Launch Vehicle Design Process: Characterization, Technical Integration, and Lessons Learned

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Acknowledgments

PREFACE

The combined experience of the authors extends over 150 years. During that time, they have participated in the design activities associated with the following programs: Redstone, Saturn I, Saturn IB, Saturn Apollo, Skylab, Space Shuttle, Spacelab, Hubble Space Telescope, HEAO, Chandra, Space Station, X–33, and various payloads. At present, they are participating in training activities at Marshall Space Flight Center. In that capacity, they are active in publications, course development and teaching, process modeling, mentoring and advising, and interactive computer tools.

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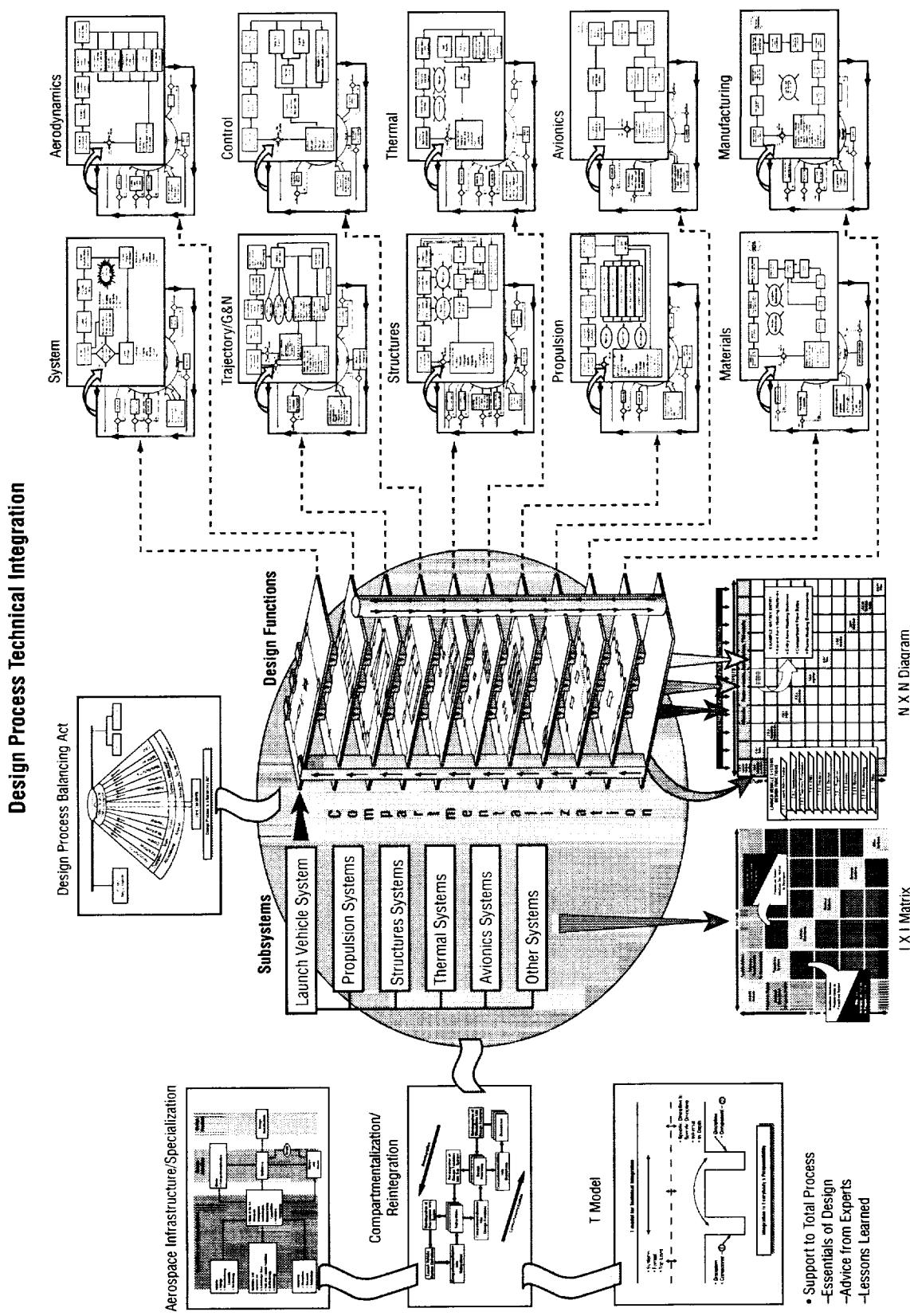
Figure 1. Design process overview.

FOREWORD

This report deals with the design process for launch vehicles. It extracts information from the experience of the authors, their associates, and related literature. The initial sections of the report address essential groundwork and fundamentals, and the final sections address guidance for achieving a successful design and advancing design process technology. However, the core of the report is the characterization or description of the design process itself given in section 4.3. An overview of the process description is represented in figure 1 which illustrates the main elements and connections of the process. Main elements include compartmentalization/reintegration, subsystem tree, design function planes, discipline functions, decision gates, IxI and NxN diagrams, and the process balancing act.

A reader concerned specifically with the process description can go directly to section 4.3 for the detailed discussion. The description then serves as a basis for (1) understanding the design process and how its various elements interact, (2) incorporating subtleties necessary for a successful design, and (3) achieving advances in design process effectiveness and efficiency.

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AFSIG	Ascent Flight Integration Working Group
AIAA	American Institute of Aeronautics and Astronautics
ASSC	alternate Space Shuttle concept
ATP	authority to proceed
CAD	computer aided design
CAM	computer aided manufacturer
CC	controlled convergence
CDR	critical design review
CFD	computational fluid dynamics
CG	concept generation
CIL	critical items list
DCR	design certification review
DDT&E	design, development, test, and evaluation
DMS	data management subsystem
DOD	Department of Defense
DR	disposal review
ECLSS	environmental control and life support system
EGSE	electrical ground support equipment
ELV	expendable launch vehicle
EMI	electromagnetic interference
EPA	Environmental Protection Agency
EPS	electrical power system
ET	external tank
FA	further addition
FDL	Flight Dynamics Laboratory
FM	functional manager
FMEA	failure modes and effects analysis
FPR	flight performance reserve
FR	further reduction
FRR	flight readiness review
G&N	guidance and navigation
GD	General Dynamics
GN&C	guidance, navigation, and control
GSE	ground support equipment
I^2CS	interactive information and communication system
ICD	interface control documents
IPCL	instrumentation program and component list
IPT	integrated product teams
ISO	International Standards Organization

I_{sp}	specific impulse
JSC	Johnson Space Center
L	liaison representative
LEO	low Earth orbit
LSEAT	Launch System Evaluation Advisory Team
MAC-DAC	McDonnell Douglas
MCR	mission concept review
MDR	mission definition review
MIU	material identification and usage list
MM	Martin Marietta
MPS	main propulsion system
MSC	Manned Space Center
MSFC	Marshall Space Flight Center
MUA	material usage agreement
NAR	North American Rockwell
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
NMI	NASA Management Initiatives
NPSP	net positive suction pressure
OMB	Office of Management and Budget
OPS	operations
ORR	operational readiness review
OSHA	Occupational Safety and Health Administration
PDS	product design specification
PDR	preliminary design review
PRR	preliminary requirements review; also, program readiness review
PSIG	Propulsion System Integration Working Group
QFD	quality function deployment
RBCC	rocket based combined launch
RCS	reaction control system
RFP	request for proposal
RLV	reusable launch vehicle
RSS	root-sum-square
S/W	software
SAR	system acceptance review
SDR	system definition review
SEA	statistical energy analysis
SLWT	Super Light Weight Tank
SN	stress versus number of cycles to failure
SOA	state of the art
SRB	solid rocket booster
SRM	solid rocket motor

SRR	system requirements review
SSME	Space Shuttle main engine
SSTG	Space Shuttle Task Group
SSTO	single-stage-to-orbit
STG	Space Task Group
STS	space transportation system
T/W	thrust to weight
TCS	thermal control systems
TPS	thermal protection system
TRIZ	Russian acronym meaning "theory of inventive problem solving"
TRL	technology readiness level
TSTO	two-stage-to-orbit
TVC	thrust vector control
WBS	work breakdown structure
v&v	verify and validate

TECHNICAL PUBLICATION

LAUNCH VEHICLE DESIGN PROCESS: CHARACTERIZATION, TECHNICAL INTEGRATION, AND LESSONS LEARNED

1. INTRODUCTION

1.1 Motivation and Approach

There is a strong need within NASA and the aerospace industry to reduce the cost and improve the effectiveness of launching payloads into orbit. Understanding and improving the design process for launch vehicles are essential ingredients in obtaining a low cost, effective launch capability. This report addresses characterizing, understanding, and improving the launch vehicle design process. It grew out of an initiative of the former Structures and Dynamics Laboratory at NASA Marshall Space Flight Center (MSFC).

The goal of this activity is to enable effective and efficient launch vehicle design by (1) providing an understanding of the current design process as a basis for improving effectiveness and efficiency and (2) providing a design process reference guide for less experienced engineers. This report characterizes and clarifies the current design process. It examines common problems encountered and provides guidance for effective implementation. It also includes an initial listing of improvements to the current design process and initial observations on advanced technologies that might revolutionize the design process.

Engineering design is a challenging activity for any product. Since launch vehicles are highly complex and interconnected and have extreme energy density, their successful design represents a challenge of the highest order.

Most new launch vehicles require very high propulsion efficiency and mass efficiency, have significant uncertainties in environmental and system parameters, and involve advanced technologies. They have stringent requirements for performance, cost, reliability, safety, operability, and schedule. Meeting the design challenge resulting from the combination of the above factors demands the best of engineering skill, organization, communication, integration, and judgment.

The currently accepted design approach to space systems is to compartmentalize the hardware subsystems, subsystem design functions, and discipline functions. The substructuring is driven by the need to distribute the workload into manageable portions, the need to utilize multiple discipline specialties, and the need to capitalize on industrial specialization. The functional characteristics of the subsystems enable decoupling which allows for the distribution of the workload to the design functions and allows for the utilization of the industrial specialization. Industrial specialization refers to the specific expertise that has evolved in industry to provide unique subsystems (e.g., avionics, rocket engines, etc.) and parts

(e.g., o-rings, transducers, etc.). Achieving the highest quality and lowest cost for a launch vehicle entails utilizing this specialized expertise of the industrial base. Industrial specialization also provides hardware availability and schedule reduction. The specialization also enhances technology development. Compartmentalization results in two distinct functions: (1) The design function and (2) the discipline function. The design functions are supported and accomplished through the discipline functions. The approach revolves around allocating requirements, constraints, etc., to the subsystems, elements, and components. The hardware and software are designed and produced through analysis, testing, simulation, and manufacturing processes. The design and discipline functions accomplish these tasks. As is true with industrial specialization, this compartmentalization focuses specialization and technology development. The inherent problem with compartmentalization is that it necessarily creates artificial boundaries in the process and organization. These boundaries create the tendency toward sandboxing or territorial syndromes. This creates communication problems in properly exchanging interacting parameters and data. These boundaries have made it difficult, if not impossible, to establish an ideal, seamless design process.

When the process works properly and interactions occur among subsystems, design functions, and disciplines, design iterations must occur to converge the total system to achieve requirements. Key decisions in the iterative design process are based on analysis, simulation, test results, and keen engineering judgment. In this method, the system design is accomplished by assembling these separately designed subsystems, etc., and iterating or balancing between conflicting outputs. As stated previously, the system has evolved along the specialization (competencies) of industry and academia. This standardization and specialization result in higher quality and lower cost parts, components, etc. The design process takes advantage of these specialties. Design function and discipline function compartmentalization follow from standard specialties of universities and design organizations. The approach is applicable in general; however, it is usually based on the assumption of weak coupling between the subsystems, design functions, and disciplines. If the coupling is not weak, there are more difficulties in allocating requirements, communicating, and interacting within the total system.

It is a generally stated axiom that 80 to 90 percent of design problems are not caused by a lack of discipline understanding but are due to a breakdown in communication. As a result, there are risks associated with the process that must be assessed and understood.

First, the higher the performance requirements of a system, the higher the sensitivities and interactions. This means extensive emphasis must be placed on allocations, interactions, integration, and communications' reliability; otherwise major problems occur.

Second, compartmentalization naturally introduces boundaries, setting up the tendency for industry and discipline nearsightedness.

Third, system design must be recognized as a balancing act between the conflicting requirements and interactions.
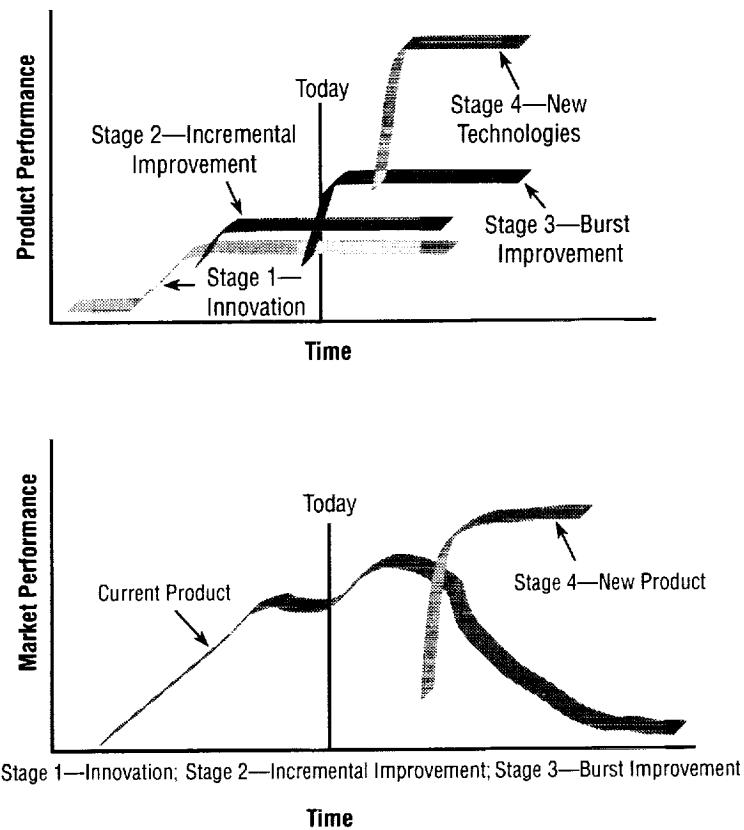
In summary, ensuring that the current design approach works requires proper attention be given to allocating and refining requirements, to understanding sensitivities and interactions, and to ensuring technical integration through adequate communication.

The first part of the activity reported here is intended to characterize and baseline the launch vehicle design process. In section 4.3.1, the process has been characterized by compartmentalizing the system into subsystems, with each subsystem having design function planes overlaid with a system design function plane. Within each design function plane are the contributing discipline and design activities along with output attributes. This description includes both the tasks and how design decisions are made fractionally and incrementally and how design decisions are integrated into the total design. For each plane a flow diagram is developed for illustrating the various decision gates and a description of top-level attributes to be compared with requirements. This approach was developed to characterize the launch vehicle detail design stage and can be applied to other design stages; e.g., conceptual and preliminary design stages.

The typical process as practiced currently is referred to herein as the baseline. The characterization of the baseline serves as a reference point for refining and improving the present process (evolutionary). It also serves as a reference point to develop revolutionary technologies for the design process that could produce orders of magnitude jumps in process efficiency and effectiveness. The effort reported here is the initial task of determining the essence of the launch vehicle design process. If we are to meet the launch capability demands, then breakthrough must occur.

Utterback in *Mastering the Dynamics of Innovation*[1] discusses how companies can seize opportunities in the face of technological change. Others have dealt with the subject also. Utterback characterizes the development of a product in steps. First, the company concentrates on product innovation until it is an established product. Second, they concentrate on process improvement. Third, the product is then in a specific phase and is firmly established. During this time, the product performance (sales, use) continues to rise with minor attention to product or process improvement. As invading technologies or the requirement for them come in, the product will accomplish bursts of improvements. However, this is not sufficient to save the product as it is, and the invading technologies take over. For example, digital watches replaced the Swiss jeweled watch. The manual and electric typewriters were replaced by the word processor. The household refrigerator replaced the ice factories. None of these invading technologies were implemented by the parent companies. Utterback's concept, as discussed above, was applied to aerospace as indicated in figure 2. So, NASA and the major aerospace industries should follow a three-pronged attack:

1. Delineate and baseline the launch vehicle design process

2. Refine and improve the baseline process—evolutionary

3. Implement new innovative technologies to advance the process—revolutionary.

Stage 1—Innovation; Stage 2—Incremental Improvement; Stage 3—Burst Improvement

Time

Utterback's Characterization of Product Development:[1]

First Stage: Concentration is on product innovation until it becomes an established product
Second Stage: Concentration is on process improvement
Third Stage: Burst improvements in product stimulated by new requirements and new technologies
Fourth Stage: New technologies take over; e.g., quartz watch, word processor, refrigerator

Recommendation:
(1)   Work hard to accomplish major burst in the current suboptimum approach, fine tuning it for more efficiency in performance, cost, reliability, safety, operability, and scheduling.
(2)   Pursue new technologies that can revolutionize vehicles.

Figure 2. Product evolution cycle.

4

1.2 Report Overview and Organization

The results presented in this report characterize and baseline the launch vehicle design processes. This was achieved by systematically defining, delineating, and explaining the key features of the design process. This overview is intended to illustrate that method via the organization of the report. The following is a brief explanation of the various sections of the report.

1.2.1 Introduction

This section presents the motivation and goals of this activity. In addition, the complexity of the process is explained as well as the challenges. The scope of the effort is delineated, and the process is briefly characterized and explained. Utterback's characterization of product development is introduced to reflect the potential impact on the aerospace community.[1]

1.2.2 Process Overview

A top-level description of the design process is presented to show the connectivity between the space transportation system (STS), launch vehicle system and subsystems, design functions/discipline functions with compartmentalization and allocation, and the technical integration process. Additionally, a thumbnail sketch is presented to delineate concept selection, preliminary design, and detailed design.

1.2.3 Essentials

While the design process itself is key to evolving a design, there are also 11 essential engineering considerations that must be recognized and carefully implemented. These considerations are subtle and implicit in the process, but they are of such importance that we have called them "essentials." These essential engineering considerations are as follows: basis of good engineering; constraints; derived requirements; formal design criteria; categories of modeling/activities; analyses, tests, and simulations; parameter matrix uncertainties; sensitivities; failure modes; judgment; and probing questions that should be asked throughout the design process.

1.2.4 Design Process Description

The main results of this entire activity are developed in this section. First, important aspects of the project technical framework are addressed. Then the T-model for technical integration is introduced. In this model formal and informal integration are defined. Finally, a symbolic model is developed that characterizes technical integration and the design process. This model consists of design function planes associated with the vehicle subsystems. These design functions are systems, aerodynamics, trajectory/ guidance and navigation (G&N), controls, structures, thermal, propulsion, avionics, materials, manufacturing, and others. In addition to the design function planes, the characterization also includes their associated decision gates and engineering tasks. This model is also linked to an existing, detailed discipline description via its work breakdown structure (WBS) and N×N matrix from reference 2. While the basic characterization has been developed, there are some detailed aspects of the model that are still being investigated.

1.2.5 Process Improvement

It is thought that process improvement can be achieved by fine-tuning the present design process and implementing revolutionary technologies. While it is planned to investigate these activities in follow-on efforts, some ideas associated with process improvements are delineated in this section. Some categories associated with fine-tuning are as follows: requirements and criteria, designing for simplicity, improved modeling tools, and integration of discipline analyses. The categories associated with revolutionary technologies are compartmentalization/reintegration, synthesis and design, and interactive information and communications systems.

1.2.6 Illustrations of Process

The baseline design process that is characterized in this work was implemented in the Saturn/Apollo and Space Shuttle programs. Examples of the application of this characterization are given in this section. An overview of the conceptual design stage is given, and an example is presented of the Space Shuttle conceptual design process.

1.2.7 Distilled Wisdom

This section pertains to lessons learned and the results of a survey of experienced practitioners. During the evolution of the effort presented herein, key ideas were noted. Then upon completion of the baseline characterization effort, the process was reviewed to extract important ideas. From these two resources, lessons learned were distilled, and they are presented in this section. In addition, a survey of experienced practitioners was taken to determine "What is the essence of engineering design based on your many years of experience?" Their collective wisdom is also presented in this section.

The remainder of the report contains conclusions, recommendations, three appendices including a glossary, references, and a bibliography.

2. DESIGN PROCESS OVERVIEW
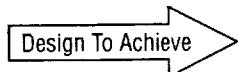
The launch vehicle design process presents a challenge of the highest order. This challenge is illustrated in figure 3. It can be seen that after the mission statement is defined, the project must achieve the system attributes related to performance, cost, reliability, safety, operability, and schedule via the design process. The challenges that the system designer must address are high energy densities, propulsion efficiency, dry mass efficiency, and loss management, along with technology readiness and requirements on cost and "-ilities." As can be seen, the loss management falls into the categories of uncertainties and interactions. The design process must rely upon analyses, testing, simulations, and past experience to provide insight for trading within and among the various challenges to achieve the best design. In addition, this same knowledge base is applied to develop philosophies and methods to support subsequent design judgments. The design and associated judgments are eventually assessed after development testing and/or in the operations stage and may lead to operational constraints.

Mission Statement: Insert a specified payload into a specified orbit to the required tolerances, within cost, reliability, operability, safety, and schedule requirements.

Engineering Challenges:

Design and Management Considerations   Project Requirements

• High Energy Densities   • Performance
• Propulsion Efficiency   • Cost
• Dry Weight Efficiency   Design To Achieve   • Reliability
• Managing Losses   • Operability
  – Uncertainties   • Safety
    • Manufacturing Variables   • Schedule
    • Environmental Variables
  – Interactions
    • Multidisciplinary
    • Interfaces
    • Operations
• Failure to Meet Technology
  Readiness Level (TRL) Target
• Cost, Reliability, Operability

Figure 3. STS design—highest order challenge.

This section provides an overview of the main features of the launch vehicle design process, along with associated challenges and connectivity. The details will be included in subsequent sections of the report. A thumbnail sketch of the design process sequence is provided to show the ordering of main activities of each design stage.

