelines.

Legally binding criteria are therefore defined as the requirements governing the design, verification, and operation of a project. Programmatically, the system must meet these requirements or a waiver is required for acceptance. Figure 2 shows this approach and how the requirements not only are used to steer the design, but also become the standard governing the project verification and acceptance. During verification, the product must be shown to meet or exceed these requirements.

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 task engineering faces. Legal all-encompassing requirements produce order but, if excessive, remove responsibility, kill innovation, suppress opportunities to find the best solution, and stifle creativity. "Optimal performance needs administration for order and consistency (formal), and leadership (informal) so as to mitigate the efforts of administration on initiative and creativity and to build team effort to give these qualities extraordinary encouragement. The result, then, is a tension between order and consistency on the one hand and initiative and creativity and team effort on the other. The

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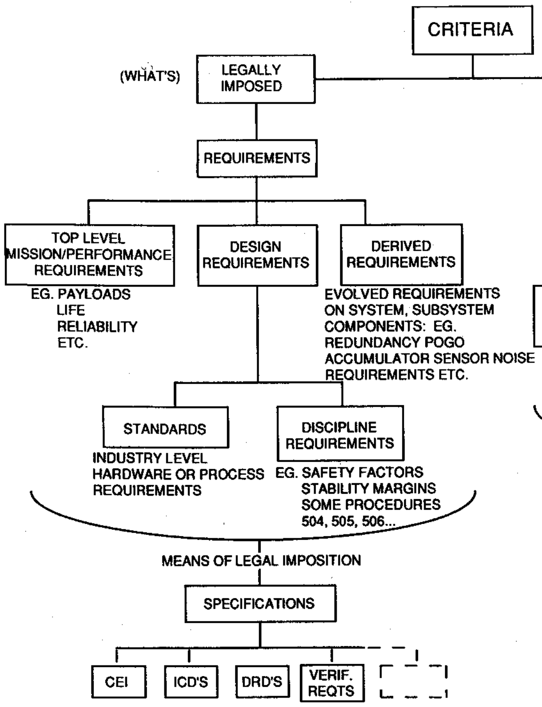

Fig. 1 Role of requirements in product design.