2.1 Top-Level Characterization

The engineering design process has five major areas of emphasis that flow in sequential order: (1) Requirements definition, (2) design, (3) build (make or buy), (4) system integration and verification, and (5) operations (fig. 4).
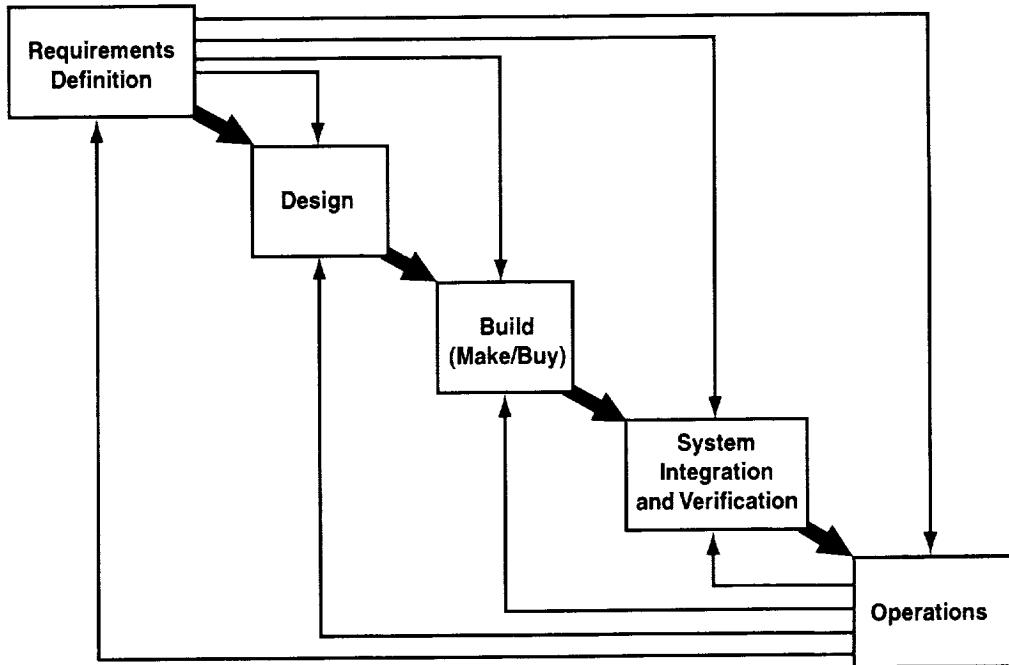
Figure 4. Design process/life-cycle flow.

Requirements definition specifies what the product is to do and how well it is to do it. It also specifies constraints, philosophy, and criteria (e.g., margins, etc.). Therefore, the design process starts with the mission statement and requirements. These are defined in terms of the requirements of the orbital characteristics (orbit inclination, altitude, etc.) and the payload to be delivered. In addition to the mission requirements, other requirements and constraints are also levied. These include cost (design, development, testing, and evaluation (DDT&E); operations; life cycle), reliability, development time, etc. NASA has program requirements such as design reviews and verification requirements that are contractually levied. Many times additional requirements are provided as constraints which may include such things as geometry, payload size, and environmental impacts. In conjunction with these mission and programmatic requirements, most design and discipline functions have legal criteria that must be met by the design. Finally, requirements evolve as the design progresses. These are called derived requirements and take many forms; for example, load relief controls and engine turbopump temperatures cut off or shut down. An STS must be formally verified to meet all these requirements and constraints before operation; figure 4 illustrates the top-level flow down of the process ending with a verified system at the flight readiness review (FRR), thus providing an operational system. The process works through system, design, and discipline functions, technical working groups, technical interchange meetings, boards, etc., which enhance technical integration and communications, thus enabling the design.

In order for the design process to work efficiently and take advantage of the state of the art (SOA) knowledge base, the STS must be compartmentalized into workable units after the mission and programmatic requirements are defined. The SOA information exists in three general areas: (1) Industrial specialization, (2) Governmental specialization, and (3)Academic specialization. Figure 5 shows the influence of aerospace infrastructure and specialization on design. The capabilities and knowledge bases of these three areas constitute the SOA which is captured by standards, monographs, technologies, manufacturing processes, etc., shown in the center block of the figure. These become the basis for the design process. The design activities consist of (1) compartmentalization of the hardware and tasks into workable units, (2) synthesis (concept identification), and (3) analysis and assessment of the synthesized concept. There is a major iteration loop between the synthesis activity and the analysis and assessment activity. The results of the design activities produce the design specifications. The heart of this approach of compartmentalization is the SOA knowledge and specialized processes that have been developed. Design can thus start with SOA capabilities that have already been developed. For example, the characteristics of various airfoil shapes have been investigated and demonstrated. The designer can choose the one that best fits the product concept under design. As another example, joints are a major design problem. Industry and academia have standardized various joint concepts and analysis techniques. All these standards, data bases, and processes are used for the initial synthesis process. The analysis and assessment function then fine-tunes and optimizes
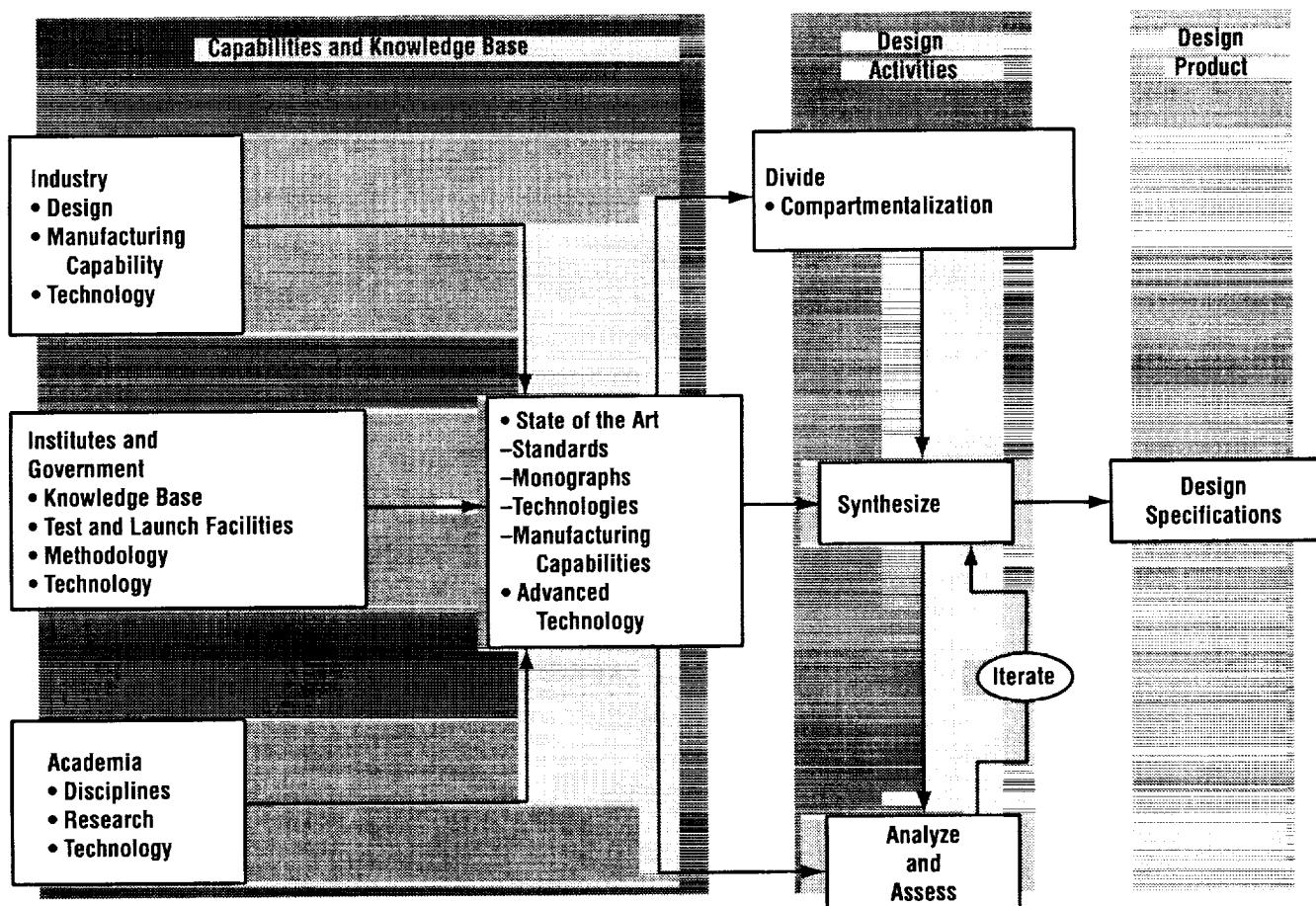
Figure 5. Influence of aerospace infrastructure and specialization in design.

and, thus, resynthesizes the product. (The iteration loop on the figure.) This approach of taking advantage of the three specializations, if used properly, can result in a higher quality product at lower cost. Compartmentalization by industrial specialization takes advantage of existing industrial expertise and infrastructure, thus cutting cost and increasing quality. Government and academia compartmentalization is along discipline lines as taught in universities and practiced in Government research labs. Most of the complex theories and the corresponding computer codes have evolved along these discipline lines. Discipline compartmentalization provides for indepth technical penetration and more efficient analysis efforts. Discipline codes are available, including computer aided design (CAD)/computer aided manufactuerers (CAM), structural codes, computational fluid dynamics (CFD), thermal codes, as well as many others. Government also has many specialized facilities for testing and massive computing, etc., not available in industry. Wind tunnels and rocket engine test stands are examples. The three areas of specialization produce synergistic technologies critical to the design of future systems.

The compartmentalization process starts with the definition of the top-level systems that comprise the STS overall system, as delineated in figure 6. These are based on specilized capabilities of Government and industry. Typically, the first level of compartmentalization is composed of the following.

- Launch vehicle (design and build)
- Payload interfaces (accommodations)
- Operations systems (hardware and software required for assembly, mission operations, and refurbishment).

Depending on the complexity of the STS and the industrial specialization, these systems can be defined differently; however, the compartmentalization process is essentially the same. As will be discussed later, each of these systems has its own design, manufacturing, and verification processes.
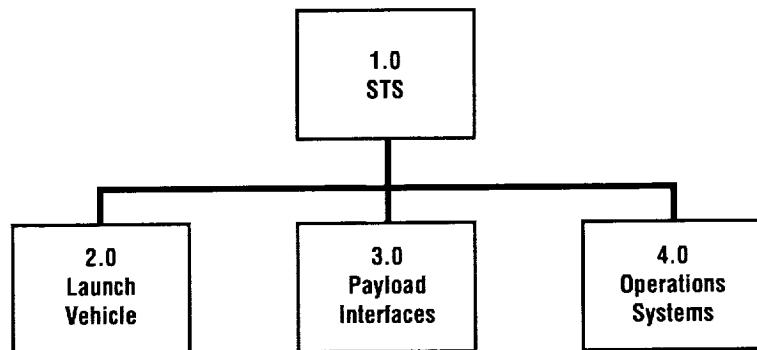
Figure 6. Top-level compartmentalization of design process.

The next step in the process is the allocation and levying of requirements. At this level of compartmentalization, the requirements are apportioned to the three systems. For example, top-level management decides what proportion of the STS budget is allocated to each of these.

Several techniques are available for enhancing requirement allocation to the STS systems and subsystems. Quality function deployment (QFD) is the most accepted approach for accomplishing this task. It starts with the customer's wants and translates them into designable attributes of the system. It weights the importance of each, providing an indication of priority. The QFD process is described in detail in many of the listings in the bibliography; therefore, no further discussion here is warranted. QFD is a useful tool to aid the allocation process; however, allocation typically must draw on the judgment and experience base of the leader and others involved.

After the allocations are completed, there are interactions/interfaces between the various systems that must be determined and traded in order to achieve overall balance. The vehicle affects the launch pad; the launch pad affects other facilities. The same is true of the payloads, etc. These couplings are generally weak and can mainly be treated with allocations via interface control documents (ICD's), etc.; however, they must be engineered and balanced to achieve some level of optimization.

The compartmentalization of the hardware/software systems continues down the tree, with the launch vehicle being compartmentalized into subsystems, then into a hierarchy of sub-subsystems, and so on into smaller entities, as indicated on the left side of figure 7. Each of the entities on the tree is a hardware/software item that must be designed. For purposes of this discussion, we will generically call the hardware/software item a *subsystem*.

The process of designing each subsystem entails a second type of compartmentalization, as indicated on the middle portion of figure 7. This second type of compartmentalization divides the subsystem design process into a set of *design functions*. These design functions are represented by a "stack" of design function planes. The specific design functions needed will vary from subsystem to subsystem, but typically include the design functions of structures, propulsion, thermal, avionics, manufacturing, etc. The products of the design functions are the specifications for their portions of the subsystem design. The top plane in the stack is the "system" plane that integrates the other design functions into an integrated design (specification) for the subsystem that corresponds to the stack.

(Note that each subsystem on the tree has its own design function stack. As we move down the tree into smaller subsystems, there will be an associated stack with each subsystem until we arrive at parts that can be designed by a single designer, making use of handbooks, etc. At this point, further compartmentalization is not necessary.)

A third type of compartmentalization occurs on each design function plane, involving *discipline functions*. Disciplines are technical areas of specialty and expertise. They perform analyses, tests, and simulations in support of the design functions, and they can be thought of as residing on the design function planes. This third compartmentalization is indicated on the right side of figure 7. On each design function plane, there is an iterative synthesis/analysis activity that draws on all the pertinent disciplines to arrive at a design (specification) whose attributes meet its allocated requirements.
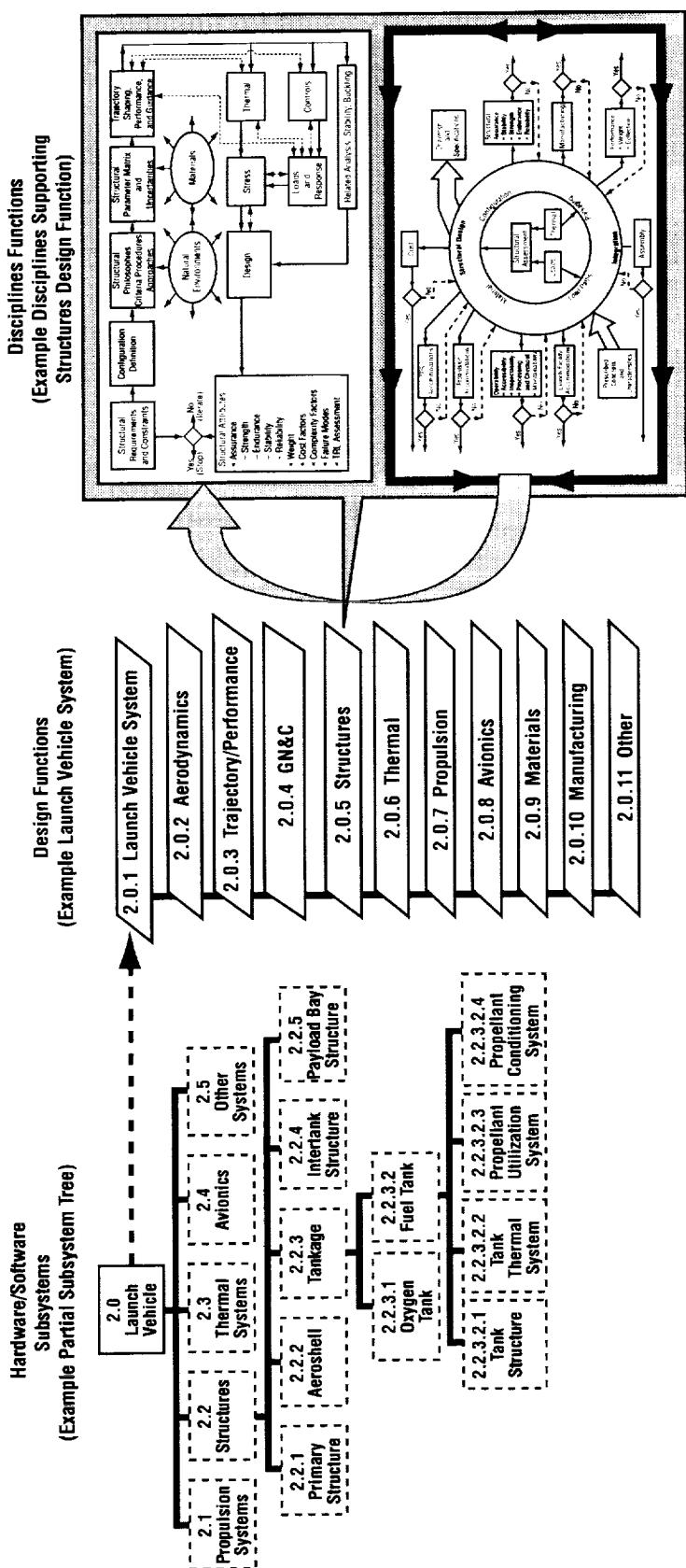
Figure 7. Categories of compartmentalization of design process.

Thus, there are three types of compartmentalization—*subsystem*, *design function*, and *discipline function*. Each compartmentalization in turn requires reintegration to constitute the complete system design. Figure 9 illustrates the three interconnected types of compartmentalization (proceeding downward to the right) and their subsequent reintegration (proceeding upward to the left). Completion of the final reintegration then results in the total system design.

These concepts will be further expanded and explained in section 4. The process of technically integrating the compartmentalized parts into a successful design is a primary challenge and constitutes a main subject of this report.

To further address the design and discipline function characterization, consider the design function "stack" associated with the launch vehicle system, as shown on the left of figure 8. The design functions shown are:

- System
- Aerodynamics
- Trajectory/G&N
- Control
- Structures
- Thermal
- Propulsion
- Avionics
- Materials
- Manufacturing
- Others

The structures design function plane is expanded on the right side of the figure as an example of the plane content. Also, there is an additional expansion below to show the decision gates that reside on the plane. Each plane is a flow diagram which shows top-level activities, beginning with requirements and architecture allotted to that design function, then compartmentalizing and reintegrating the discipline functions necessary to execute the iterative synthesis/analysis activity to converge on a design specification that meets the requirements. As the design matures through the iterative process, its attributes are assessed and compared with the requirements. Attributes are the numerous measures of "goodness" of the design in categories of performance, cost, reliability, safety, operability, etc., and are related one-for-one with requirements. The comparisons of these numerous attributes with the requirements are represented on the decision gate diagram where satisfying all gates means satisfying the summary decision gate on the design function plane.

The top plane of the stack of design function planes is the system plane. It provides the compartmentalization, allocation, and reintegration for the other planes. Its product then is the design specification for the subsystem entity on the tree for which the stack corresponds. A major feature of the process represented by the stack is the information flow that must occur among the planes. Critical formal feedback between the design function planes and the system plane is shown, as well as informal feedback between and within the planes. The rectangular vertical conduits with arrows pointing downward represent the

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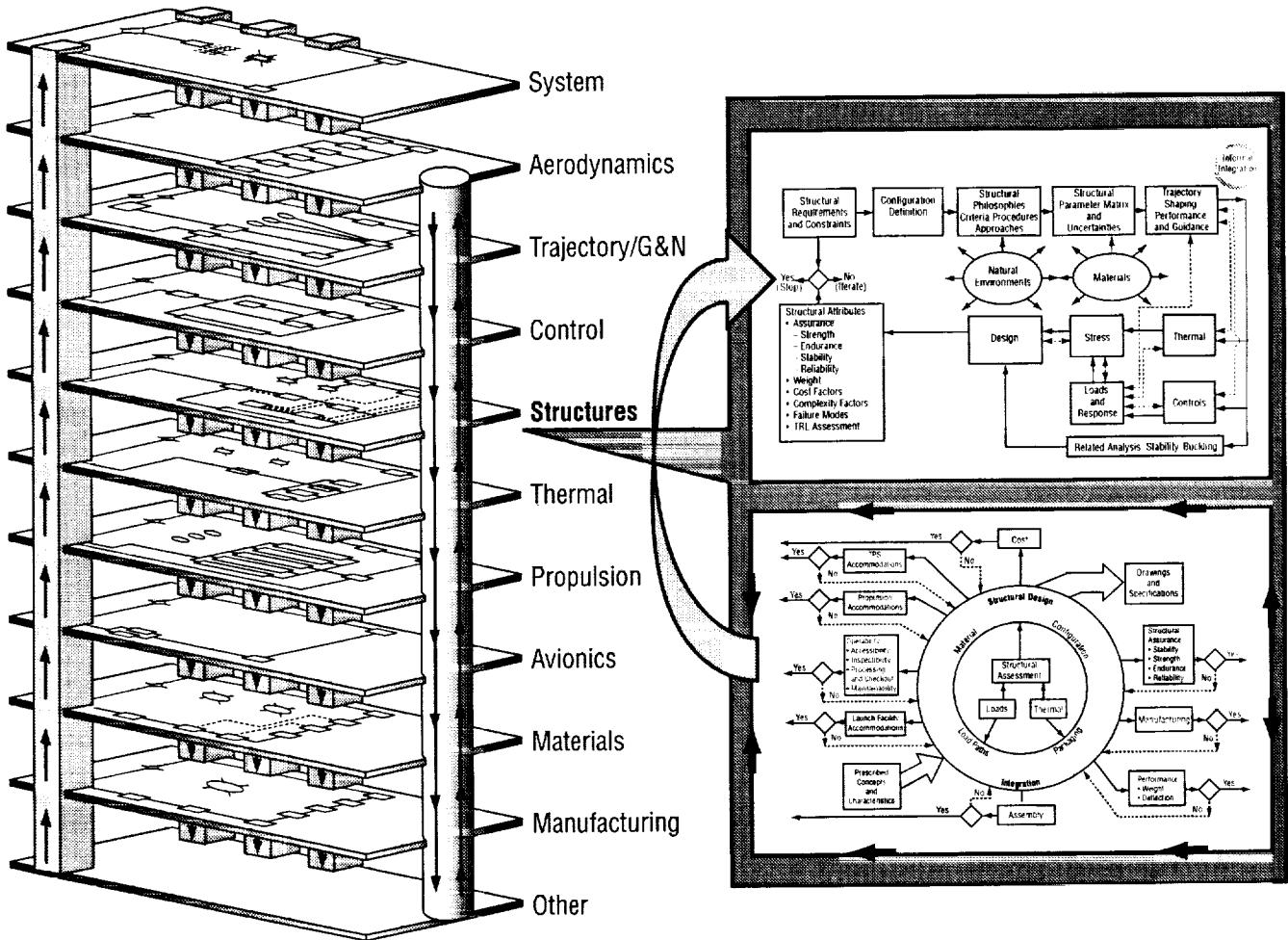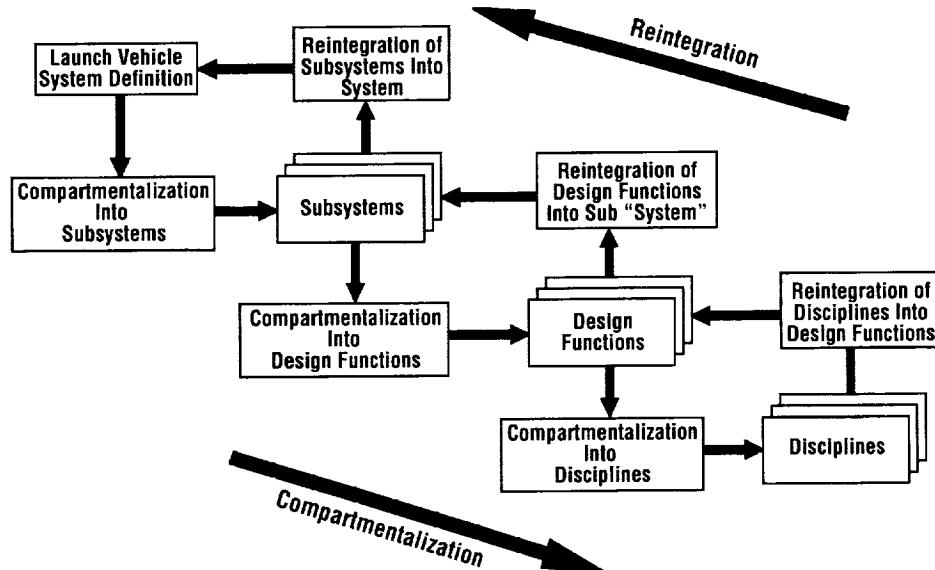
Figure 8. Illustration of design function stack with structures plane example.

flowdown of requirement allocations, architecture, and approach. The vertical column with arrows pointing upward represents the upward flow of the design attributes from the design function plane to the system plane. These conduits represent formal integration. The circular conduit with arrows pointing both upward and downward represents informal integration among the design function planes. Informal integration also occurs on the design function plane within and among the various disciplines.