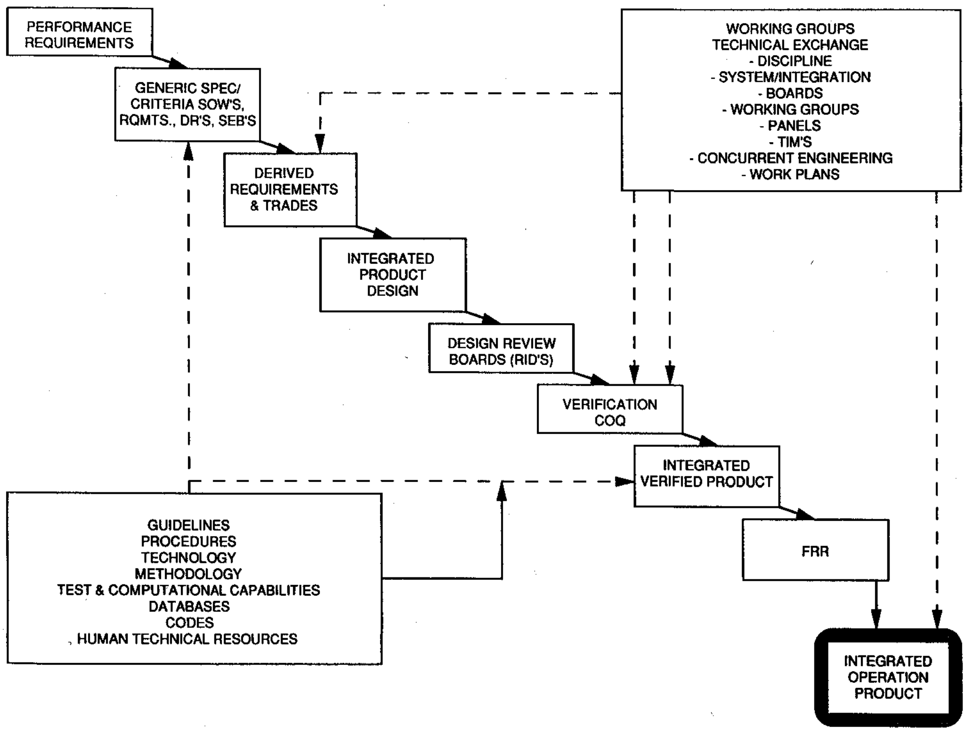

Fig. 2 Criteria in the design and operational cycle.

problem is to keep this tension at a healthy level that has an optimizing effect."[2]

The model developed has a sharp line of demarcation between legally binding requirements and informal guidelines providing the basis for the healthy level of tension that optimizes. Greenleaf again stated the case well in emphasizing the creation of teamwork. Teamwork is the method for insuring the quality product. It is mandatory that government, industry, project, and engineering work as a team. If any group becomes the priest, the judge, excessively binding the others in a legal manner, it destroys the team effort along with creativity. Space engineering is always pushing the edge of technology, requiring the optimum development of creativity to meet the combined performance, risks, and cost goals. This means that a constant awareness and struggle is required to balance between the legal requirements (formal) and the creativity (informal) of the individual. This is one of the highest priority tasks. Requirements and standards are needed for all facets of the project. They start with the general performance requirements and evolve to include management, finances, all design disciplines, manufacturing, operations, and maintenance. In summary, they tell the what and the when of the project, defining what the customer desires, whereas the informal insures communication and information transfer without repeating the mistakes of the past.

The content, structure, and philosophy of criteria have far-reaching influences on the evolution and success of the project to which they are applied. It is easily recognized that design parameters, margins, and robustness are directly affected by the criteria imposed. What is less apparent is the pervasive effect that criteria have on the relationships, teamwork, balance, and management within the project framework.

Criteria quite naturally set the technical design point, the balance between performance, reliability, and operability. Furthermore, beyond directing the technical evolution of a design, the philosophy and content of the criteria used can enhance or retard the nature of the relationships among the engineering and project manpower elements.

Also, the tone of contractor-customer relationships can be greatly influenced by the way in which the criteria are deployed, ranging from an at-arms-length, adversarial relationship to that of a cooperative team effort. These influences will be discussed in subsequent sections.

II. Misuses of Criteria

Requirements can be misused in several ways. In one extreme, they are so loose and ill defined that they do not provide order to the process. In the other extreme, they specify too restrictively not only the necessary requirements but also the procedures, guidelines, and codes and many times include undue constraints such as shape, mass, cost, and schedule. In the first case, there are no order or standards, and hence the product has no form, may become very costly, and may not meet the customer's needs. The overspecified case also results in a costly product that ends up compromising the customer's performance goals because proper trades cannot be accomplished and the system optimized. Features not accounted for in the design must be covered in maintenance and operations. This not only increases the cost and complexity but generally causes longer operations turn-around time as well.

The Space Shuttle is an example of constraints misused. Clearly the Space Shuttle exemplifies many correct uses of criteria because it is the world's greatest space system. Yet, the complexity and cost exceeded all predictions along with some performance compromises. The performance requirements, manned, reuse, etc., in conjunction with early geometric weight and cost constraints, drove the design to very high derived performance requirements. For example, 55-mission life, 109% engine thrust, etc., dictated high performance structures (welded, lightweight), high energy concentration, and the like. The result is a very costly maintenance and operations system. Inspections are numerous as well as hardware changeout, and refurbishment required to maintain safety is huge. In other words, the Space Shuttle evolved into a performance-driven instead of a cost-driven design, which resulted in costly maintenance and operations to maintain reliability and safety.