The large amount of information flow throughout the process will be further characterized in section 4, using information flow matrices. Two types of matrices will be used: an interface information matrix (designated I×I matrix) to address information flow among the subsystems on the tree, and an N×N matrix to address information flow among design functions and disciplines. Material related to the information flow in the launch vehicle design/analysis process has been developed by MSFC[2] that

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Launch Vehicle System Definition → Reintegration of Subsystems Into System

Compartmentalization Into Subsystems → Subsystems ← Reintegration of Design Functions Into Sub "System"

Reintegration

Compartmentalization Into Design Functions → Design Functions ← Reintegration of Disciplines Into Design Functions

Compartmentalization Into Disciplines → Disciplines

Compartmentalization

Example Design Functions
(Develop Specifications for Hardware and Software)

- System
- Aerodynamics Design
- Trajectory
- GN&C
- Structures
- Thermal Protection System (TPS) and Thermal Control Systems (TCS)
- Propulsion
- Avionics
- Materials
- Manufacturing
- Facilities and Ground Support Equipment (GSE)
- Operations Software
- Other Systems; e.g.,
  - Pyrotechnics
  - Recovery Subsystem
  - Life Support
  - Etc.

Example Discipline Functions
(Perform Analyses, Tests, and Simulations)

- System
- Structures (Example Expanded Below*)
- Aerodynamics
- Control
- G&N
- Trajectory and Flight Mechanics
- Materials
- Manufacturing
- Testing
- Simulation
- Mission Analysis
- Propulsion
- Thermal
- Life Support

* Categories of Discipline Tasks:
  - Structures
    - Dynamics
    - Stress
    - Durability
    - Stability
    - Vibroacoustics

The Discipline Functions Enable the Design Functions

Figure 9. Design process compartmentalization and reintegration.

addresses discipline inputs and outputs, tasks, and products of the design process. This includes the N×N matrix mentioned above, discipline flow charts, and task definitions. These details are integrated into the process description given in this document.

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Figure 10 is another way of illustrating the complexity of design/discipline interactions, data exchanges, and balancing. This figure illustrates some (but not all) aspects of design interactions. Expanding it to include all aspects would cloud the visualization process. Another example of visualization of design interactions is shown in figure 11. This figure includes some details of the internal process flow for the structural subsystem. Technical integration is a complex process, as this top-level discussion shows. This document will probe further into its definition.
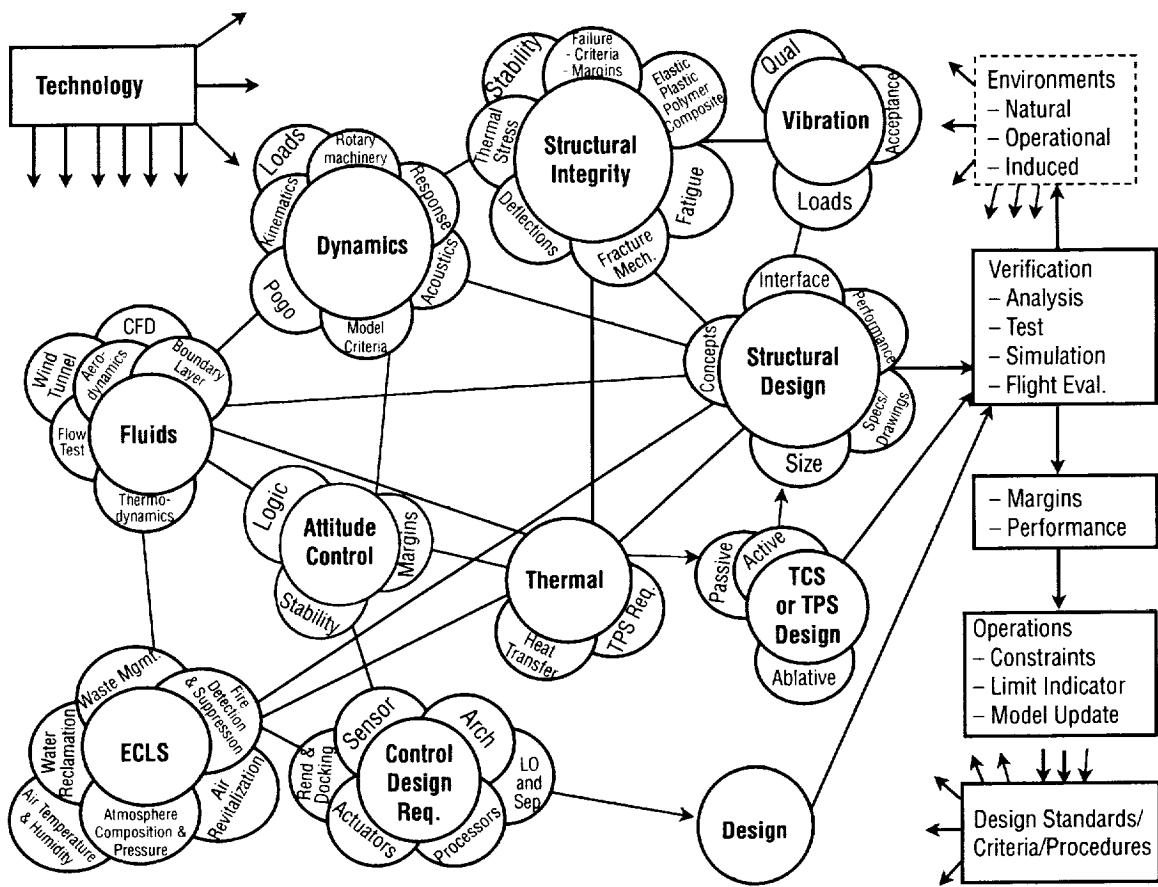
Figure 10. Design/discipline interactions.

In summary, the process starts with requirements definition, moves to top-level system studies, then to the compartmentalization of the overall system by comprising systems by subsystems, etc. Their design is accomplished by the design functions, supported by the discipline functions. Design is followed by manufacturing/assembly/checkout. The design as built must be verified to meet the requirements through analysis, test, and simulation. Operational procedures are derived from the design and verification process. A schematic of the interaction of the design functions and discipline functions is depicted in figure 12. The process (integration) is very complex and requires focused communication, both formal and informal. Detailed discussion of these aspects is given in section 4.
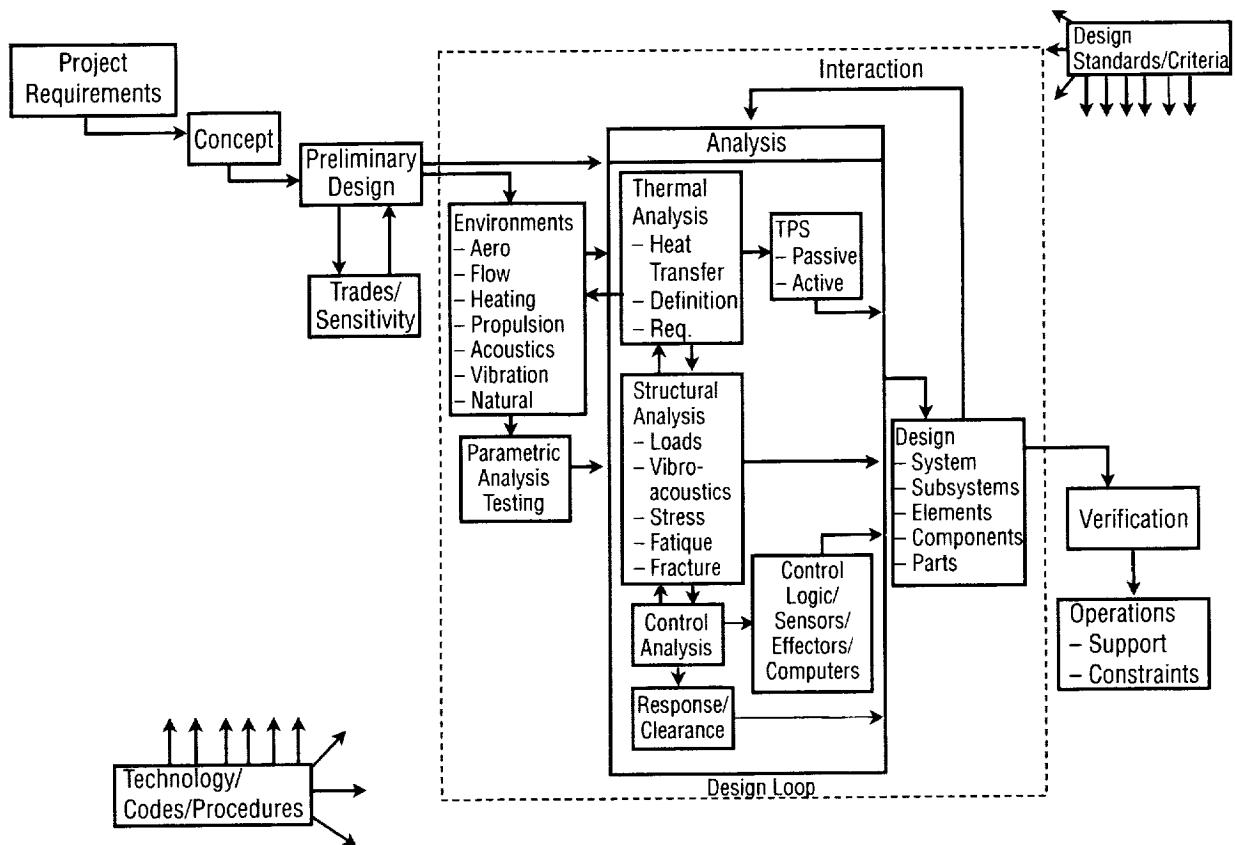
Figure 11. Structural design process flow.
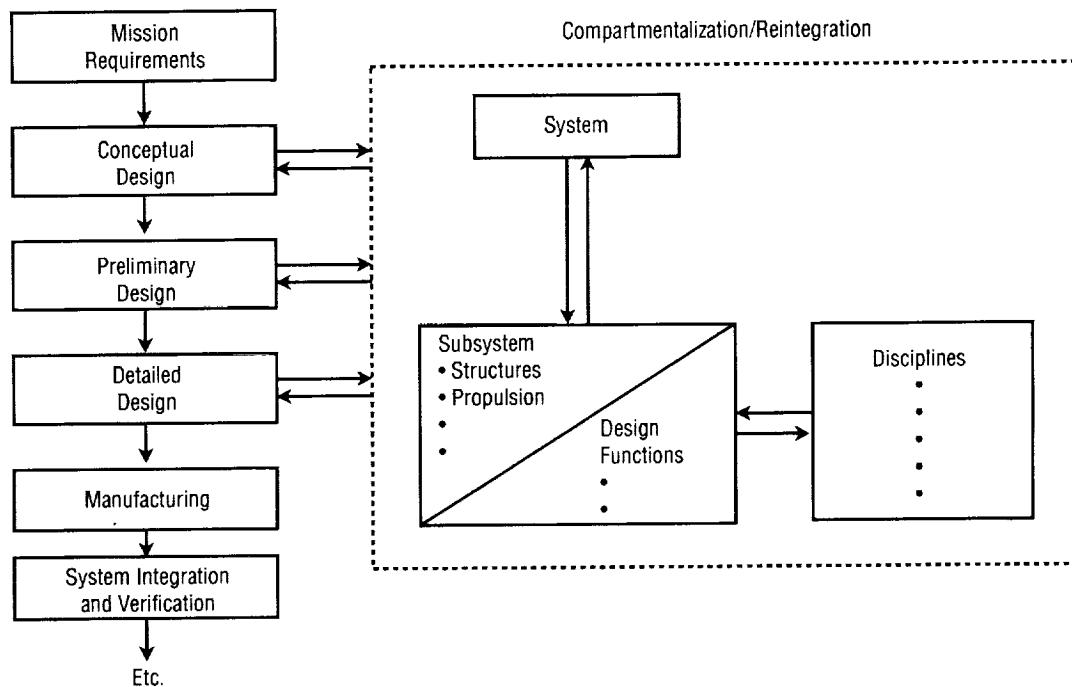
Figure 12. Design process flow.

2.2 Engineering the System

The design process must be focused on achieving the best *total system design* to meet the requirements. The leader is responsible for managing the design process, for engineering the system. His responsibilities are reflected on the top-level system design function plane, and entail wide-ranging judgment and constant communication with members of the design team. Engineering the system involves the following essential functions.

Essential Functions of Engineering the System

- Obtaining and Assessing Requirements
- Synthesizing Concepts and Designs
- Compartmentalization
- Technical Integration
- Risk Management, including Technology Development Risks
- Trading and Balancing
- Downselecting Concepts and Designs
- Manufacturing, Integrating, and Verifying the Design
- Developing the Flight Operations Rules and Constraints.

There are numerous tools used to accomplish these essential functions. In addition to generic management tools, there are tools that are more specific to the design process. Categories of such tools include the following.

Typical Tool Categories

- Requirements generation tools, such as QFD
- Synthesis-aiding tools, such as TRIZ
- Sizing programs
- Computer-aided design programs
- Design optimization tools
- Engineering analysis
- Manufacturing process simulation tools
- Engineering test
- Sensitivity analysis
- Cost analysis
- Decision tools for trade studies
- Risk management tools, including FMEA, fault trees, and risk/consequence analysis
- Classical systems engineering tools, including requirements flowdown, WBS, configuration management, and verification plan
- Design reviews
- Integrated Information and Communication System.

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2.3 Thumbnail Sketch of Process

This section provides an overview of the process sequence, divided by design stages.

2.3.1. Conceptual Design

2.3.1.1 Conceptual Design Definition. After the mission statement, requirements, and constraints are defined and understood, feasible alternative top-level system concepts are defined and their attributes determined via trade and sensitivity studies. Along with each concept there are supporting studies related to risk, cost, reliability, schedule, safety, operability, refined requirements, facility/GSE concepts, TRL, project plans and other documents, etc. Selection criteria are also developed to evaluate the alternative concepts. At the completion of conceptual design, there is a review called the system definition review (SDR).

2.3.1.2 Activities. Conceptual design follows a process with the following steps:

a. Identify the basic mission requirements (mission definition, pounds of payload to orbit, cost, schedule, etc.)

b. At the top level, define potential concepts to meet requirements (includes overall architecture, staging, reusability, and broad definitions of propulsion system(s), structural systems, avionics, and thermal systems).

c. Define evaluation metrics.

d. Perform top-level sizing and analysis of the concepts.

(1) Preliminary estimates of geometry, mass, environments, and propulsion characteristics

(2) Trajectory and performance definition

(3) Induced environment definition

(4) Top-level sensitivity study (example: dry weight versus dry weight margin)

(5) Margin determination necessary to envelope uncertainties

(6) Determination of performance, cost, and other attributes

(7) Risk assessment and technology development needs

(8) Trade and balance among alternatives to improve attributes and risks

e. Develop selection criteria and select top contenders.

f. Modify the contending concepts based on evaluation data.

g. Repeat the above process with more in-depth evaluation.

h. Downselect to remaining candidate concepts.

i. Modify the remaining candidate concepts based on evaluation; add new ones (if data indicate).

j. Modify requirements (if data indicate).

k. Continue to repeat the above process until clear, leading concepts emerge.

l. Define the leading concepts with general configuration definition, sensitivity data, and induced environments.

2.3.1.3 Products of Conceptual Design. The products of conceptual design are a reduced set of feasible alternative concepts that have attributes which satisfy the mission statement, requirements, and constraints with acceptable margins and risk. In addition, there are additional supporting data as mentioned above in the definition. In some situations there may be only one concept selected.

The concept selection quantification leading to selection therefore requires a small cadre of inventive, sound engineering specialists who carry out the tasks. The tasks in the early part of conceptual design can be integrated together into one program for overall sizing; however, the operational requirements and output of this program must be assessed by the respective disciplines for technical soundness. The tasks for the subsequent program stages, however, have increasing levels of penetration, detail, and scope as the program matures and is verified.

2.3.2. Preliminary and Detail Design

Preliminary and detail design follow the same general approach; i.e., the steps; however, the depth of penetration and the results differ significantly.

2.3.2.1 Preliminary Design Definition. The purpose of preliminary design is to determine which of the selected concepts from the conceptual design stage is the best and to provide greater assurance that the concept is capable of meeting requirements. To achieve these results, the fidelity of the architecture is increased and refined; in addition, the significant subsystems and their requirements are defined. The depth of penetration of trade and sensitivity studies is increased through analyses, tests, and simulations. Then the requirements, risk, cost, reliability, safety, operability, schedule, and TRL are refined and reassessed. Interfaces, interactions, pertinent tests, top-level verification plans, and preliminary facility and GSE requirements/concepts are defined and the fidelity of the project plans and documents is updated. Preliminary design can occur in iterations as concepts are downselected after each iteration until the best concept remains. This concept then goes to detail design. In the situation where only one concept goes to preliminary design from conceptual design, the above procedure is still utilized but for a single concept. At the completion of preliminary design, there is a review called the preliminary design review (PDR).

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2.3.2.2 Detail Design Definition. The purpose of detail design is to provide drawings and specifications for all the hardware and software of the fully analyzed, tested, and simulated STS that can be manufactured and operated within cost and flown with an acceptable risk. The performance, cost, reliability, safety, operability, schedule, and technology readiness attributes of this system must satisfy the mission statement, requirements, and constraints. At the completion of detail design, there is a review called the critical design review (CDR).

2.3.2.3 Activities. Preliminary and detail design follow the same general approach (steps). Preliminary design operates at less depth because the analysis and test data have not matured. Detail design is in-depth and finalizes all the design trades and the configuration for production. The steps are in general the following:

a. Using the database and the concept selected, apportion the design task by first—

    (1) Delineating the major subsystems, elements, components, etc.

    (2) Allocating requirements, constraints, etc., to these entities and their associated design functions.

b. Start the design function and discipline process for each major subsystem.

    (1) Define in more detail the data base required for the discipline task. Data bases include mass properties, aerodynamics, thermal, materials properties, etc.

    (Note: Steps b(2) through b(7) are examples pertaining to structure design.)

    (2) Run the trajectory/performance analysis. Provide data to other disciplines.

    (3) Using the baseline trajectory, conduct the control analysis determining the control logic, control requirements, and responses.

    (4) Conduct the loads analysis definition using the control results, determining the induced structural environments.

    (5) Determine the thermal environments, loads, etc.

    (6) Perform stress analysis and its subsets of strength, stability, deflections, and durability. Durability also includes fracture and fatigue.

    (7) Determine sensitivities and margins.

    (8) Perform trade studies among alternatives.

    (9) Assess risks and technology development plan.

    (10) Reintegrate design functions and subsystems at each level.

(11) Perform risk assessments and trade studies, and balance design at each integrated level.

c. Modify the design based on the results.

d. Repeat the process in more depth.

The above sequence overviews trajectory/performance design, some controls design, and structural design. There are concurrent parallel design activities for other subsystems and design functions, such as:

- Thermal protection and thermal control
- Manufacturing
- Avionics
- Propulsion
- Other systems such as pyrotechnics, recovery, etc.

These subsystems and design functions have their own design sequence and also interact with the design process of other subsystems.

Two major activities that permeate the design process are (1) trading among design alternatives to balance the competing aspects of the design, and (2) assessing and managing risks. Trades range in complexity from straightforward judgment decisions to detailed trade studies that drive out the differences in design alternatives. Because of the strongly coupled nature of launch vehicles, trade studies are usually numerous and constitute a significant part of the design process. A balance must be achieved among the cost, performance, operability, etc., of the design. Achieving the best design also requires balancing among the subsystems, design functions, and technical disciplines.

Technical, cost, and schedule risks must be actively managed throughout development. Active risk assessment is an essential element of the design process. Failure mode analyses and risk/consequence assessments are done for each design alternative. A technology assessment for each design alternative identifies technology development required, along with the risk associated with maturing the technologies to an acceptable level.

2.3.2.4 Products of Preliminary Design. The major product of preliminary design is a single concept that has attributes that satisfy the mission statement, requirements, and constraints with acceptable margins and risk. The margins and risks at the completion of preliminary design should be reduced from those at the completion of conceptual design. The concept at the completion of preliminary design is the baseline for detail design. In addition, all system support, manufacturing, test, and operations requirements are also defined.

2.3.2.5 Products of Detail Design. The products of detail design are engineering descriptions of the hardware and software pertaining to STS. These descriptions are drawings, specifications, plans, etc. The attributes associated with the system must satisfy the mission statement, requirements, and constraints with acceptable margins and risk. At this point the margins and risks should be at a minimum. Additional products include plans for final development, manufacturing, verification, and operations.

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2.3.3 Successive Refinement.

During the design process, there are various stages. The process has been divided into stages in order to provide discipline and order while demonstrating evolving technical maturity with cost and schedule adherence. The idea of successive refinement adds emphasis by focusing attention on convergence to a concept (see fig. 13 and references 3 and 4). When the design process is first initiated, there is considerable uncertainty (i.e., risk) associated with technical, schedule, and cost feasibility. In addition, the knowledge base can be very limited. As the project proceeds, concepts are studied and assessed in regard to satisfying all the requirements and constraints. These studies are iterative, and on each cycle the penetration is deeper and deeper. The results provide information about the concept options and then decisions are made that eliminate certain options. As the design continues, the knowledge base is refined and increased iteratively while the uncertainty is decreased. Eventually, through this successive refinement of knowledge, decisions can be made to downselect to the best concept. There have been projects where the downselect was achieved in the conceptual design stage, and there are others where it was late in the preliminary design stage. There are other government agencies where protoflight hardware is developed, and the downselect is determined by comparison of the actual function, cost, and production schedule.
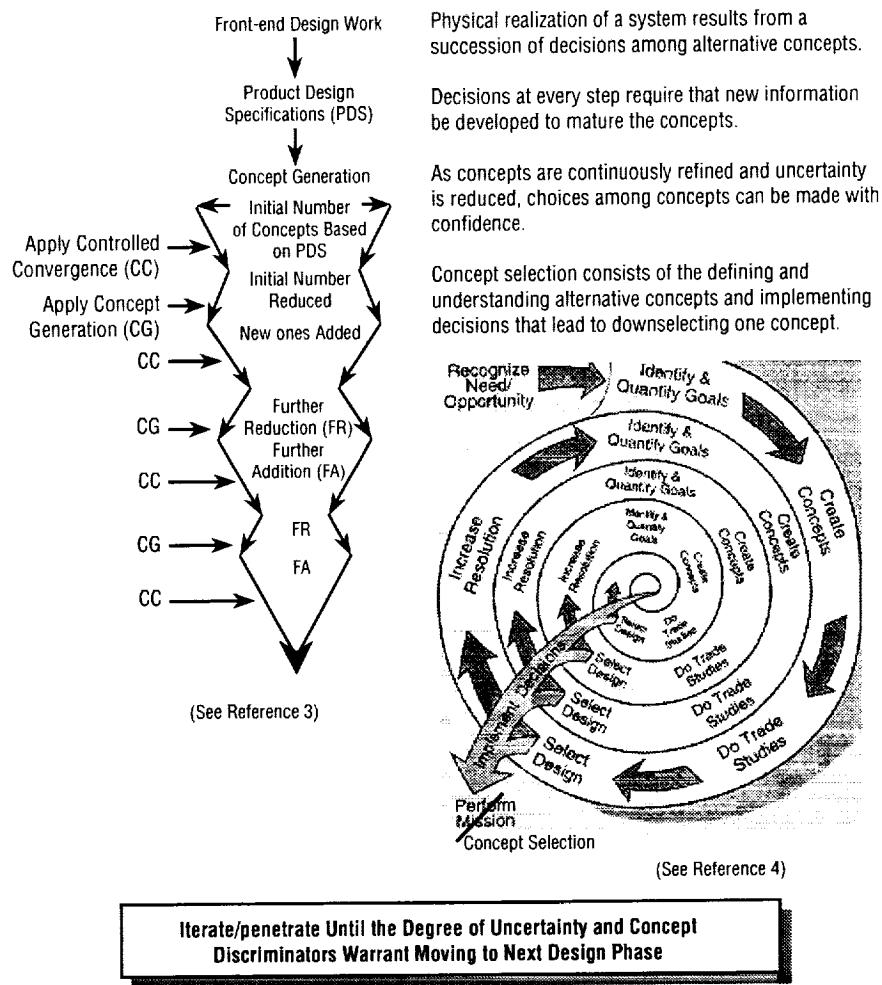
Figure 13. Successive refinement.

3. ESSENTIALS

Before presenting the methodology in detail, it is necessary to understand some essentials that are applicable to each design function and program stage. These considerations sometimes are subtle and implicit in the process, but they are of such importance that we have called them "essentials."

3.1 Basis of Good Engineering

The process described is logical and depends on methodology, not dogma. Guidelines, procedures, and criteria augment the process but can never replace the human mind, the human judgment. In the end it is the individual or collective judgment that results in key design decisions. The methodology is based on the scientific method geared to question the validity of the data and logic. Furthermore, the basis of good engineering can be characterized as (1) sound physical principles and logic (design must be based on the physics of the problem), (2) depth of engineering experience as a basis for judgment, and (3) communications, communications, communications.

3.2 Constraints

The constraints must be defined and evaluated, because they greatly alter a design. Therefore, it is imperative that their effects be understood and quantified before acceptance. Most constraints are initially based on historical data. For example, the maximum dynamic pressure for the Space Shuttle is constrained to 650 psf nominal and 815 psf dispersed. Manned flight levies an acceleration constraint of 3.15 G's maximum. As the studies/design progress, constraints evolve, and changes are made based on the effects of sensitivities and trades. Cost and schedule constraints are much more difficult to implement, because they have both programmatic and technical interactions that occur in a variety of ways.

3.3 Derived Requirements

During the design process additional requirements evolve. These derived requirements are necessary to balance the system and are determined through basic trade studies where top-level requirements must be met. These are usually the basis of how the system is flown and/or how it is made to work. Examples of derived requirements are load-relief control, monthly mean-wind biasing, day-of-launch I-load updates, ground wind operational constraints, etc. Typically, derived requirements are evolved and implemented; however, they in general introduce additional failure modes that must be identified and assessed.

3.4 Formal Design Criteria

In the design process, the design must meet numerous requirements and constraints. Among these are the formalized design criteria applicable to all NASA projects. These are in the form of formal documents, and they exist at both NASA Headquarters and at the various Centers. The Center-levied criteria and requirements can be tailored for individual projects; however, the NASA Headquarters criteria must not be violated in intent. The discipline specialists develop most of these Center-associated criteria even

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though they may be listed in the systems requirements. One of the main activities of the system design function is to determine what criteria will be imposed on the design. It is very important for the system design function and the project to tailor the criteria for their specific needs. First, these requirements/criteria delineate the various design stages and the levels of project maturity required for each. The main discipline criteria apply at each stage but recognize the level of project maturity. Also at the system levels are the verification requirements, including the requirements for the verification matrix, documentation, etc. Each individual discipline provides input to verification requirements; however, the individual design functions are responsible for their development and implementation.

Many specialized discipline criteria exist for use by the design functions. Structures have formal criteria for strength, endurance, stability, etc. Safety factors are defined as well as detailed approaches for verification (test and analysis), model correlation, model update, uncertainty factors as a function of program maturity, etc. These criteria become very formal gates in the structures design function and must be met or waivers developed. For example, loads analysis initially uses a 1.5 factor on loads; as the project matures, this factor may drop to 1.25. At the completion of the modal survey test and when the dynamic model correlation is finalized, the factor becomes 1. The strength and fracture disciplines assessment requires an indentured parts list to ensure that all parts have been analyzed. From this list a fracture critical parts list is developed which requires fracture analysis and nondestructive evaluation (NDE). Proof pressure testing of various parts is specified along with the proof factor. Materials have a comparable set of criteria, from material usage, to processing, to characterization. The control discipline has a less rigid set of criteria. It depends more upon judgment using established guidelines such as phase and gain margins, as well as response characteristics. The thermal discipline mainly depends on conservatism in the analysis and design process without having specific margins defined. In the aerodynamic discipline, stability margins exist for flutter, etc., and are spelled out in the NASA documents. There is an old but very good set of NASA design monographs that can be applied as guidelines for design. Most industries have design manuals spelling out procedures as well as criteria. There are many good books also on the subject. Pugh in *Total Design*[3] says that development of these criteria for each project by the various disciplines is very critical to development of successful products and can be considered the mantle which envelops the project. This document is focused on the design process and not the detailed design criteria; however, they are very important.

3.5 Categories of Modeling/Activities

Throughout the vehicle design and operations processes, the vehicle performance and physical attributes are characterized by descriptions or models of varying fidelity. At today's state of the art, it is not possible to have one single model that describes in full fidelity all of the vehicle constituents and interactions. Likewise, it is not possible to address total vehicle design as a single comprehensive synthesis/analysis activity. In the category of vehicle performance and physical attributes, there are three parallel sets of descriptions and activities:

1. A generalized description of the vehicle that is evolved through synthesis/analysis activities directed toward overall vehicle performance. This category encompasses trajectory/performance, load cycles, and overall vehicle design for ascent and return.

2. Discipline-specific descriptions that are developed from discipline analyses, tests, and simulations. This set of models feeds its information to the other two sets. The descriptions increase in fidelity as the design matures and additional analyses and tests are performed.

3. Specialized descriptions and synthesis/analysis activities that are applicable to specific interactive aspects of the vehicle, such as flutter, pogo, rendezvous and docking, etc. These issues are addressed separately from the generalized description with their design consequences being fed into the generalized description. (The generalized description should initially allow "headroom" for the accommodation of the specialized interactive aspects.)

The generalized description is the "backbone" of the design. It increases in fidelity throughout the design process. Upon entering the operations stage, a less-detailed description is extracted from the generalized description to serve as a basis for executing operational constraints.

In addition, there is a second category of models that must also be developed. These models are other than those associated with vehicle performance and physical attributes. They are in a general category related to constraints but could include some ancillary requirements. These models are associated with risk (technical, cost, and schedule), cost, reliability, safety, operations, and other associated –ilities, and they provide the means to assess and manage this category of associated design activities.

3.6 Analyses, Test, and Simulation

To design a successful launch vehicle, the design and discipline functions must produce correct and effective technical results. While technical integration is emphasized herein, it can be no better than the information flowing within it. Consequently, correct and effective discipline results are essential foundations of the design process. The discipline functions accomplish their tasks using analysis, test, and simulations. For example, the analysis starts by formulating describing equations or a mathematical description of the plant. This model can never exactly describe the response of the system nor of the natural and induced environments. Therefore, the model is an approximation of the plant and the environments. In other words, the analysis uses a model based on a set of assumptions derived from experience and what is known about the system. These assumptions must be constantly challenged and revised. Many errors occur because assumptions are considered sacred and are not challenged. The evolving database is the anchor for the modeling process. Engineering judgment in drawing from the database and applying assumptions to the models is based on experience. These models should be validated by benchmarking methods and verified in developmental testing.

The testing process has similar limitations. The actual flight environment cannot be duplicated. In order to reduce cost, etc., only the essentials of the hardware are tested. For example, in dynamic testing many of the parts are mass simulated. Programmatic and technical constraints dictate these approximations. As in analysis, engineering judgment based on experience and the evolving databases is the basis for assumptions regarding what hardware is to be tested and what critical combined environments are to be applied. Simulations are subject to the same considerations as analysis and test.

In summary, a successful design depends upon the discipline functions understanding physical principles, applying proper assumptions, and producing accurate results.

3.7 Parameter Matrix and Uncertainties

Each design and discipline function must define and quantify all parameters and their uncertainties. Initially, they are based on engineering judgment. As tests are run and analyses refined, the bands of uncertainty are reduced. In general these uncertainties are defined with some statistical measure, e.g. 3-sigma, level relative to a nominal or mean. When possible, a distribution is defined. Also, procedures for proper application of these uncertainties are developed. The discipline specialists are the only ones knowledgeable enough to develop this data. Management's job is to question the assumptions and assure that unneeded conservatism is avoided. In the early design stages of the Space Shuttle, the Ascent Flight Integration Working Group (AFSIG) spent approximately 4 months developing the parameter uncertainties matrix for each flight phase along with the analysis/test philosophy and procedures. Although prior program history can serve as guidelines, the process must be repeated for each new project. Future trends are toward more probabilistic methods of design.

3.8 Sensitivities

The response of the system and its sensitivities must be determined. This can be accomplished through analyses, simulations, or tests; however, it is usually accomplished through analyses. The higher the sensitivity, the tougher the design problem.

3.9 Failure Modes

Failure modes must be identified. Classically, there are two ways to identify failure modes. In the first, failure modes are defined and assessed by discipline and design functions relative to criteria, for instance various design limits, etc. On the structures plane designers and stress analysts routinely assess and eliminate or mitigate failure modes. For example, structural failure modes are assessed using specified factors of safety for strength, stability, endurance, and others that are specific to the structures design function. The assessment consists of comparing the structural capability with respect to the design limit to determine the structural margin. In the second, potential failure modes are defined by a team of discipline, design, and system specialists, but from the systems perspective. This activity is orchestrated by the system plane.The failure modes are usually put into some formal tree or cascading logic diagram. The uncertainty/sensitivity data are used to assess the failure modes and the trade study results. This assessment is made using engineering judgment augmented with risk versus consequence logic which relates to quantification and impact using uncertainties, sensitivities, risks, and consequences. This process utilizes failure modes and effects analysis (FMEA), critical items list (CIL), and hazards analysis.

In the final analysis this is a balancing act between wanted and unwanted characteristics. Gordon in *Structures or Why Things Don't Fall Down*[5] says: "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?" Pye in *The Nature of Design*[6] discusses the source of problems and their compromises. He talks about the source of problems dealing with the manifestation and transfer of energy. He says: "Any of these forms of energy is capable of producing changes, changes in things; more exactly, redistribution of matter. Now whenever a change is made by the passage of energy and a result is left, this event takes place in a group of things. Things are always together. They do not exist separately and they cannot act separately. When you put

energy into a system, you can never choose what kind of changes shall take place and what results shall remain. All you can do, and that only within limits, is to regulate the amounts of the various changes. This you do by design." He talks about the compromises in the "design for failures." "The requirements for design conflict and cannot be reconciled. All design for devices are to some degree failures." The designer or his client has to choose to what degree and where there shall be failure. It is important in this process that engineers have a network of specialists that can be called upon for understanding these problems.

3.10 Judgments

Good engineering judgment is a critical essential to the design process. Judgment is based on insights gained through experience. Whenever possible it should be backed up with either a quantitative or qualitative assessment. Many times it is hard to quantify the decision; however, in these cases, relative comparisons can be used to support the decision.

Judgment comes into play in many aspects of the design process. First, the compartmentalization process of deciding which components can be lumped into a subsystem or sub-subsystem is a judgment based upon the coupling and complexity of the components and industrial specialization. Second, the balance between performance and programmatic issues (costs, schedule, risk, etc.) are generally made using judgment in the presence of available data. Third, many desirable technical refinements must be balanced against priorities, risks, etc. Although some parts of the decision can be quantified, most become a judgment. Fourth, test options, test configurations, and test conditions are also judgment calls.

Finally, technical judgments are targeted to be within some acceptable risk that ensures eventual flight success. In fact, detail design and operations eventually become a process of managing risk since STS systems are so finely tuned.

3.11 Probing Questions

The question always arises, "How does management ensure the job is done correctly, and when do they know that it is completed?" In general this is accomplished through asking a series of questions. Typical questions are—

- Does the design meet requirements with adequate margins considering uncertainties and sensitivities?
- Have all discipline analyses/tests/simulations been completed to the appropriate fidelity?
- Has adequate interdisciplinary technical integration been done?
- Have issues and concerns been adequately identified and dispositioned?

These questions lead to the general question, "How do I determine adequacy?" The answer is usually a judgment for which the following questions offer assistance:

(Method)

- Define and explain ground rules and assumptions.
- What was your analysis method? How was it benchmarked?
- What comparative analyses, simulations, and tests have been done?

- What affects your system? What is it sensitive to? Have the interactions been considered?
- What does your system affect? Have you worked these interfaces?
- What concerns do you have with the design (or analysis/test process)?

(Results)

- What trends/patterns are present?
- Are they consistent? Explainable?
- What are the margins and the basis for the margins?
- Can the observed characteristics be explained using a simple analogy? Using a free body diagram? How does one explain the load paths?
- Does it pass "the physics of the problem" check?

(Specialist)

- What is the engineer's understanding and feeling of the uncertainties?
- What is the specialist's track record?
- What is your specialist comfort level?

J.R. Thompson told Bob Ryan the following story that gives insight into how decisions are made. At the time, J.R. Thompson was MSFC's Chief Engineer following his tenure as the Space Shuttle Main Engine (SSME) Project Manager. He said that when he and Bob Ryan were working together to solve some SSME problems to get the first Shuttle flight off (had slipped at the time more than 1 year), Bob Ryan would talk to him about dynamic issues that needed to be resolved through redesign. He said, "Those dynamic problems scared the hell out of me." He went on to talk about the only way he could honor the political viability was to delay the redesign, handling the safety issue by changing parts after each flight, imposing stringent inspections and strict process control, thus launching the first six Shuttle flights successfully. At the same time he supported efforts which downstream resolved the issues. He asked Bob Ryan to write a paper on the dynamic issues and their resolution as lessons learned, because he said, "Their resolution was one of the keys to Shuttle's success, and he felt it was a meritorious accomplishment." He understood that the approach he took was more costly but politically necessary. The approach effectively managed risks versus consequences. Engineering in general involves not only technical factors but also managing risks driven by political factors.

Bob Ryan asked Bob Thompson, Level II Shuttle Program Manager at Johnson Space Center (JSC), how he made decisions. Bob Thompson was a master at listening to technical presentations in detail and asking penetrating questions. His answer, paraphrased as best Bob Ryan can remember, "I must effectively listen to each and understand what is said; however, I try to gauge the different technical people in terms of their integrity and their conservatism. If the decision I think is correct is agreed to by the specialists that I have confidence in and who are conservative, the decision is easy. If they don't agree, I consider what I believe to be their level of conservatism versus the level of unconservatism others have, balancing in my mind the risks and consequences between the conservative and unconservative; then I make a decision. The decision can be somewhere between the differences or can be the unconservative if the risks versus consequences are acceptable. In the discussion of the various task examples in the following sections, further elaboration of these general points will be presented.
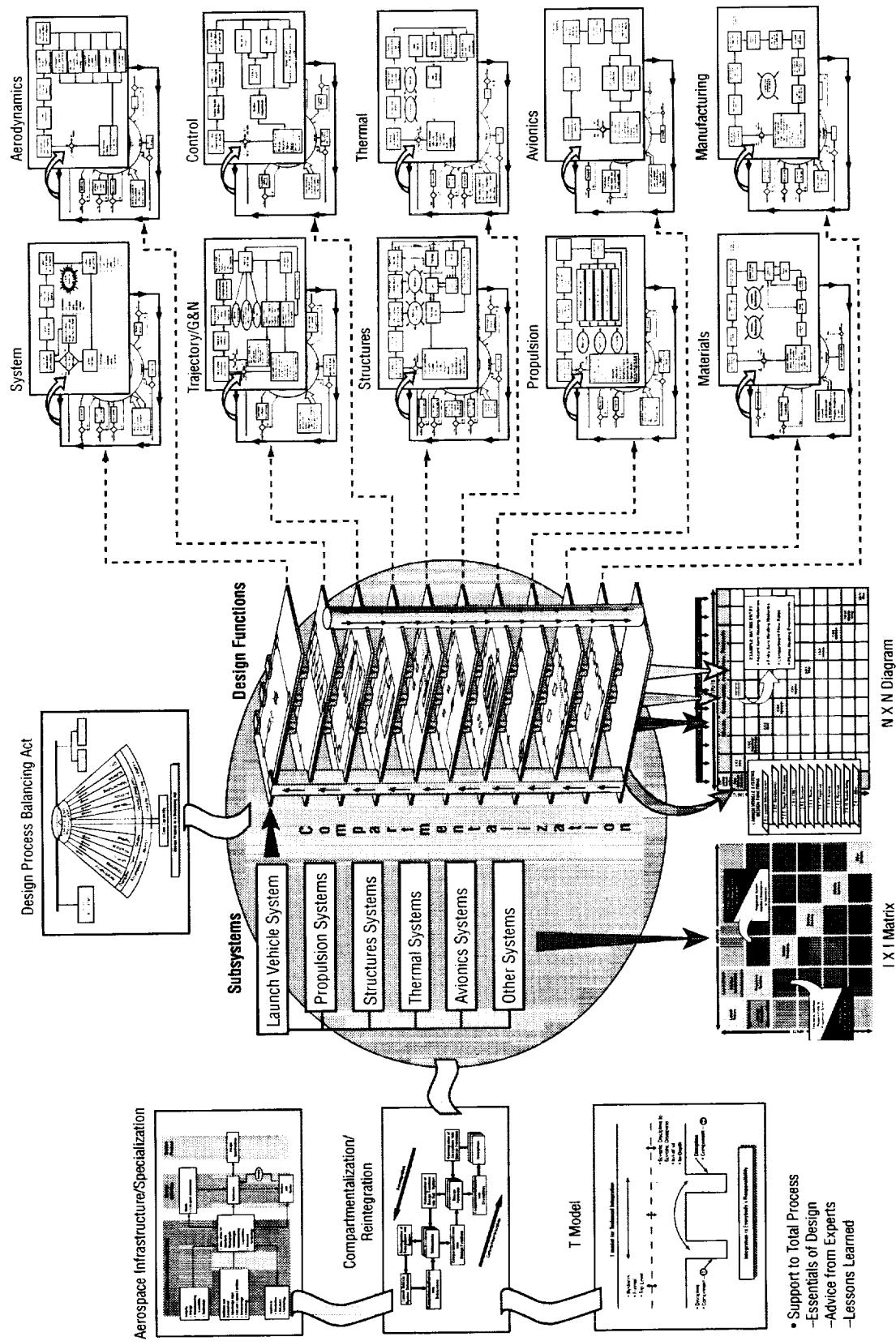
Figure 14. Design process overview.

4. DESIGN PROCESS CHARACTERIZATION

The purpose of this section is to describe figuratively the design process workflow, the tasks, and the key decision gates currently used in the design process for launch vehicles. The design process description is a symbolic visualization that characterizes various design functions and their associated enabling discipline functions. Included in this characterization is a representation of how significant interaction activities are achieved via vertical and horizontal technical integration. The design functions, discipline functions, and technical integration are a complex system of multidisciplinary activities. This has been studied in order to develop a characterization of a baseline launch vehicle design process which is presented in this section.

An overview of section 4 is now given, as seen in figure 14. This overview figure shows the following: Various levels of compartmentalization and reintegration; aerospace specialization; T-model; subsystem tree, stack of design function planes; the supporting decision gate diagrams; the IxI interface diagram, NxN activities diagram, and the design process balancing act. For the various design stages, compartmentalization and reintegration are generic processes that enable the structure of the design process technical integration. The system is compartmentalized into a subsystem tree with an IxI diagram representing interface data flow among the tree elements. The design functions are responsible for hardware and software products that are supported by analysis, simulation, and testing activities of the discipline functions. The flow of technical information is managed through formal (represented by the square conduits) and informal (represented by the circular conduits) technical integration. The NxN diagram illustrates information flow among the design functions and disciplines. The technical information (i.e., all of the attributes) flows to the system plane where it is appropriately balanced to the achieve project requirements.

To set the stage for the characterzation, a discussion of project technical framework and a "T-model" of technical integration are provided first. Then the design process characterization is presented which delineates the launch vehicle design functions with vertical and horizontal integration that is overarched with the system design function. Subsequently, each of the design functions is specifically addressed in order to show the flowdown of requirements; implementation of philosophies, procedures, and criteria; development of parameter matrices with associated uncertainties; specific enabling disciplines and associated multidisciplinary horizontal integration; and, eventually, the desired product attributes. In parallel a discussion of the decision gates and the tasks associated with each specific design function is presented to complete the characterization of the baseline launch vehicle design process. The baseline process is merged with the launch vehicle generic information flow description.[2]

This process description is applicable to all the launch vehicle design stages. To demonstrate this wide-ranging applicability, it has been applied to the design sequence at a top level. First, it is applied to the conceptual design stage, and then it is applied to the preliminary and detailed design stages.

4.1 Project Technical Framework

Technical integration is required to be accomplished in an orderly fashion; therefore, a framework is needed to provide an organized and disciplined structure to requirements definition, project workflow, WBS, configuration control, systems analyses, trade studies, system verification, reporting, documentation, etc. This framework is developed, maintained, and coordinated via the functions of project planning, control, and documentation. The activities associated with these functions are accomplished by the systems engineering discipline. In reference 6, the systems engineering discipline is delineated in a global sense; i.e., the definition is generic and considered by many to be the "classical systems engineering" view. In the application of classical systems engineering discipline to the STS design process, it supports the activities of the project leader on the system plane. From that view, the systems engineering discipline contribution is through the *system design function* in the same way that stress analysis contributes to the structures design function (see sections 4.3.2 and 4.3.6, respectively).