A trap that is present in using criteria is the dependence on them ("the set of criteria") to accomplish a good design while relaxing good engineering practice. In the final analysis, skilled personnel applying good engineering thoughts and practices are the roots of good products. Nowhere is this more true than the aerospace industry where technology is pushing state of the art, requiring innovation and creativity of the highest order.

III. Proper Use of Criteria

Pugh, in his book *Total Design*, speaks of the role of the product design specifications (PDS), which coresponds to the "specifications" block of Fig. 1. He says that "the product design specifications (PDS) is the mantle enveloping the whole design core activity. It is the document or documents that unambiguously delineates all the legally binding requirements. It is dynamic rather than static. Evolutionary, comprehensively written document which, upon completion of the design activity, has itself evolved to match the characteristics of the final product. It (PDS) must be comprehensive and unambiguous, otherwise the designer will fill in the gaps based on feeling and experience." He further says that "At the end of the design activity, the product must be in balance with the PDS. It sets the design in context, representing as it does a comprehensive set of constraints which are always in a unique combination."

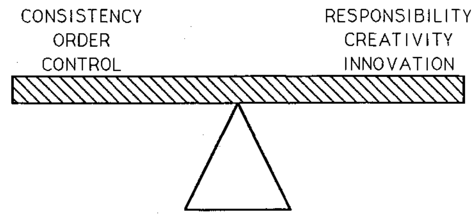

Fig. 3 Balancing act.

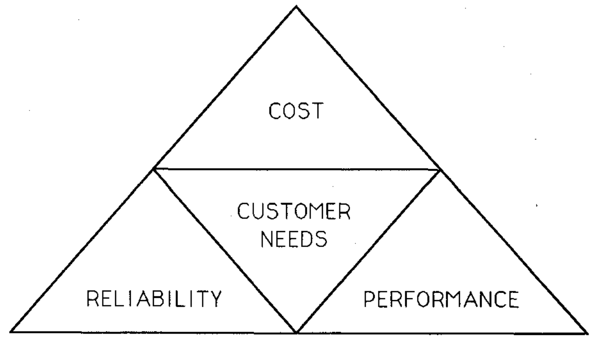

Fig. 4 Basis for criteria.

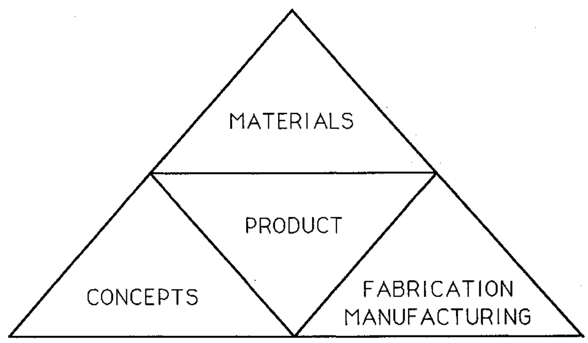

Fig. 5 Triangle of product design.

Criteria then are of two types. First and foremost, as Pugh says, they are the legally binding mantle developed to make the product conform to the customer's needs and good engineering practices. The second set is not legally binding. They are used to properly evaluate the trades for concept selection and during detailed design drive out the derived requirements. They are very important because they become the standards against which decisions are made and guide the design, etc. In other words, the informal guidelines drive formally derived requirements. This is accomplished by providing the lessons learned, handbooks, and other communications gathered through practical engineering and past space programs.

All organizations use criteria in these two roles; however, as was discussed in the last section, many times they are misused and thus create problems. If criteria can be misused, then the next question arises: What is the proper role and use of criteria? As was stated in the introduction, criteria must provide the balance between order and control and freedom to draw out creativity and innovation (Fig. 3).

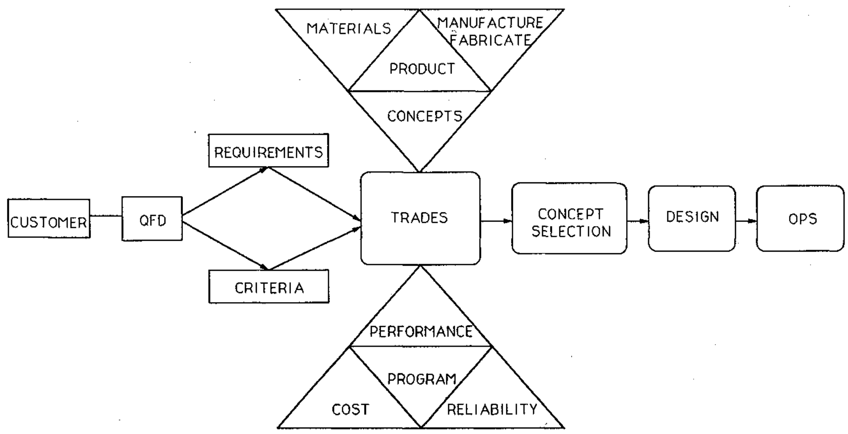

Fig. 6 Proper use of criteria.

While accomplishing this task, management must also balance the product optimally between performance, cost, and reliability (Fig. 4). Criteria must be derived and selected for each while maintaining political viability. This is also a balancing act. Space vehicles, by definition, are always performance critical, and performance can overdrive the product. Great care must be exercised to develop a balanced set of criteria in these areas.

The most optimum product is determined by conducting proper trades between the potential configuration concepts (for example, liquid vs solid propellants), materials potentials (steel vs aluminum vs composites, etc.), and the manufacturing/fabrication possibilities (casting, extruding, etc.). This relationship must be considered simultaneously, requiring properly defined, balanced criteria jointly derived by all disciplines involved (Fig. 5).

On the surface, it appears these diverse areas could be treated separately. This is not the case. They are highly interactive, often in a contradictory way. They must be put together properly to produce the appropriate product (Fig. 6).

When taken in this light, proper use of criteria performs many functions: 1) serves as management tool; 2) sets the design boundaries; 3) sets the verification limits; 4) controls the design optimization, trades, and concept selection; 5) sets operational constraints and procedures; and 6) enhances communication and technology transfer.

To properly perform these functions, criteria must cover all aspects of the product. They include, but are not limited to, the following: 1) performance, 2) environments (natural and induced), 3) service life, 4) maintenance, 5) transportation, 6) manufacturing, 7) assembly, 8) size and weight, 9) materials, 10) finish, 11) shelf life/storage, 12) standards, 13) processing, 14) testing/verification, 15) documentation, 16) operations, 17) reliability/availability, 18) schedule, and 19) cost.

The management approach must be consistent with the criteria. The criteria control the product design; thus, management must provide the framework and business control within which the design operates, providing resources, common objectives, understanding, and project direction. Management is responsible for organizing and planning design reviews, operational plans, etc. The next section will deal with the philosophy and approach for the management concept.

IV. Project Management as Influenced by Criteria

The management approach for a space project can be reflected in, or can be a reflection of, the philosophy taken in establishing its criteria. The content of criteria and the methods used in their development can set the tone for relationships among the various parties involved: project management, engineering, and business management on both sides of the customer-contractor interface.

Excessive criteria, which overspecify the how-tos, not only short-circuit creativity in the attempt to arrive at the best design but also can drive a wedge between engineering and project management groups. Overspecification results in excessive waiver and deviation traffic and leads to "lawyering" vs good engineering. Underspecification, although less common, is likewise to be avoided to preclude major downstream shortfalls. The proper balance of criteria enhances a healthy and productive relationship between engineering and project management.

If criteria are developed unilaterally and are imposed arbitrarily on the contractor, the two parties are set at odds from the beginning. In its extreme form, this arbitrariness encourages an adversarial customer-contractor relationship. At best, it promulgates a "throw-it-over-the-fence" approach where problems are not addressed as a team but wait on the formulation of a design review or other major legal milestone.