The primary activities of the systems engineering discipline, as delineated above, are in executing the functions of planning, control, and documentation, see references 7, 8, and 9. It should be noted from section 4.3.2, that the products of the *system design function* are validated STS design specifications and attributes, balanced design attributes and requirements, and an operations plan. All these are achieved via technical integration (see section 4.3), which is orchestrated by the project leader. The project leader needs to accomplish the demanding multidisciplinary interaction tasks associated with technical integration in an efficient and effective manner. The project framework enables him to orchestrate the design and to balance its attributes in an orderly fashion by providing the necessary discipline and structure. While he uses the tools and functions of the systems engineering discipline to achieve order in the process, he leads and orchestrates the other design functions to achieve balanced design specifications. The tools of the other engineering disciplines are implemented interactively among and between the various design planes to accomplish the complex multidisciplinary engineering tasks and then their results are integrated and balanced by the project leader via technical integration.

The purpose of this section is to delineate select key aspects associated with the STS design process project framework. In this sense, it focuses on specific highlights that are considered typical. They are project stages, project main products, technical effort distribution, typical organizations, and roles and challenges. For more details related to the STS design process functions of planning, control, and documentation (see references 7, 8, and 9).

4.1.1 Project Stages

Most projects are subdivided into stages (see fig. 15). It has been demonstrated through various projects that this approach is successful. Historically the phases associated with most NASA projects are A, B, C, D, and E. In phase A, the major goals are to determine the project objectives along with assessment of feasibility. These activities correspond to the conceptual design stage. Additionally, the need for technology is assessed, and various concepts are selected for trade studies. In phase B, the focus is on refining the selected concepts through trade studies; system analysis and simulations; refined system and support requirements; definition of preliminary manufacturing and test requirements; definition of advanced technology and advanced developments requirements for focused funding; and assessment of technical, cost, and schedule risks. These activities correspond to the preliminary design stage. In phase C, the focus is on completion of

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detail design of the selected concept; performance of detail systems analysis; and development of final manu-facturing, testing, operations, supporting systems and facilities plans. These activities correspond to the detail design stage. In phase D, the focus is on development and test of prototype/protoflight hardware; verification, validation, and qualification of hardware and software for flight; manufacturing and integration of flight hardware; checkout of flight systems; launch operations; and initial flight operations. These activities corre-spond to the manufacturing and systems integration/verification stages. In phase E, the focus is on mission operations and disposal. This corresponds to the operational stage.

Throughout the duration of the design process the aforementioned phases of the program are final-ized with formal reviews. These reviews represent the project milestones; i.e., project gates, and are shown in figure 16. The purpose of these reviews is to focus the progress of the project and verify that the project is proceeding as planned. Throughout the design process there are about 12 major reviews; however, there are numerous intermediate reviews. The project reviews that must receive major support from the design laboratories are as follows:

- Systems requirements review (SRR)
- Preliminary Design Review (PDR)
- Critical Design Review (CDR)
- Design Certification Review (DCR).

For all formal reviews that occurred in the past, there was a specific process that was required to be followed with clearly specified outputs. The guidelines for these reviews were contained in NASA Management Instructions (NMI's).

Recently, NASA issued updated procedures and guidelines for the management of systems.[10] It defines the requirements that managers must meet in formulating, approving, implementing, and evaluat-ing programs and projects. The program phases discussed above (i.e., A, B, C, D, and E) have been replaced with four subprocesses. They are as follows: (1) Formulation, (2) approval, (3) implementation, and (4) evaluation. The various design stages delineated in figure 15 must still be accomplished by the
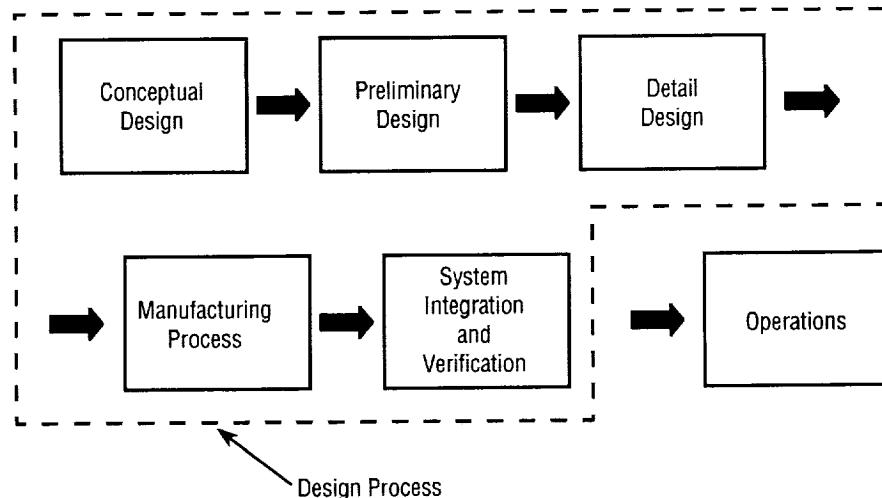
Figure 15. Major project stages.

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leader whether they are called phases or subprocesses. However, the manner that they are accomplished must be appropriately tailored for efficiency and effectiveness. The rationale behind the management guideline is "faster, better, and cheaper." The themes are as follows: (1) Tailoring the process, (2) end-to-end customer involvement, (3) comprehensive definition and requirements control, (4) risk management, (5) missions enabled by technology, (6) technology commercialization, and (7) International Standards Organization (ISO) 9000.
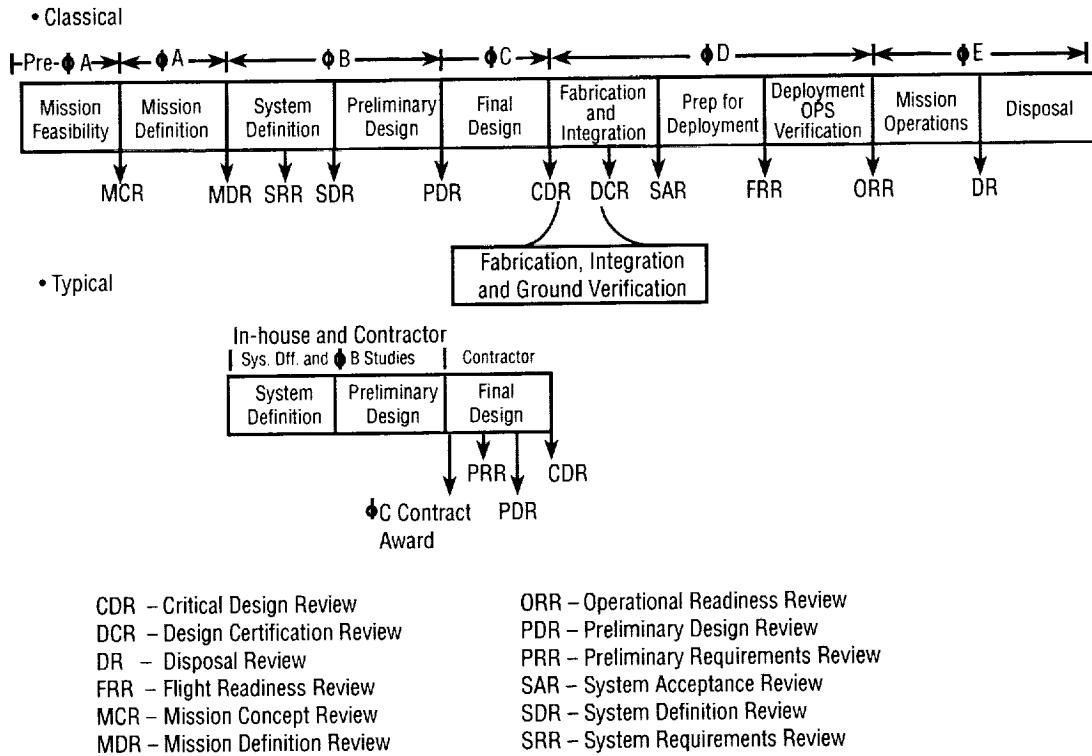
Figure 16. Project phases.

4.1.2 Main Project Products

For each design stage there are certain products that are required. A generic specification of these products is given in various NASA documents. These specifications are meant to be guidelines in the sense that each project can tailor the products consistent with the specific design stages. However, the projects are subject to peer review, and certain products are required and others are expected. It is the responsibility of the leader to determine what products are needed to demonstrate that their project is technically sound, on schedule, and cost effective. Typical products associated with the various stages are shown in figure 17. The products delineated here are meant to be illustrative and are not all inclusive; however, they provide some indication of what is needed. In cases where the peer review results in excessive criticisms, referred to as review item discrepancies, there is usually a delta review for that stage and additional products can be added at that time. This can happen in very complex programs, and the value added is that the peer review forces the project to become technically sound, on schedule, and cost effective. Reviews are successful when the products are completely integrated through formal and informal communications. The systems engineering discipline supports all these activities by organizing and coordinating the various reviews and subsequently tracking/documenting results and action items.

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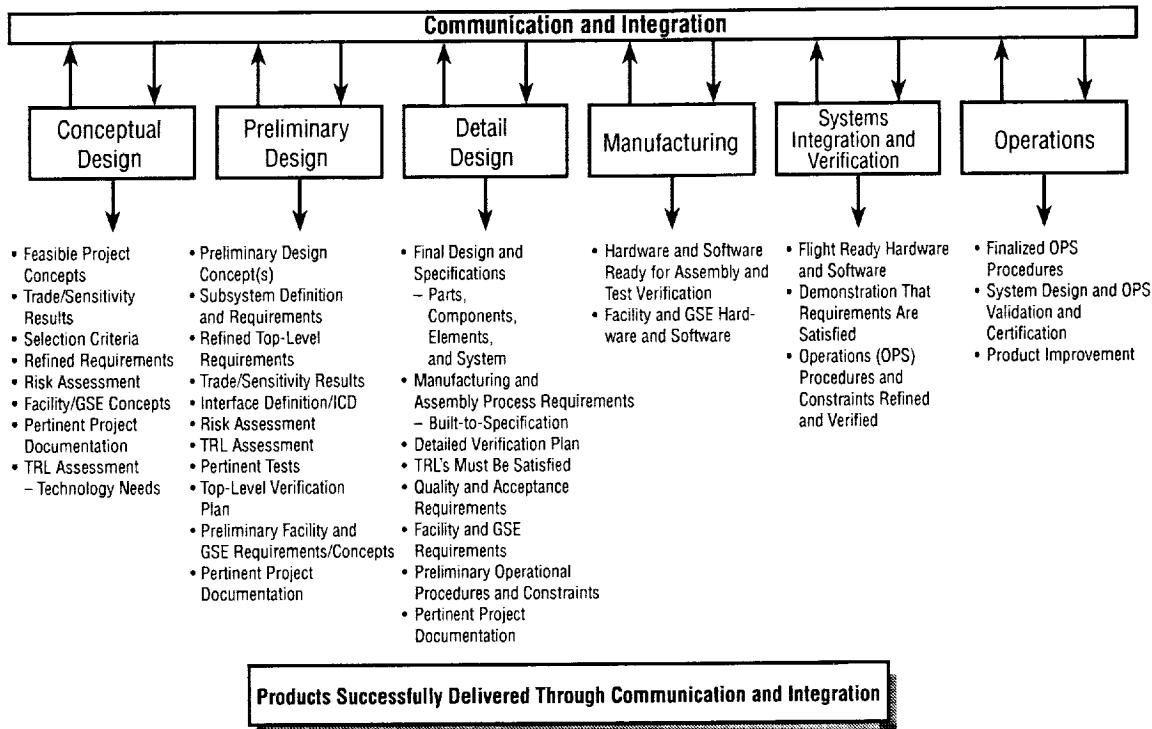
Figure 17. Project main products.

4.1.3 Technical Effort Rate Distribution

A typical technical effort rate distribution is illustrated in figure 18 for the various project stages. It should be clear that each specific project will have its own particular distribution. It can be seen that about 6 percent of the technical effort is allotted to the conceptual design stage and about 20 percent allotted to the preliminary design stage. The remainder of the effort goes into detailed design, manufacturing, systems integration, and verification. At this time there is some controversy regarding the amount of effort that should be allotted to the conceptual design stage. There is a trend in the engineering community to put more effort into the conceptual design stage, especially in situations where the design concept is revolutionary. At least 80 percent of the life-cycle costs are determined by decisions made during the conceptual design stage (see section 4.4.1.1).

4.1.4 Typical Organizations

Engineering projects can be organized as shown in figure 19. In this figure is shown the leader and supporting subsystem teams. While this structure can be considered typical of a project type organization, it is noted that the design process as characterized herein does not depend upon any organizational structure. The elements of the design process must be executed regardless of the organizational structure. In the past, several different types of structures have been implemented to achieve the project goals. Figure 20 from reference 11, but slightly modified, shows four basic types of organizations that have been
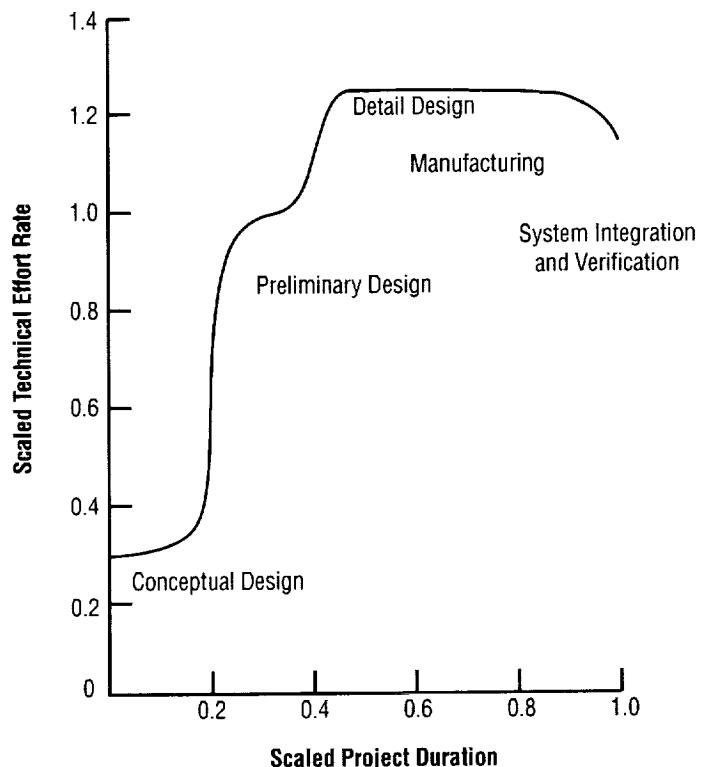
Figure 18. Project total technical effort rate distribution.
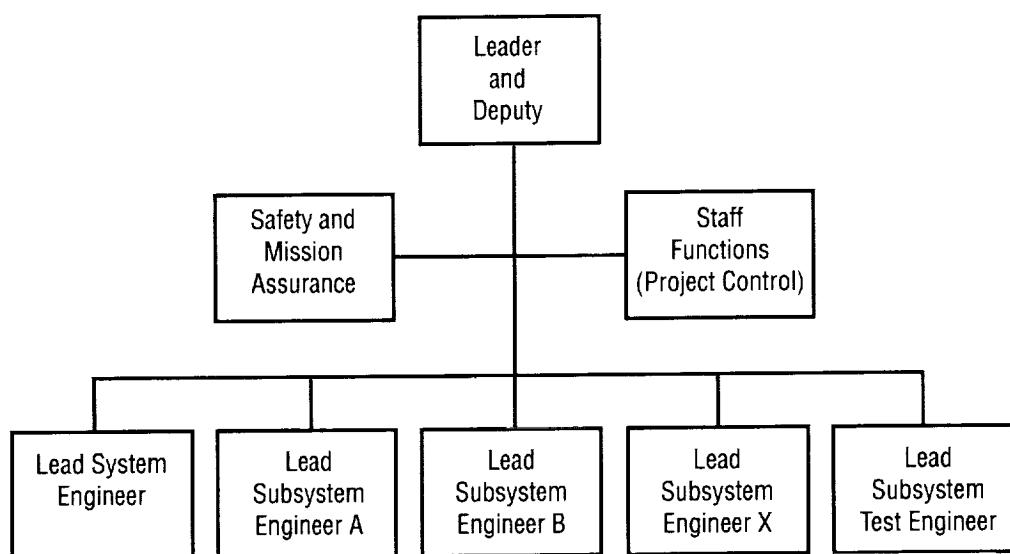
Figure 19. Typical project management organization.

implemented in the past. Figure 21 is intended to show various types of organizations where integrated product teams (IPT) have been used in the near recent past. These organizational structures are briefly discussed below.

Engineering organizational types have been structured to achieve project goals in the most cost effective manner. As mentioned above, four of the most commonly used organizational structures are shown in figure 20. The functionally organized structure is frequently used when the product development is not too complex and the functional managers can achieve the necessary system design function in addition to the functional operation of the organization. On the other hand, a certain product may require special attention such that a project specific leader is required. Again, if the project is not too large, then a light-weighted matrix organization can be suitable. In this case, representatives from some of the functional organizations usually support the project; in addition, the leader interacts with the functional managers. If the engineering task is complex, then a heavy-weighted matrix organization is favored. The leader interacts formally and on a regular basis with the functional lead engineers and the functional managers. All other engineers work informally with the functional lead engineer and report technically to functional managers. This type of organizational structure has been very popular in the aerospace and automotive industry. The final organizational structure is the project organization. In this structure the lead engineers and the working level engineers are directly responsible to the leader. Their relationship to the functional manager is to maintain functional discipline but the functional manager is not technically responsible for their work. The leader interacts with the functional managers as needed. There has been a recent trend in the automobile industry to use the project organization as opposed to the matrix organization. The four organizational structures delineated here are basic, and many variations of these have been implemented.

Functionally Organized Structure

Light-Weighted Matrix Organization

Heavy-Weighted Matrix Organization

Project Organization
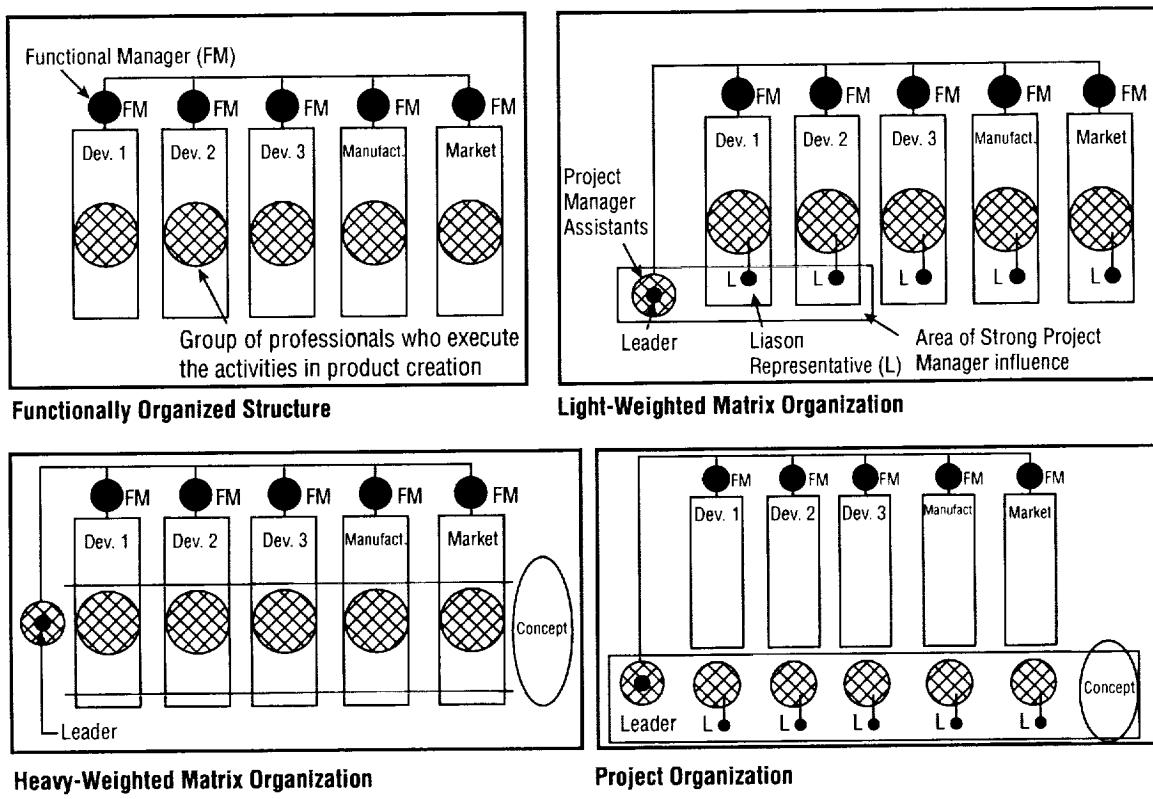
Figure 20. Typical organizations.

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Engineering organizational structures have been fine-tuned recently with the implementation of IPT's. The IPT's are a variation of a project team. Shown in figure 21 are three variations of IPT's. The first team structure is of a type where the IPT is technically connected to the functional organization. The teams can be colocated or the members can remain in the functional organization. The functional managers are responsible for the technical engineering work, and the informal integration is within and between teams. The leader is responsible for activities associated with the system design function. This structure has been popular and very successful. In the second type, the IPT is connected to the functional organization through procedures and standards. The teams are located within the project, and the informal integration is within and among teams. Again, the leader is responsible for activities associated with the system design function. The functional manager maintains technical discipline but is not technically responsible for the engineering work. The third type of organizational structure is where the IPT is completely independent of the functional organization. The teams are located with the project and the informal integration is within and among teams. The leader is responsible for activities associated with the system design function. There is no connection between the working engineers and the functional managers. This particular structure has proven to be unsuccessful in some cases.
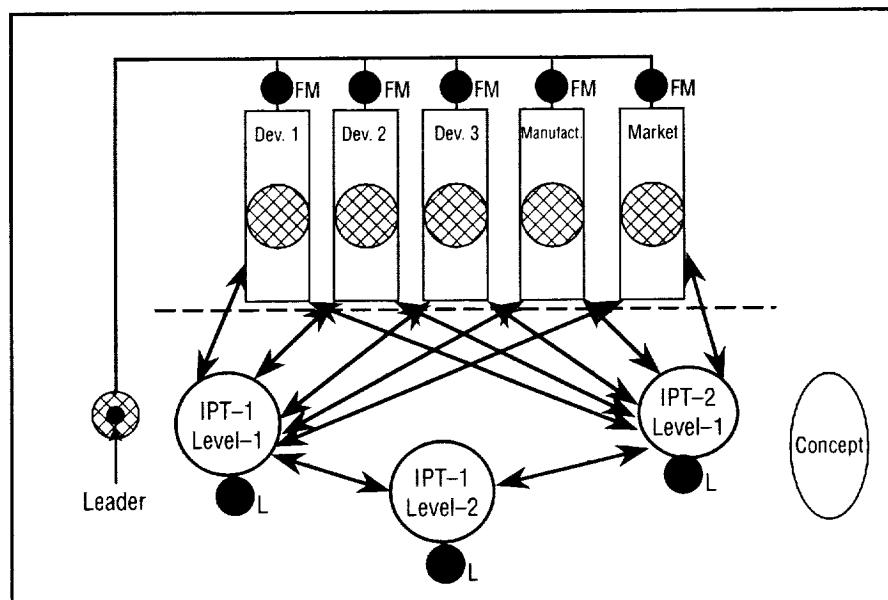
It has been learned that when engineering specialists are separated from the functional organization for more than about two years, there is an erosion of their technical expertise. Some organizations move the technical specialist back to the functional organization after about two years.