A much more proactive approach is to make criteria development a joint effort between contractor and customer. In this effort, both parties work together to tailor the specifications to the needs of the particular project with a goal of achieving the ideal balance of control and innovation described earlier. The joint effort produces joint ownership of the criteria and lays the groundwork for teamwork and communication. This relationship leads to a proactive approach to project evolution, with early problem identification and resolution. Such teamwork brings all available resources to bear toward successful project maturity.

This is not to say that such teamwork is without disagreement and tension. Rather, tension is to be expected because of the different emphases and subgoals of each participant. This is not necessarily bad. When all parties are communicating and working toward the overall objective, there is room for disagreement. One must draw a distinction between creative and destructive tensions. A tension exists between the subgoals of performance, reliability, cost, and schedule. If openly recognized, communicated, and dealt with in a teamwork environment, this can be creative tension that in fact directs the evolving design to its ideal balancing point. Likewise, tension is natural between engineering and project management or between customer and contractor. Dealing with these natural tensions in a teamwork approach can provide the creative balance to direct the evolving project to its ideal operating point.

V. Proper Development of Criteria

Proper development of criteria is based on two fundamental concepts: 1) breadth, which covers all necessary areas, and 2) minimum required to produce the optimum design. This section will deal with the breadth question, whereas Sec. VI will deal with ways of achieving the minimum required set.

A. Performance Requirements

The performance requirements say what a product is to do. The origin of the basic performance requirements is the customer. The performance demanded should be defined. Space systems have many performance requirements, most of which are unique to that particular system such as aperture and pointing accuracy for a telescope, payload size and weight to specified orbits, manned or unmanned, cost, reliability, reuse (how many times), operational turnaround, to name a few. Quality Function Deployment (QFD) is an excellent tool for developing and flowing these requirements down throughout the project.

These requirements are very crucial to the design because they determine what is to be done. Overly tight requirements may drive the economics of the system out of the range of affordability. Yet, if the requirements are necessary to accomplish the job, then technology must be considered as well as cost. Space projects as a rule require the extension of some technology to meet the requirements. A general rule that is applicable is do not start a project that requires the development of more than one major technology.

B. Derived Requirements

In the process of concept selection and detail design, performance requirements or criteria dictate additional requirements necessary to meet the project's goals. These are commonly called derived requirements because they occur as the project evolves. For example, launch vehicle load relief control balances between structural weight, performance loss, and cost. The Pogo suppression system stabilizes the vehicle from pro-

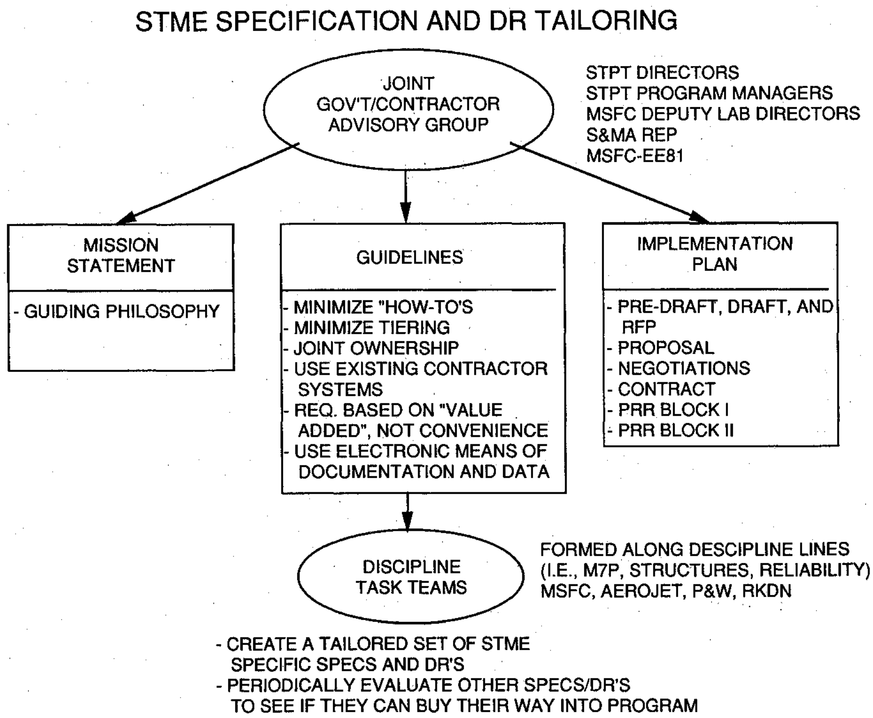

Fig. 7 Space Transportation Main Engine (STME) management and criteria development approach.

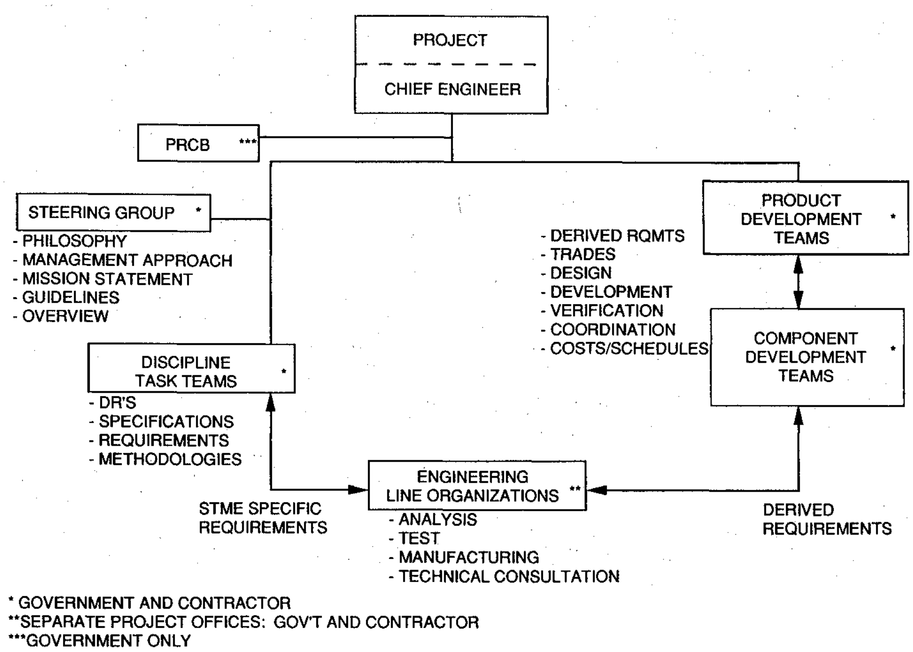

Fig. 8 Functional design groups.