4.1.5 Roles
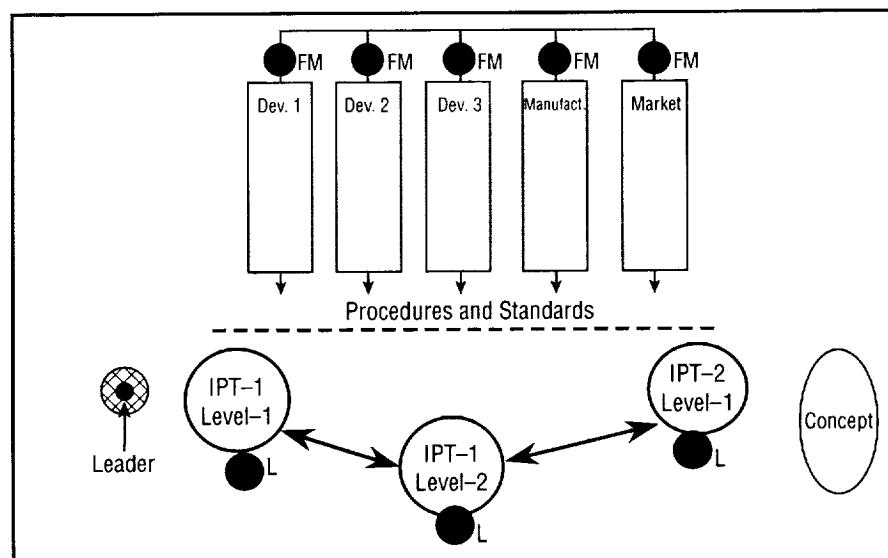
The system design function uses systems engineering discipline tools like QFD to transform the mission statement into a description of system requirements and a system configuration. These are then allocated to the other design functions. All system requirements must be integrated to ensure balance and compatibility of all interfaces. All other factors must be integrated into the total engineering effort to meet the cost, schedule, and technical objectives.

The systems design function is responsible for the overall technical management and certification of the system. There must be technical interchanges with all contributing parties as well as requirements definition, management, analysis, and flowdown. In addition, there must be verification planning and audit, interface management, risk analysis and management, configuration management, etc. Again, the tools of the systems engineering discipline are applied to support these activities.
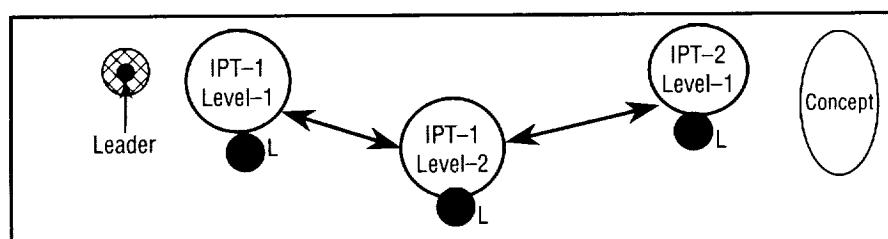
The challenge of systems design function is to provide the best system that meets all the requirements and provides a proper balance of performance, cost, reliability, safety, operability, schedule, and TRL. The systems engineering discipline plays an important role in this process where the discipline-specific tools are implemented to aid planning, to achieve design process control, and to provide the documentation of all critical process elements. The system design function is the responsibility of the leader, who is supported by the systems engineering discipline in planning, controlling, and documenting the process.

IPT Technically Connected to Functional Organization

IPT Connected to Functional Organization Through Procedures and Standards

IPT Completely Independent of Functional Organization

Figure 21. Integrated product teams.

4.2 Technical Integration

Technical integration is the fundamental fiber that goes through every aspect of the STS design process. It is accomplished with an increasing intensity as the design process progresses through the various stages. Technical integration will be illustrated using a symbolic representation; i.e., a model. In addition, there are various other factors that are known to enable it. These factors can be thought of as describing attributes of technical integration. In this section a model is provided for technical integration, along with a description of the enabling factors and a typical activities distribution.

4.2.1 Technical Integration Model

The T-model has been chosen to illustrate technical integration in this document. Helmut Horn (Peenemünde Team) discussed the T-model for technical integration during Saturn/Apollo era. Contemporary literature discusses the attributes and advantages of this model in today's environment. This model has been called the T-model because it has vertical and horizontal components. The stem of the T represents in-depth discipline (or component) activities and penetration while the crossbar represents interactions; i.e., technical integration. The model, when applied to the space transportation design process, results in two specific levels of technical integration shown as parts of the T's crossbar in figure 22. The upper level (i.e., above the dashed crossbar) of technical integration is known by the interchangeable names of system integration, formal integration, or top-level integration. The leader and his office are the primary facilitators and operatives of this level of integration. The emphasis of this level of technical integration is primarily upon the system aspects of the design process; i.e., the focus is on overall technical management and certification of the system. The concerns are delivering the product with a proper balance of performance, cost, reliability, safety, operability, schedule, and TRL. Technical integration is achieved through communication and interaction with all contributing parties, customers, and similar interfaces associated with the design process. The continual purpose is to converge to a balanced product via managing and resolving conflict. All system related decisions and all system related technical conflicts are respectively made and resolved at this level. In addition, all system planning, control, and documentation related to the design
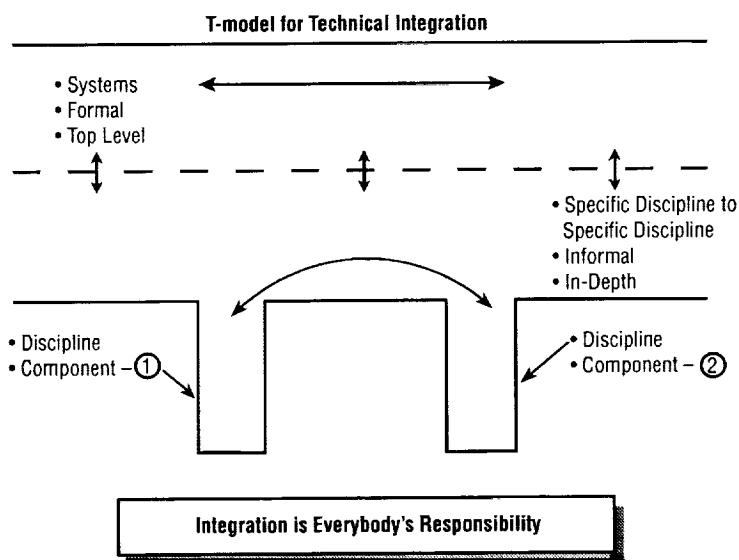
Figure 22. Technical integration—T-model.

process is maintained at this level. The level of intensity of the activities increases as the design process progresses through the various stages.

The lower level of integration (i.e., below the dashed crossbar) is given by the interchangeable names of specific discipline to specific discipline, informal integration, or in-depth integration (see fig. 22). The emphasis of technical integration in the horizontal portion below the crossbar represents discipline-to-discipline or component-to-component interactions of the design process. The functional organizations are the primary operatives of integration for discipline-to-discipline aspects of the design process, while the engineering design functions (see section 4.3.1) are the primary facilitators of integration for the component-to-component specific aspects of the design process. The vertical legs of the T-model can also denote activities of discipline engineers. It signifies that individual engineers must have in-depth discipline capability with a systems perspective. These engineers must be knowledgeable, aware, and responsive to their respective interacting disciplines, as well as the systems aspects of the process that they impact throughout the various design stages.

The design considerations are the pedigree of input data, maturity of configuration, interactions, compatibility, sensitivity, uncertainty, etc. The focus is on the technical adequacy of all the discipline specific design attributes and how they horizontally integrate with other disciplines to achieve a balance of the allotted attributes for the specific design functions. This is accomplished through an iterative process. If proper balance cannot be achieved, then the design function must bring the conflict to the upper level for reallocation of requirements or some other system resolution. It is the responsibility of the discipline organizations to document and report their technical results.

4.2.2 Technical Integration Enabling Factors

The factors that enable effective technical integration include (1) an electronic communications system; (2) the internal connectivity of sizing programs that inherently connect certain disciplines (caveat—not a substitute for personal interactions among the specialists); (3) interactive team members having strong leadership that in turn fosters interactivity; (4) proper overview by leader, functional managers, advisors, etc., to ensure correct integration; and (5) interactive feedback of requirements, strategy/philosophy, and architecture.

How does one know if proper technical integration is occurring? Throughout the process, management and participants must be very alert to the integration issues. Use a state-of-the-art communications system tailored to provide pertinent information to the participants. Check inputs and outputs required to ensure cognizance and understanding among design functions and disciplines. Determine the extent of continuous interactions by being aware of informal integration and have participants display integration activities and accomplishments. At each iteration, check to determine if the right problems are being worked, verify data trends, determine if uncertainty is converging, and have independent experts evaluate critical items. Throughout, check for consistency, compatibility, and convergence.

4.2.3 Technical Integration Activities Distribution

Throughout the various stages of the design process the distribution of the technical effort rate changes. Figure 23 delineates the scaled technical effort rate variation with scaled project duration.

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The major total technical effort rate can be categorized into two groups: (1) Technical activities and (2) technical integration. Technical activities include all design function and discipline engineering and other technical efforts required to complete the project. Technical integration is composed of formal and informal integration. From figure 23, it can be seen that the technical activity peaks about midway through the project where the major expenditure of design function and discipline engineering effort occurs. The technical integration starts off at a low level, ramps up, and then levels out throughout the project. The major formal and informal balancing acts are being achieved during this part of the project. The formal integration tends to increase at the end of a project, since the project comes together as a validated hardware product. In summary, the rate distribution shown in figure 23 represents a typical distribution of a representative project. In each specific engineering project, the distributions may be different; however, if there is a significant difference, this difference should be studied to ensure that there is an appropriate focus of all the activities.
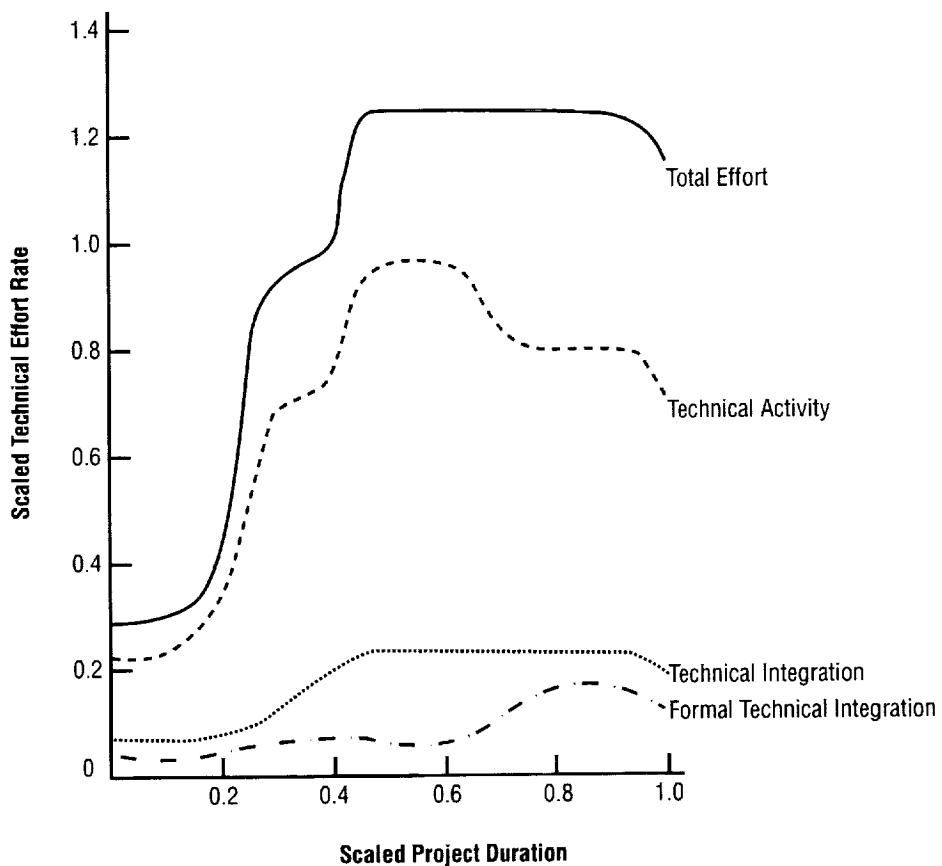
Figure 23. Technical integration—activities distribution.

4.3 Characterization Model

A symbolic representation of the launch vehicle design process is developed in this section. It consists of three categories of compartmentalization. They are hardware/software subsystems, design functions, and discipline functions. After compartmentalization, the T-model of technical integration is applied to the subsystems and to the design and discipline functions. All this enables the symbolic representation and enhances the capability to achieve technical integration. The features of hardware/software subsystems, design functions, and discipline functions are delineated. In addition, the I×I and N×N matrices and the balancing act are illustrated. This is followed by a description of the launch vehicle system. This description illustrates each design function, connections between design functions, how they are enabled by various discipline functions, and the launch vehicle system I×I and N×N matrices. In addition, this section includes what tasks must be achieved, what product attributes are developed, and what decision gates must be passed. All of the aforementioned is discussed in a parallel fashion for each design function. Also, the N×N matrix, WBS's, and tasks in reference 2 are included to show the relationship to the process symbolic representation.

4.3.1 Features of Description

The success of the design process depends upon achieving technical integration and achieving it in an effective and efficient manner. Initially, the principal engineers from the systems design function and the principal engineers from the functional organizations accomplish compartmentalization (see section 2.0).

The first category of compartmentalization consists of dividing the STS program into the launch vehicle system, payload interfaces, and operations system. Then the launch vehicle system is further divided into subsystems and so on, as illustrated in figure 24. Each division results in a "system," and there are supporting design functions and discipline functions for each system. The design and discipline functions will be illustrated below. The information flow associated with these systems consists of allocations from the parent system and suballocations to the lower-level subordinate systems (subsystems). Then there is also information flow associated with interface requirements. It can flow from the parent system, from its peer (i.e., mating interfaces, subsystems) and from its lower-level subordinate systems. In addition to those types of information flow between these systems, there are also interactions. The interactions are physical, functional, and informational. It is of paramount importance to track and account for all interface interactions. These can be determined through experience, analysis, test, or simulation. The information flow and interactions in this category of compartmentalization are important aspects of technical integration.

The second and third categories of compartmentalization pertain to mechanics of how the design specifications of the system are actually achieved. To further illustrate the design process, a distinction must be made between the sometime misunderstood design functions (the second category) and discipline functions (the third category). The distinction between design functions and discipline functions is illustrated in the following example. First, consider the design of the fuel tank subsystem (see the fuel tank subsystem 2.2.3.2 in fig. 25). Recall, the fuel tank system design specifications are the responsibility of the fuel tank system design function. It is shown in figure 25 at the top of the "stack" and is designated as 2.2.3.2.0.1 From the figure, it can be seen that the entire fuel tank system design activity is supported by other design functions in the corresponding stack. The design functions design from their own perspective but with cognizance of the other design functions in the stack. This aspect of technical integration that is

(Selected compartmentalization subsystems shown as an example)
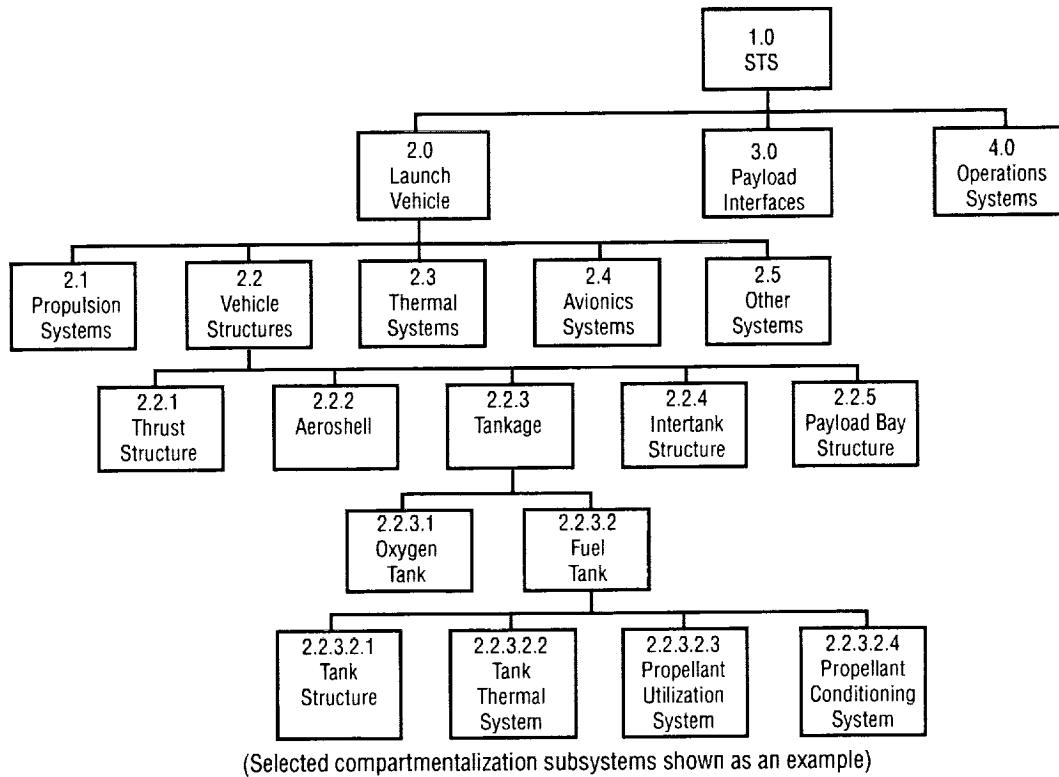
Figure 24. Launch vehicle hardware subsystems compartmentalization.

associated with the stack will be discussed in a following section. Ideally, each design function in the stack provides hardware/software design specifications (that satisfies the allocated requirements) to the system design function. In turn the system design function is responsible for developing integrated fuel tank system design specifications. The following is a typical list of the design functions that support the fuel tank subsystem design:

- Fuel tank systems
- GN&C (for slosh baffle requirements)
- Structures
- Thermal
- Avionics
- Materials
- Manufacturing
- Other systems.

The hardware/software specifications delivered by design functions are designed by a person or persons called designers. The designer has the ultimate responsibility for specifying the final hardware/software configuration along with the associated attributes. Designers conceive (hypothesize, synthesize) candidate subsystem configurations that are then analyzed to see if they will successfully perform as desired. Designers' products are drawings and software specifications that define their subsystem. For the fuel tank system example, the specifications (drawings, manufacturing instructions, etc.) would be those of all tank structure, tank thermal systems, propellant utilization system, and propellant conditioning system. In addition, it would also include the associated design attributes such as performance, cost, reliability, etc.

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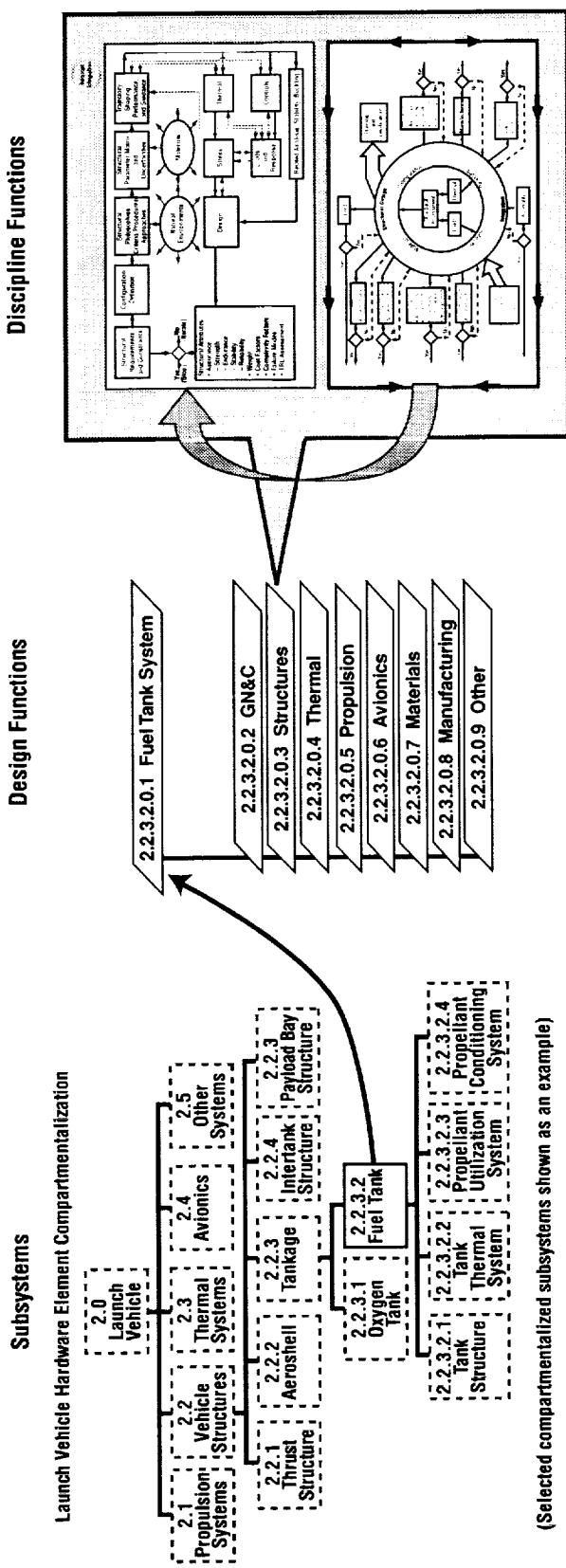
Figure 25. Fuel tank example: Subsystems, design functions, and discipline functions.

In summary, what the designer does is called the design function for his or her respective design function. As can be seen, there are design function "stacks" corresponding one to one to each hardware/software subsystem. The same principle applies as the subsystems are further compartmentalized into sub-subsystems, components, etc.

On the other hand, discipline functions (third category of compartmentalization) are technical areas of specialty and expertise. Discipline functions perform analyses, tests, and simulations of a given design concept. The discipline functions support the design functions to achieve the desired attributes, and they reside on the design function "plane." This particular aspect of technical integration will also be discussed in a following section. A typical list of disciplines includes the following:

- Structural analysis
  - Structural dynamics
  - Stress
  - Durability
  - Vibroacoustics
- Control system analysis
- Etc.