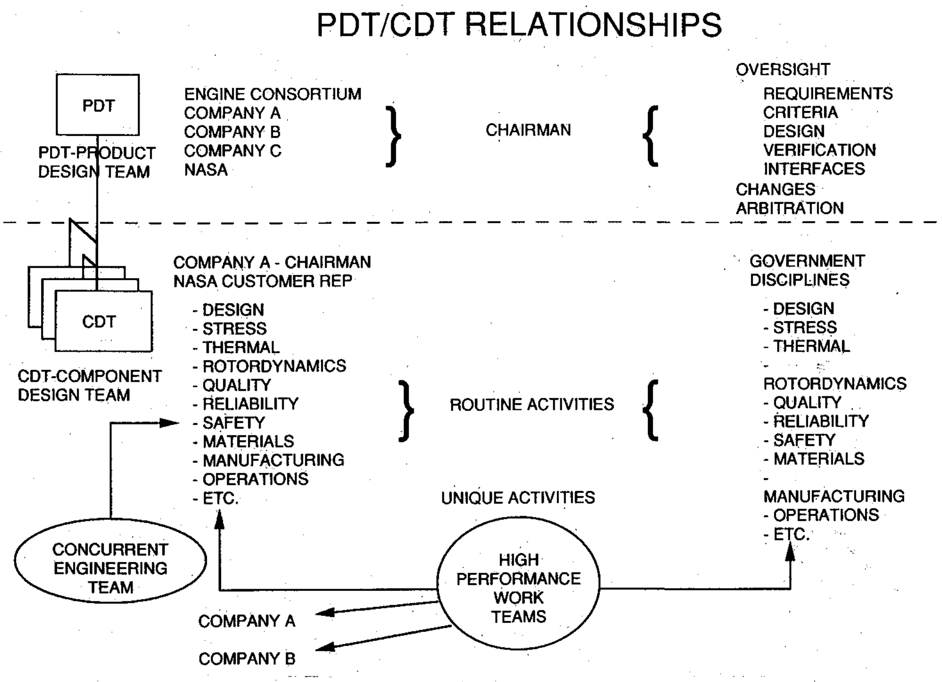

Fig. 9 STME specification and data requirements tailoring.

MISSION STATEMENT
FOR STME SPECIFICATIONS AND DRD'S

Create contractual requirements with and innovative approach consistent with TQM principles which include performance, reliability, traceability, and verification, and eliminates restrictive "how-to" requirements. The specifications and DR's must embody and implement the concurrent engineering management approach established for the STME probram. Encourage innovation and creativity while incorporating good engineering practice, mutual acceptance of goals, and concurrent engineering. Impose only necessary requirements which ensure order, add value to the end product, do not anticipate solution, and produces a robust design. Use subordinate documents and lessons learned for reference, rather than as contractual requirements. Eliminate non-value added documentation and data deliverables. Ensure adequate risk mitigation with proper control over design and development, while ensuring program meets the performance and reliability requirements.

Fig. 10 Mission statement.

pulsion structural coupling. The list goes on, ad infinitum, and evolves from all design disciplines such as manufacturing, transportation, assembly, and operations.

Derived requirements are therefore mandatory for the product success; however, they should be only those that are mandatory, not nice to have, overly complex, or a patchwork quilt. They should evolve to be a coherent part of the design. In other words, they must buy their way in. Great care must be taken in properly testing, evaluating, and baselining these requirements. Once baselined, they must be designed and verified as all other subsystem and component requirements.

C. Design Requirements

Design requirements fall into two basic categories: 1) the standards and 2) discipline requirements. They are the controlling factors in the design. They spell out in unambiguous terms the margins in all disciplines (safety factor, lifetime, etc.), the process controls, environments, documentation, and probability required to produce an acceptable product. As was stated in Sec. I, they flow down into the documents such as ICDs, CEIs, etc. Pugh says that they detail the performance demanded or likely to be demanded and should fully define all aspects of design. They not only play the role of providing the standards by which the product is verified and operated, but they also serve as a management tool. Performance in this case is not just how fast, how slow, or how much but includes all of the specifications for the product, including, but not limited to, verification, testing, environments, margins, life, maintenance, transportation, manufacturing, assembling, materials, and reliability. The roles of design requirements in summary are as 1) a management tool and 2) legal controls for the design boundaries. As stated earlier, they bring order to the process without killing creativity and insure that the product achieves the goals assigned it.

D. Whats vs How-Tos, Lessons Learned, Guidelines

The whats spell out the necessary conditions that must be met in a design such as how long, when, speed, cleanliness, environments, etc. These are in general mandatory and legal, setting the basics for a design. Good design dictates that a comprehensive set of whats be established and adhered to. As was stated earlier, these should be binding on the project and enforced by the management.

How-tos are the history, the lessons learned, technology, and procedures. These generally are not a part of the contractural binding requirements; however, they serve a very useful purpose both to enhance communication and document good things to do. Their influence is not to be discounted, in that they are a voluminous source of information that has a profound influence on the project design cycle. There are some cases when the how-tos are so overriding that they must become a part of the contractural requirements. The sources of these lessons are contained in handbooks, technical papers and reports, monographs, and, more importantly, in the experience of the individuals making up the organization.