It is possible for an engineer to have both a design function role and a discipline function role. This is uncommon in structures, but in some other areas such as control, the same engineer may both conceive (hypothesize, synthesize) a control system and perform analysis on that system. That engineer can be found at different locations on the plane depending upon the activity engaged in at the time.

In summary, design functions can be represented as planes that produce the design specifications. On each plane are the interacting discipline functions needed to support the development of those specifications. There is a "stack" of design function planes associated with each system, subsystem, etc. The top "system" plane of the stack is responsible for integrating the other design functions in the stack and is responsible for providing the hardware/software specifications for its respective system or subsystem. Discipline functions reside on the plane of the specific design function that they are analyzing or testing. If they are involved in multiple subsystems, they reside on more than one plane. (For example, a stress analyst doing work on both the fuel tank structure and the main engine structure would find his respective activities on the fuel tank structures plane and the main engine structures plane.)

In the previous discussion, the fuel tank system was addressed to illustrate the three categories of compartmentalization. In the following discussion the focus will be on the launch vehicle system (see 2.0 on fig. 24). In this situation, the top-level system plane represents the system design function for the total vehicle system. The designer in this case is the leader who has the ultimate responsibility for producing the total vehicle drawings in addition to hardware/software specifications. Also resident on the system plane is the discipline of system engineering that performs the discipline functions related to design process planning, control, and documentation.

After the first and second categories of compartmentalization are completed, activities on the system plane begin with a listing of hardware and software design products along with the required associated tasks to produce these products. The design functions promote the necessary integration and communication

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to effectively and efficiently execute the tasks to produce design specifications that meet the allocated requirements. To enable the determination of design functions, consideration is given both to arrangements that tend to decouple the various design functions and to arrangements where there is a logical grouping of multidisciplinary activities for each design function. Figure 26 represents typical arrangement of design functions for the launch vehicle. The launch vehicle design process consists of the following design functions: system, aerodynamics, trajectories/G&N, controls, structures, thermal, propulsion, avionics, materials, manufacturing, and others. It can be seen that all of the design functions are overarched by the systems design function. Each of the design functions is enabled by discipline functions that have activities that support the development of the design specifications. The discipline function activities include analysis, simulation, ground and flight test verifications, etc., to accomplish the design tasks.

The attributes and specifications of each of these design functions are attained through the multidisciplinary activities of all the discipline functions supporting that design function. These attributes and specifications must satisfy the system requirements and not conflict with any attributes, requirements, or constraints of the other design functions. The products, obtained via the design functions, are the launch vehicle design drawings and specifications, other associated criteria and requirements, and constraints that relate to the launch vehicle hardware and software.

All design function and discipline function activities must be technically integrated. This is accomplished by both formal and informal technical integration, represented in figure 26. The rectangular conduits represent the vertical formal technical integration. The circular conduit represents the vertical informal technical integration. In addition, there is also in-plane informal technical integration. In-plane informal technical integration is defined to mean multidisciplinary technical integration activities on a design plane.

The formal vertical integration represents the flow of information downwards and upwards. The downward flow of information is from the systems design function to the other design functions. This information mainly consists of subsystem specific requirements, architecture, philosophies, procedures, and criteria and is represented by the downward pointing arrows. The upward flow of information is from all the design functions to the systems design function. This information mainly consists of the attributes (characteristics of the design to be compared to the allocated requirements, etc.) of the design from the design functions and is represented by the upward pointing arrows. Formal in-plane integration occurs within the systems design function. This integration pertains to achieving balance among the system attributes and insuring compatibility to the requirements, managing and resolving conflict between design functions, and overall system engineering management, certification, and documentation of the entire system.

The informal integration is both vertical and in-plane. The vertical informal integration (i.e., the circular conduit) represents a flow of information that is both upwards and downwards. The information flow is between design functions and is represented by the arrow pointing upwards and downwards. Notice that this information does not go to the systems design function. This type of information flow results because of the iterative nature of the design process and the fact that the design functions are coupled; i.e., the attributes of one design function may affect the attributes, requirements, or constraints of other design functions. Thus, the final attributes from all the design functions must be balanced (i.e., mutually compatible) and satisfy all the allocated requirements. Finally, there is also informal in-plane integration. This flow of information results from the multidisciplinary activities that occur within each design
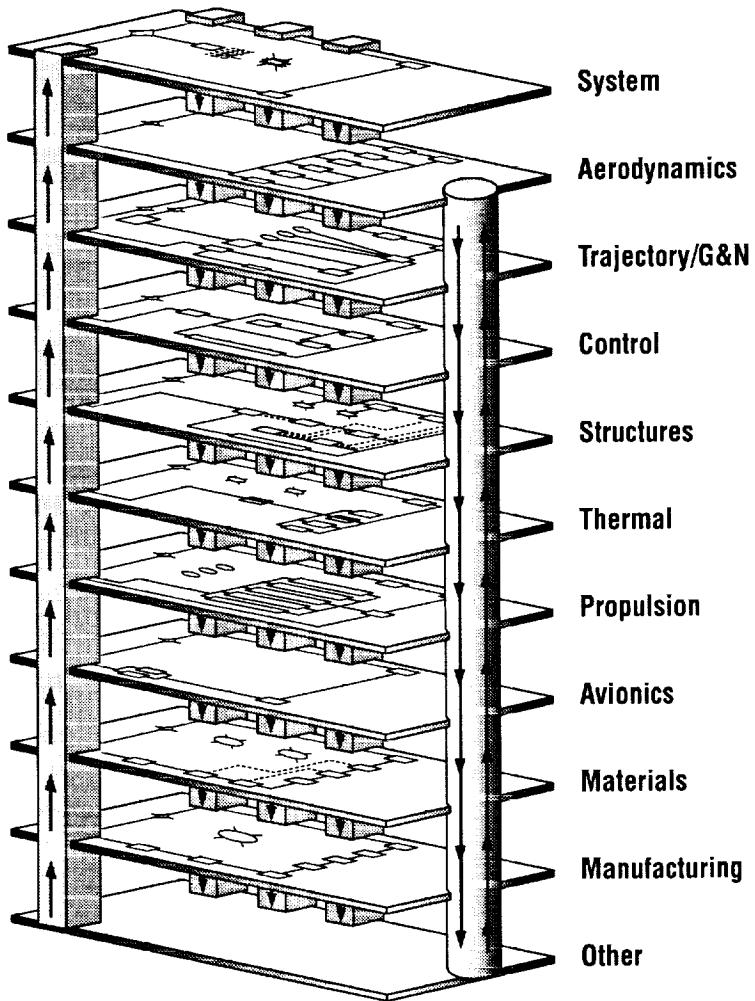
Figure 26. Technical integration of system, design, and discipline functions.

function. Again, these activities are iterative, and they are considered balanced when the attributes satisfy the system level requirements and do not conflict with the attributes, requirements, or constraints of the other design functions.

All information flow is accounted for and controlled through the utilization of the IxI and NxN matrices (see fig. 27). The IxI matrices are associated with hardware/software interfaces and the NxN matrices are associated with the design and discipline functions. As shown on the figure, the IxI matrices pertains to input and output data flow associated with the physical, functional, and informational hardware /software subsystems interfaces. This type of information is usually contained in interface control documents (ICD). Similarly, the NxN matrices pertain to input and output technical data flow associated with interacting design and discipline function activities. This aspect of the design process characterization provides a residence and a placeholder for information associated with the design process.

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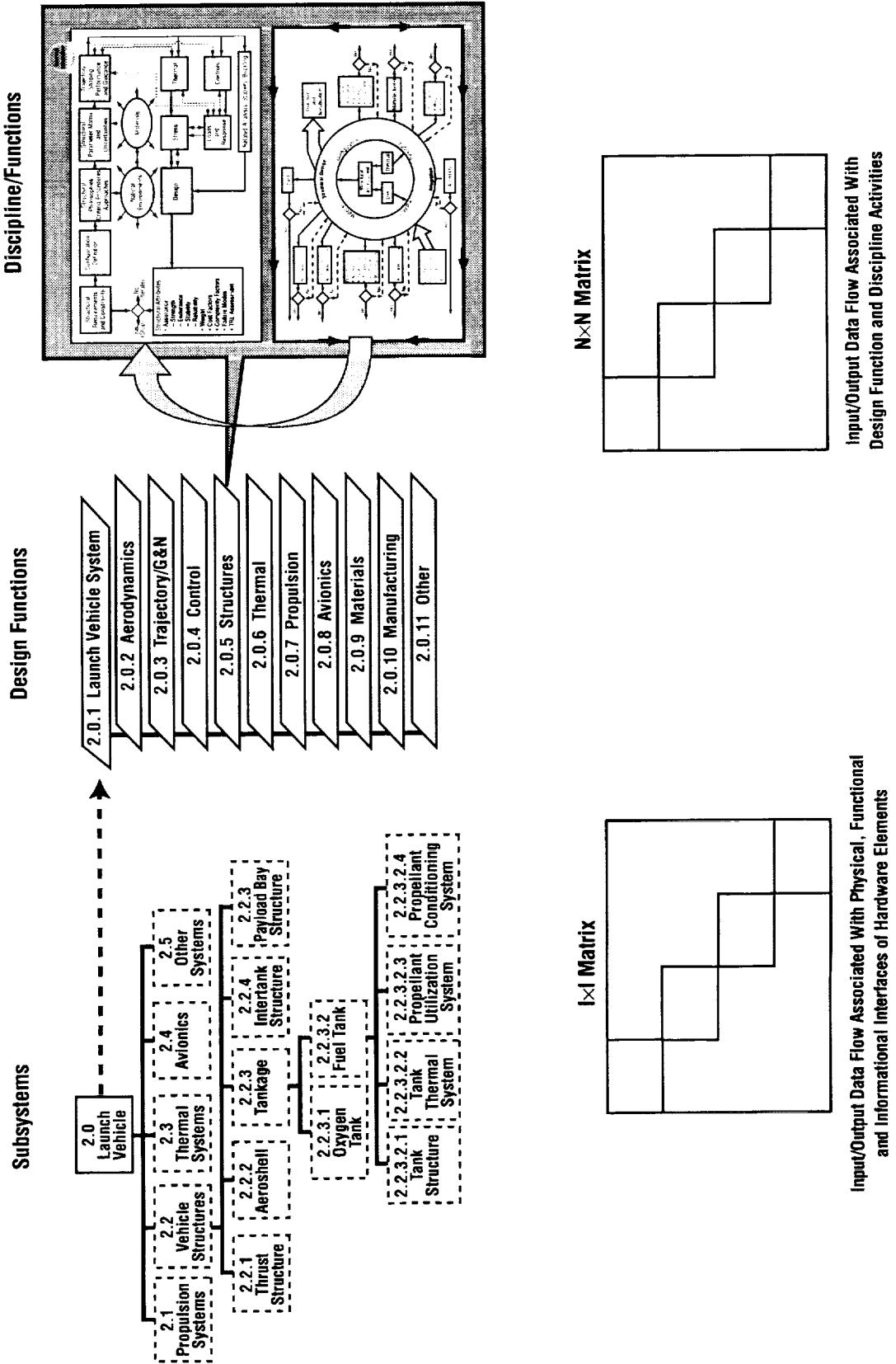
Figure 27. Matrices of input/output data flow.

Technical integration is a balancing act. At the top level the design and the operational plan must balance the program requirements (see fig. 28). During the design process there are numerous trade studies where the attributes between various design function planes are balanced to achieve the best design. (Individual engineering design functions will be interchangeably denoted as planes in some parts of this narrative. For example, the aerodynamic design function may be denoted as the aerodynamic plane.) In a specific plane there is also multidisciplinary balancing to achieve optimal attributes that satisfy the requirements. Trade studies that drive out the differences in design alternatives constitute a significant part of the design process as managed by the leader on the system plane. Because of the strongly coupled nature of launch vehicles, trade studies are usually numerous and must be performed at a sufficiently detailed level to reveal the differences in the alternatives. Trade studies usually involve multiple design functions. How well the balancing is achieved determines the success of the product. Pye states, "Any of these forms of energy is capable of producing changes, changes in things; more exactly, redistribution of matter.... Now whenever a change is made by the passage of energy and a result is left, this event takes place in a group of things. Things are always together. They do not exist separately.... All you can do, and that only within limits, is to regulate the amounts of the various changes. This you do by design." He states further, "The requirements for design conflict and cannot be reconciled. All design for devices are in some degree failures... The designer or his client has to choose to what degree and where the failures shall be..."[6] Figure 28 also shows the function of system analysis and integration in performing the balancing act. The various discipline functions provide sensitivity data that are used to perform trade studies and technical integration. Through the use of assumptions, analyses, simulation and testing, and using the core capability of the organization, these design tradeoffs can be made and aternative design solutions achieved. These solutions in general will be suboptimum and can consist of several compromises of the original requirements. Understanding and accounting for the balancing act are keys to successful design.
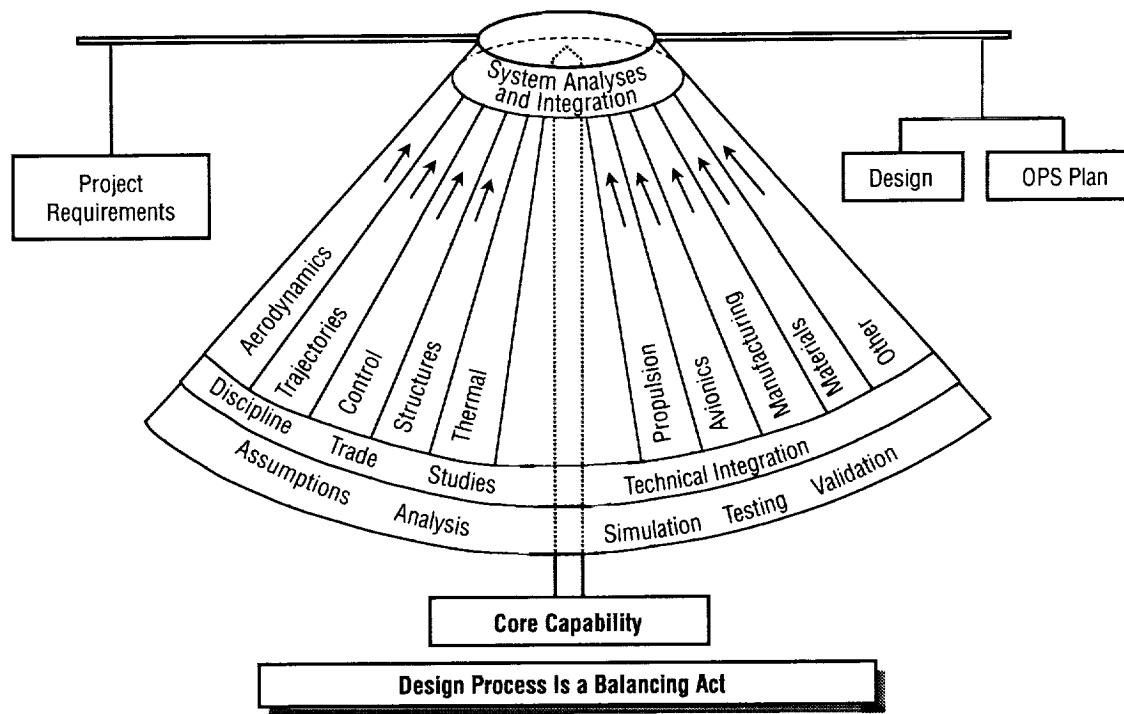
Figure 28. Design process balancing act.

Technical, cost, and schedule risks must be actively managed throughout development. Active risk assessment is an essential element of the design process. Failure mode analyses and risk/consequence assessments are done for each design alternative. A technology assessment for each design alternative identifies technology development required, along with the risk associated with maturing the technologies to an acceptable level.

In the compartmentalization process described above, the intent is to take advantage of weak coupling between design functions and between discipline functions. This approach enables the design to proceed at design function sublevels such as structures, propulsion, avionics, etc., and by the various technical disciplines. However, this assumption results in a suboptimum design from two standpoints: (1) The total system is not optimized since the design is consummated at the element, subsystem and component level. In other words, the assumption is that if all the parts are optimized, when they are put together the system will be optimized. The degree that this is true depends upon the coupling between each of the elements, subsystems, and components. (2) Elements, subsystems and components themselves are never truly optimized due to the constraints levied, as well as the trades and balancing acts that must be accomplished to make the system work.

The compartmentalization process also facilitates the allocation of requirements, etc., and the definition of tasks. An orderly set of clearly defined discipline tasks must be developed. These tasks can be discipline specific or multidisciplinary, and they must be timely (their association to the critical path should be determined). At the system level, design and interface requirements are subsequently allocated to the design functions, and these allocated requirements lead to metrics for the design function gates. It is most efficient and effective when the system design function develops the requirements in conjunction with the other design functions and is then reinforced by the discipline functions.

As illustrated in figure 9, a key aspect of the design process is the re-integration of design results from the compartmentalized discipline functions, design functions, and subsystems. In the ideal situation all of the discipline function results are integrated to support the design functions for each subsystem. The design attributes would be integrated by the system design functions via trade studies with the balancing act. Then all the subsystems are integrated (assembled) to achieve the launch vehicle assembly. During the re-integration activities, the major aspects of technical integration are to ensure design attributes satisfy requirements, constraints, etc.; interface requirements are met; interactions are appropriately accounted; significant nonlinearities are included; sensitivities, uncertainties, and margins minimized; risks minimized, mitigated and managed; verification is adequately achieved, all certification requirements defined; flight and operational constraints minimized; and all issues and concerns resolved and documented.

4.3.2 System Design Function

Shown in figure 29 is the design process technical integration with a focus on the system design function. The illustration delineates the relationship between the system design function and the other design functions. In addition, it shows the work/information flow process that is supported by key system decision gates required to develop and assess the system attributes. The details of all the above are discussed in this section.
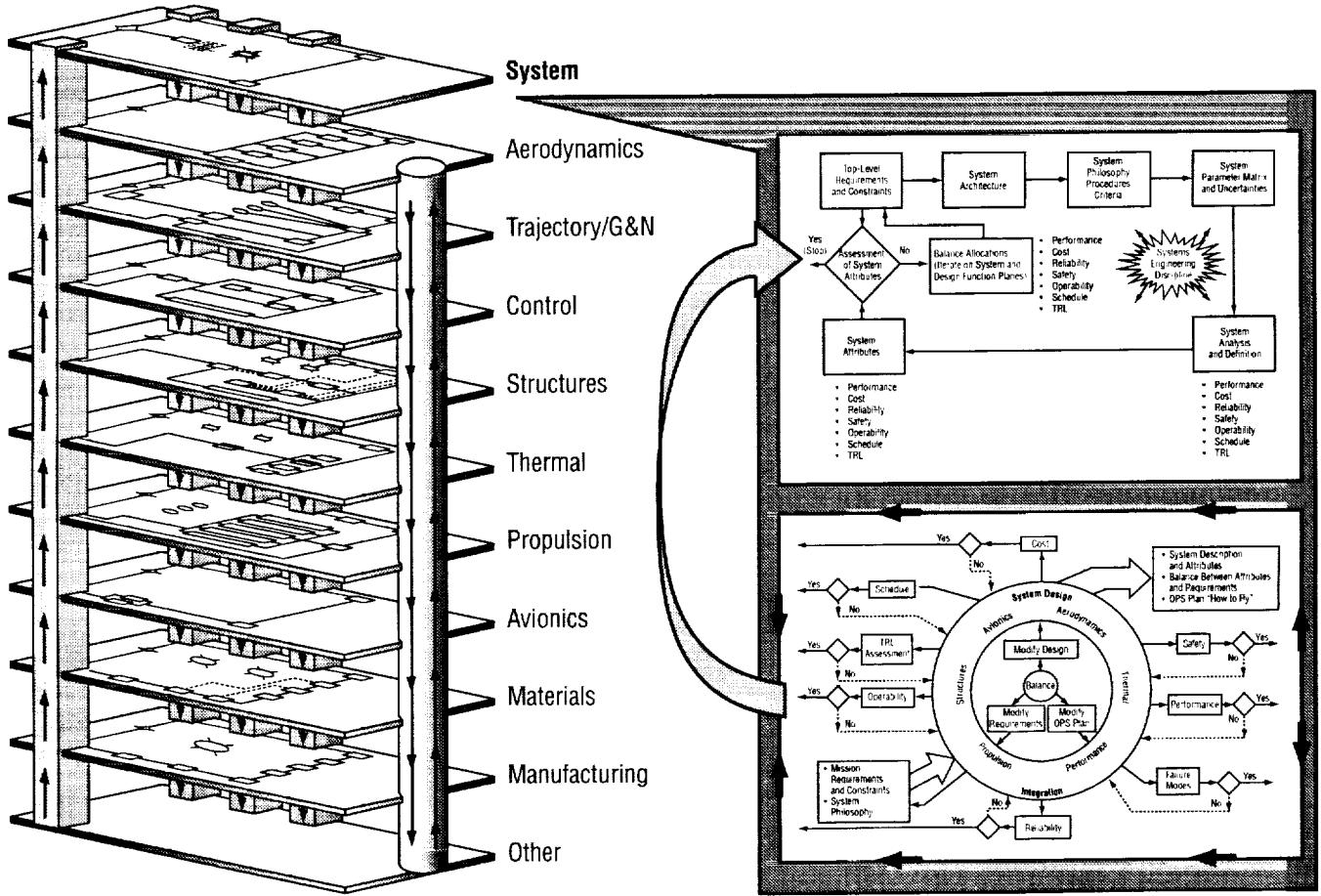
Figure 29. Design process technical integration—system design function.

The launch vehicle process as practiced is sequential. Conceptually, one could "cut and try" to achieve a design; i.e., build, test, and fix a product until it operates satisfactorily. For launch vehicles, however, because of the system complexity, challenging performance requirements and environments, the number and depth of technical disciplines, etc., the design process has evolved sequentially in order to achieve design efficiency and technical fidelity. For example, as previously discussed, trajectory outputs are inputs to control analyses, control analyses outputs are inputs to loads, etc.

Note: The systems design function is a process that involves formal technical integration of results from all the other engineering design function planes supported by the systems engineering discipline. The goal is to deliver a verified product that satisfies all the system requirements. This report does not describe the system design process in detail, but provides a top-level overview to show key features as they relate to the total vehicle design process.