VI. Approach to Restructuring Criteria to Realize Full Potential

Requirements and guidelines are the foundation for good products. It is imperative that the requirements (legally binding) particularly be derived in a meticulous and thorough manner because they not only control the design but also in the end become the specification for the product, providing the basis for operations (use). This dictates that they must be verifiable. All good design is a rule-based design. The prime question is how is this correct set of criteria reached?

Clearly, the derivation of requirements must be based on lessons learned, standards, project management approach, performance requirements, and technical requirements. It must cut across all areas of design and operation concerns for all disciplines involved in the project. Consideration should be given to failure modes and effects analyses (FMEAs), robustness, redundancy, margins, cost, and schedules.

Further, it should be a product of joint effort between the customer and the contractor. The space transportation main engineer (STME) has developed requirements in this manner under the objectives of high quality and low cost using the principles of total quality management (TQM) as the means. The requirements development evolved using an oversight steering group composed of contractors and NASA personnel. This group developed a mission statement of what the requirements developers were to accomplish and then developed the design organization approach using product and component design teams manned by NASA and contractor engineers. The steering committee next set up NASA contractor discipline teams to develop the design requirements, documentation requirements, and methodologies. Figure 7 shows these steps as carried out by the advisory or steering group. Figure 8 shows this overall structure of requirements development and design teams. The left leg illustrates the use of government contractor engineering disciplines teams to derive the criteria, develop the documentation requirements, and establish the engineering methodologies. The right leg shows the engine design teams called product and component development teams composed of government and contractor engineers, etc. Because the criteria and the design must be compatible, Fig. 9 illustrates the makeup of the component design teams (CDTs), showing the three engine contractors making up the engine development consortium (TPO) and the NASA counterparts. Team composition by disciplines, government and contractor, are shown along with the roles of the product design teams (PDTs) and component design teams (CDTs). The PDTs are the large products such as a turbopump, whereas the components are the parts that make up the pump.

Use is made of the contractor's criteria and specifications in conjunction with the voluminous set of government generic criteria. The teams took each of these documents and focused on criteria areas applicable to the specific project, weeding out all others. They next took those project-applicable areas and eliminated all how-tos, lessons learned, etc. Next, the remaining statements were rewritten clearly, keeping only those that added value to the system. The reduction in document size was phenomenal without eliminating any necessary controls. Figure 10 is the mission statement used by the team to guide specification development.

A similar approach was used recently for space station criteria to provide consistency across three NASA centers and the three prime contractors. The criteria were derived using a team approach consisting of senior technical personnel from each of the individual organizations, both government and contractor.

Pugh, in the previously referenced *Total Design*, devotes one chapter to the derivation of the PDS, recognizing the importance of criteria.

Requirements are usually written to include guidelines, procedures, and implementation schemes. This ought not to be. Requirements should be very concise and specific without justification or guidelines and should be based on sound engineering understanding. There is a need for guidelines, procedures, and implementation schemes, including engineering equations, computer codes, instrumentation plans, test approaches, etc.; however, they should be produced as separate documents and not as part of the requirements.

VII. Conclusions

In conclusion, the approach is clear. It must be based on basic principles and tools, using teamwork of government and contractors, being a project that has true joint ownership, and utilizing sound systems engineering, concurrent engineering, and continuous process improvement. All areas, from materials, to concept selection, fabrication, and operations, must be approached in this evolutionary manner. The role of criteria is then to provide order to the process without stifling creativity and innovation, the main ingredient of space system design. Criteria developed in this manner should satisfy all of the pervasive influences, without binding creativity, to produce the order required to achieve a low-cost, quality product. As important as criteria (requirements) are, there is also a balancing act between criteria and sound design engineering. The best criteria without sound engineering produce poor products as does sound engineering with poor criteria. Space product design is a multifaceted process that requires great skill in balancing between them. Criteria are only one facet and do not exist in a vacuum, but must consider all dimensions of the product.

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