4.3.2.1 System Design Function Plane. The systems design function is the overarching engineering activity that ties together all the other design function results and subsystem interface activities. The key features of the systems design function along with the associated connectivity are shown in figure 30. This figure will be referred to as the system plane. The systems design function must ensure that the design

concept becomes formally integrated as a balanced system product that has been validated to satisfy all the top-level system and all other engineering design function requirements and constraints. Top-level systems requirements and constraints are developed, analyzed, tested, balanced, formally integrated, and validated by the system design function. All other design function requirements and constraints, in contrast, are developed, analyzed, tested, balanced, informally integrated, and validated within and between the other design functions and then formally integrated into the systems design process. Most of the top-level system requirements and constraints are derived from the given mission statement, while others are determined from experience. The requirements and constraints derived from the mission statement are somewhat inflexible. The major top-level system requirements are performance, cost, schedule, TRL constraints, reliability, safety, and operability.
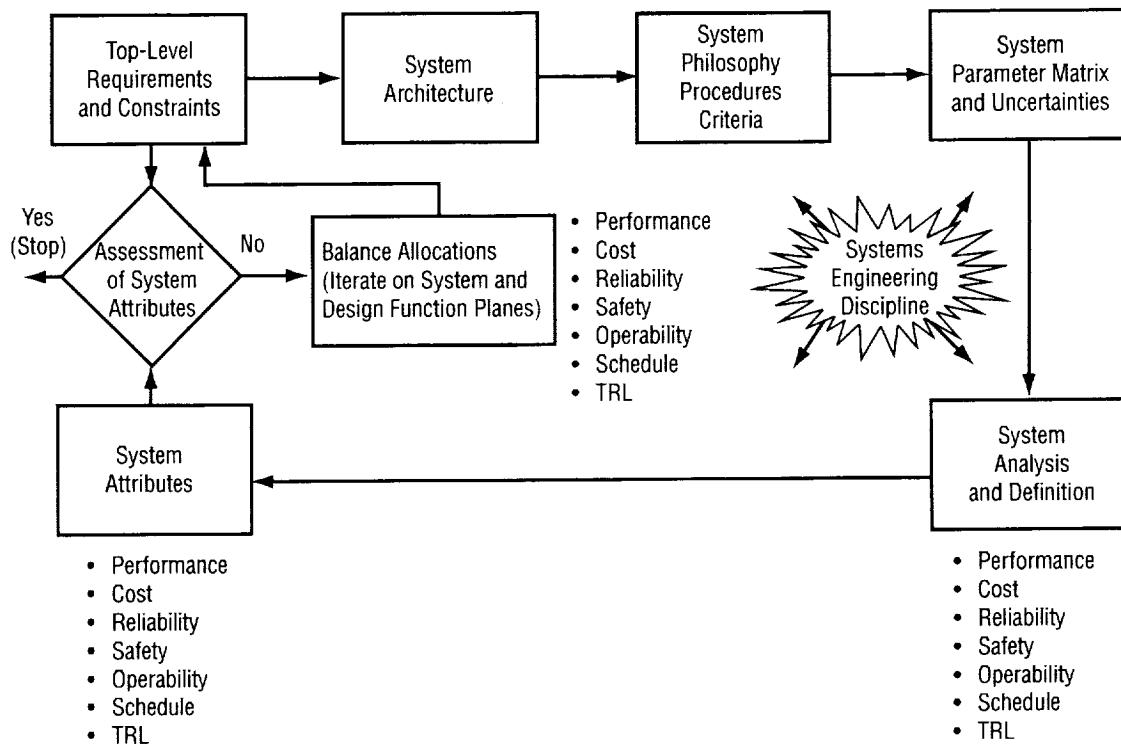
Figure 30. System design function plane.

Throughout the duration of a project all the requirements and constraints are continuously assessed and refined. In addition to the requirements and constraints, the project must also develop the system architecture, certain philosophies, procedures, criteria, and ground rules. The latter are flexible and meant as guides for the engineering development. Subsequent to the above, the associated system parameter matrix with associated uncertainties is defined. The system architecture and its associated parameter matrix with uncertainties are determined in conjunction with all the other engineering design functions. The system architecture is then evaluated and refined throughout the design process. The resulting attribute of performance, associated with the system architecture(s), must meet the requirements, constraints, philosophies, procedures, criteria, and ground rules. Other types of system analysis (e.g., cost,

reliability, etc.) are conducted for the architectural concept(s) to determine those remaining system attributes. As concepts are being selected (in some situations there can be more than one concept), requirements relating to the most promising concepts are allocated to all the other engineering design functions. These allocations include the design specific requirements or metrics for each engineering design function. Requirements are refined and updated throughout the design process; i.e., from conceptual design through preliminary and detail design. As the design progresses, the requirements can change as a result of a top-level change or because of the engineering balancing act.

Throughout the entire design process, the system design function and all other design function knowledge bases are continually increasing while the uncertainty is decreasing. All the data relating to the selected architecture(s) are assessed by systems and discipline engineers on the system plane to assure that all the requirements, constraints, philosophies, procedures, criteria, and ground rules are satisfied. In fact, the design process is iterated until all requirements are satisfied. In addition to determining and assessing the system attributes, the systems design function is also responsible for other activities related to the system. Some of these include risk determination, assessment, and management; requirement allocations, management, integration, and redistribution; tracking system design performance metrics; configuration management; etc.

Thus, the process illustrated on each design function plane is iterative, consisting of the following steps:

- Determine requirements and guiding philosophy
- Synthesize a candidate design to meet requirements
- Analyze the candidate design to determine its attributes (performance, cost, reliability, etc.)
- Compare attributes to requirements
- Modify the candidate design if attributes do not meet requirements
- Compare new attributes to requirements
- Continue iterations until design satisfies requirements.

If a design meeting requirements cannot be found, a rebalance or modification of requirements is necessary, as discussed earlier. Throughout the iterative process, all pertinent interactions with other design functions are maintained.

In the past the cost of a launch vehicle project usually has not been a serious design consideration; performance was always the primary design metric. However, in the next generation of launch vehicles, cost will be one of the most serious design considerations. Bringing cost into the design equation is not simple in that it must inculcate all the various contributing parameters, including infrastructure, manufacturing, operations, engineering, etc. These relationships to the design are not all quantified and must be dealt with using judgments, etc. Obviously, the best approach would be to have cost-estimating relationships for all the various design parameters. This is not possible since credible cost-estimating relationships are not available for most of the aforementioned; however, use must be made of those that are available. For example, cost associated with the design itself can be broken out in terms of engineering effort (analysis, testing, simulations, etc.), facilities (computational, staff, manufacturing, testing, etc.), materials, manufacturing, verification, etc. It should be noted that cost is strongly driven by the requirements imposed, whether they be top-level project requirements (e.g., payload, performance, turnaround time, reliability, etc.), formal discipline-specific criteria, or documentation and traceability requirements.

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These should be tightly controlled since they can have major cost impacts. If the aforementioned were the only costs, then the job would be fairly tractable; however, the vehicle design has a major impact on cost through operations. The vehicle combined with the mission requirements interacts in a very complex manner with operations. This can be said since it is clear that operations has to do with receiving the vehicle (usually by elements), processing and assembling, check out, launching, communications (voice and telemetry), maintainability (inspections, refurbishment, etc.), and availability (turnaround). The vehicle design and margins impact the launch constraints (allowable winds, temperatures, etc.), and the procedures for each subsystem. As a result, operations and sustaining engineering manpower carry a significant cost impact, depending on the vehicle's robustness and autonomy.

Designing for cost, therefore, implies metrics and guidelines that effect trade studies between operational design and vehicle design. These include but are not limited to—

- Requirements/criteria
- Robustness/reliability
- Infrastructure (facilities, etc.)
- Manufacturing
- Materials
- Maintenance
- Processing
- Assembly
- Checkout and verification
- Launch procedures/constraints
- Communication (voice and telemetry)
- Software.

Historical data help in formulating the cost models; however, cost specialists must assist the designer in understanding the cost drivers and achieving a cost-effective design. One warning: Do not do the cost assessment at the end. Make it a part of the up-front design process, and track it on the system plane.

All of the activities associated with the aforementioned are accomplished via formal and informal technical integration and orchestrated by the system design function. This technical integration is achieved with the utilization of IxI and NxN information flow matrices as discussed in section 4.3.1 and illustrated in figure 27. Recall the IxI matrices are associated with information flow related to hardware/software interfaces and the NxN matrices are associated with information flow related to the design and discipline functions. The specific details associated with both of these types of matrices are discussed below.

4.3.2.1.1 IxI Matrices. Figure 27 illustrates two types of information flow matrices that help in the characterization of the design process. On the lower left is shown an IxI matrix corresponding to the subsystem tree. IxI matrices represent information flow associated with the subsystem tree interfaces. An example expansion of an IxI matrix is shown in figure 31. It represents interface information flow for the launch vehicle and its next tier of subsystems. The launch vehicle is shown in the upper left block, with its next tier subsystems on the remainder of the diagonal. Elements on the horizontal rows contain outputs from the entity on the diagonal, and elements on the vertical columns contain inputs to the entity on the diagonal.

The first diagonal element contains the system (or subsystem) for which the I×I matrix is constructed. The remaining diagonal elements are the subsystems (or sub-subsystems) in the next lower tier of the tree. Along the top row are the interface requirements imposed by the system on its subsystems. The far left column then feeds back the description of the as-designed subsystem interface to the system; i.e., what the subsystem design has accomplished in response to the interface requirements from above.
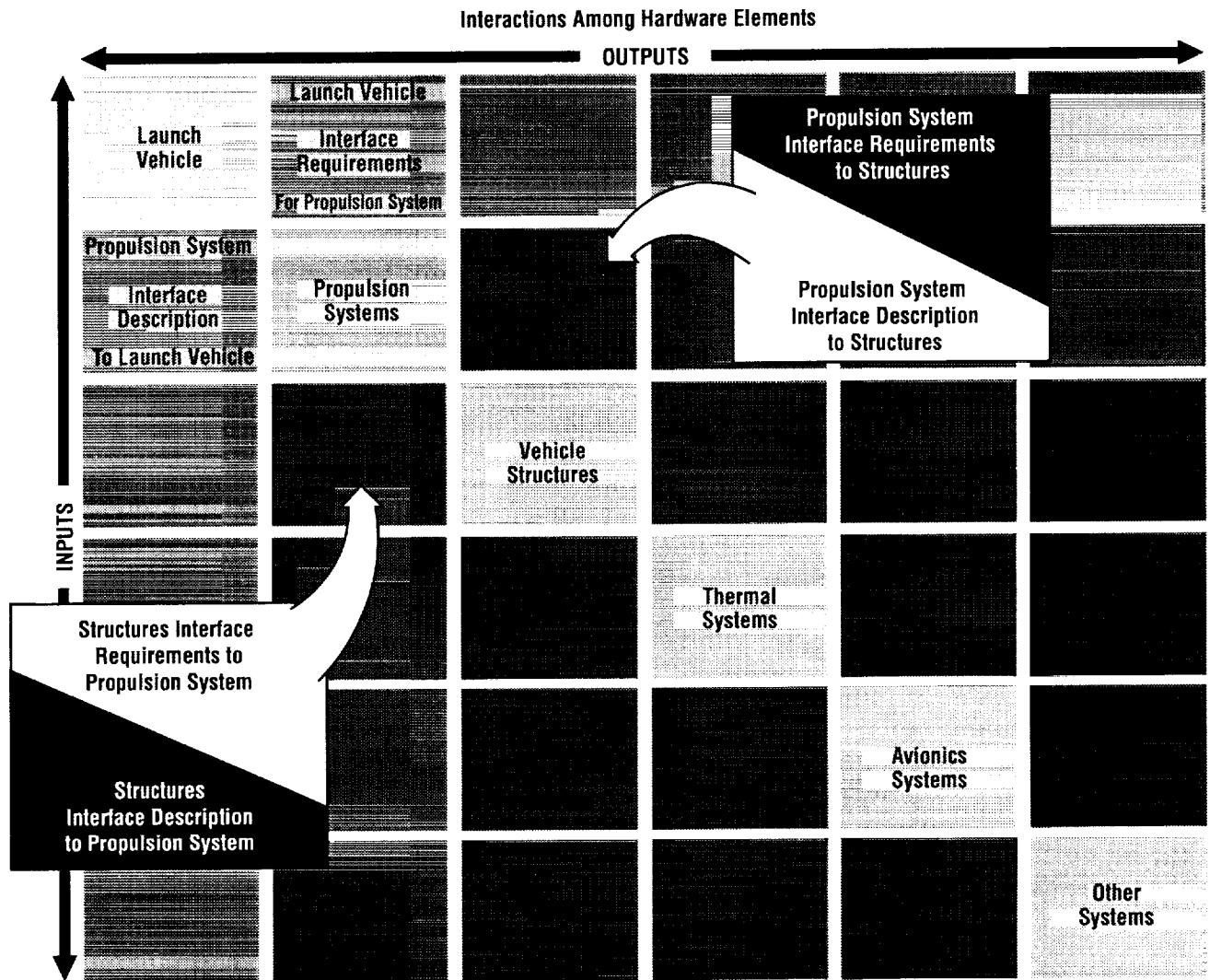
Figure 31. I×I matrix for launch vehicle.

The remaining off-diagonal elements contain interface requirements and interface descriptions among peer subsystems along the common tier. Note that the information flow between any two entities takes a clockwise path on the matrix. In the case of peer subsystems, there are two concurrent interface information flows occurring (represented by two shades on the inset blocks). One involves interface requirements of subsystem A on subsystem B, along with B's interface description fed back to A. The other flow involves requirements of B on A, along with A's interface description fed back to B.

Note that there are numerous IxI matrices. There is an IxI matrix associated with each system or subsystem that is divided into lower tier entities on the tree. Thus there is an IxI matrix for each subsystem as we proceed down the tree to its next-to-last tiers. The parts on the last tiers of the tree are sufficiently simple that no further subdivision is required. These parts are simple enough to be designed by an individual designer, using handbooks, standards, etc. These last-tier parts appear on the lower diagonal of IxI matrices, but they do not have their own IxI matrices where they would appear in the upper left element of the matrix.

4.3.2.1.2 NxN Matrices. On the lower right of figure 27 is shown an NxN matrix corresponding to the stack of design function planes and the discipline function activities resident on the planes. NxN matrices represent information flow among the design functions and the discipline functions. An example NxN matrix is shown in figure 32. The example in this case is the launch vehicle system with its associated design functions and disciplines. Note that the launch vehicle system plane is represented by the upper left element of the matrix, and the remaining lower design function planes are represented on other diagonal elements.
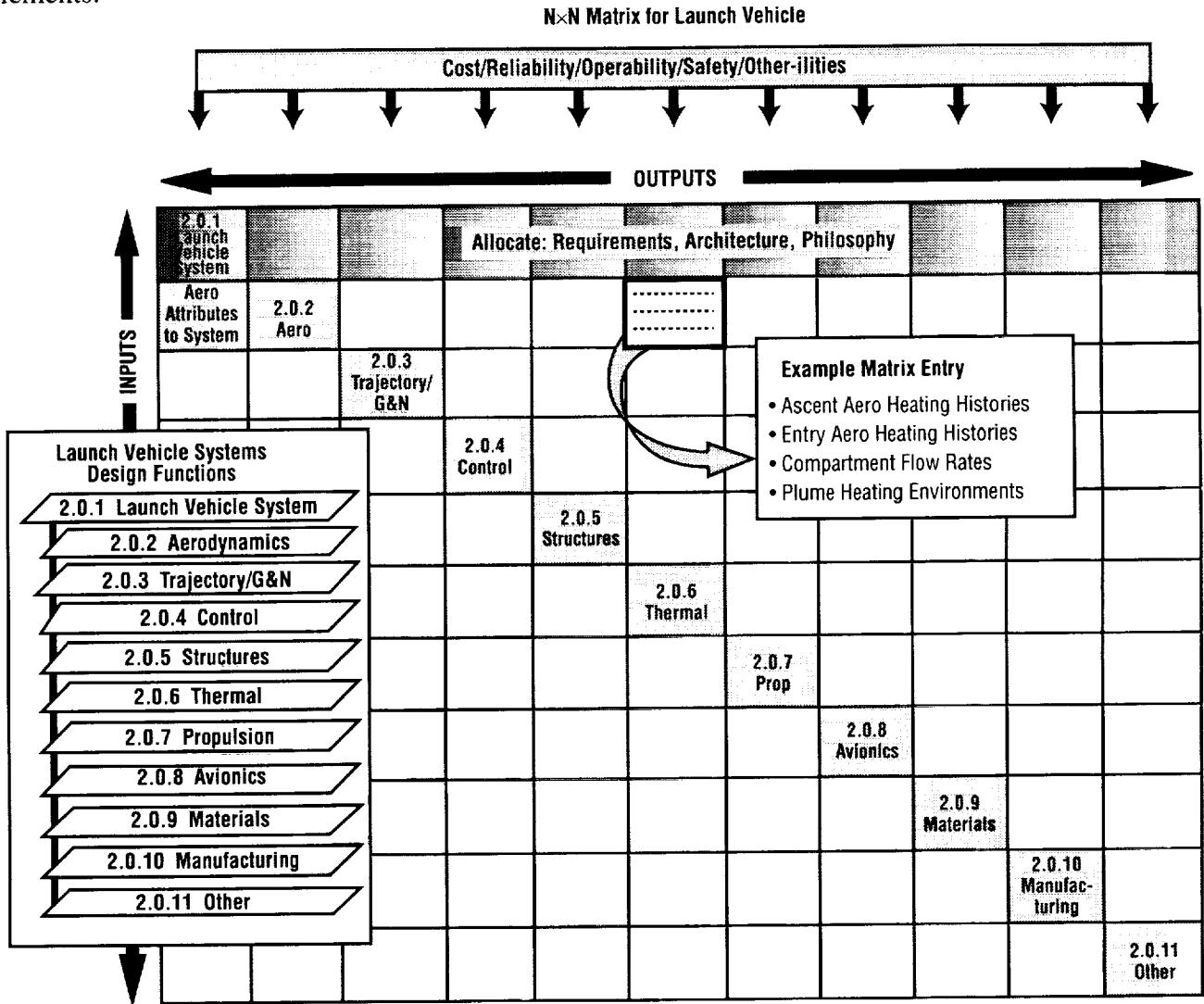
Figure 32. NxN matrix for launch vehicle.

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The input-output pattern is like that of the IxI matrix; i.e., outputs of a diagonal element are on its horizontal row, and inputs to the element are on its vertical column. Thus, the entries in the first row are the outputs from the launch vehicle system plane (allocations of requirements, architecture, and philosophy) that are inputs to the lower design function planes. This is the information that flows down the respective conduits of the stack. The entries in the first column are the outputs from the lower design function planes (attributes) that are inputs back to the launch vehicle system plane. This is the information that flows up the attribute conduit of the stack. The remaining off-diagonal elements contain information flow among the lower design function planes, as represented by the round vertical conduit of the stack. An example entry is shown for the output from aerodynamics that is input to thermal.

There is an NxN matrix associated with each design function stack. Thus, there are many NxN matrices since there is a design function stack for every element on the subsystem tree whose design involves multiple design function activities.

An example of a related NxN matrix from reference 2 is given in Appendix A.

Inclusion of IxI matrices and NxN matrices with the subsystem tree and design function stacks provides locations or placeholders for the technical information that must flow among the participants in the design process. This characterization also suggests a framework for an electronic information and communication system to enable efficient and concurrent interactions throughout the process (see section 5.2.4).

4.3.2.2 System Gates. The decision gates for the system design function are shown in figure 33. The inputs to the system design process are the mission requirements, constraints, and system philosophy. The outputs are the system description, attributes, and operations plan. There must be a proper balance among the requirements, constraints, vehicle design and associated attributes, and the operational plan. The system gates are the locations in the project where the system attributes of performance, cost, reliability, safety, schedule, operability, failure modes, and TRL are compared to the requirements, constraints, philosophies, procedures, criteria, and ground rules. If the comparisons are favorable (i.e., yes), then the design process is completed. On the other hand, if the comparisons are unfavorable (i.e., no), then there must be another design iteration. This process is repeated until the design is balanced with the attributes satisfying the requirements, constraints, etc.
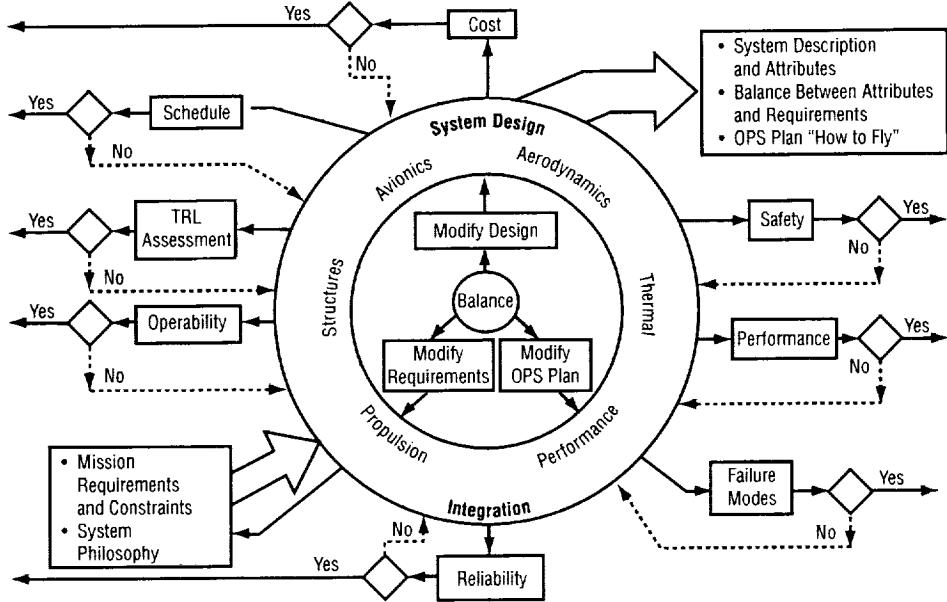
Figure 33. System design function gates.

The systems design function must provide the project overview to achieve and enforce proper balance. The balance can be accomplished by modifying the design, operations plan, requirements, constraints, philosophies, procedures, criteria, and ground rules. This is achieved through formal technical integration between and among the system and other design function planes. To achieve balance, all the results (i.e., attributes) are analyzed and assessed through informal technical integration on the system plane. If balance is achieved, the design is completed. System design and integration are completed when the attributes of performance, cost, reliability, safety, schedule, operability, and TRL satisfy the project levied requirements, constraints, philosophies, procedures, criteria, and ground rules. If balance is not achieved, the conflict must be resolved by modifying the vehicle design, requirements, constraints, operational plan, or other influencing factors. The process is iterated until balance is achieved. The final major outputs of the system design and integration process are the following: (1) Description of system with attributes, (2) balance between attributes and overall requirements, and (3) operational process of how to fly the vehicle. The formal and informal integration are a continual process in the design project, and results are documented at major reviews.

4.3.2.3 System Design Tasks. The definition of vehicle design tasks associated with the activities of the system design function begins with the definition of the mission statement. After the compartmentalization activity, the principals of the system design function, all the other design functions, and discipline organizations delineate all the major vehicle design tasks. The tasks associated with the system design function can be categorized into five major groups that are as follows: (1) Develop engineering design activity plan; (2) analyze, allocate, and manage subsystems and requirements; (3) perform system analysis; (4) integrate for balanced design product; and (5) verify system design. The specific tasks associated with the aforementioned major groups as shown in table 1 are discussed below.

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Table 1. System design function tasks.

Activities	Interactions	Tasks
1. Engineering design activity plan	Program office Design functions Discipline functions	1. Develop the engineering organizational structure. 2. Establish formal and informal communications process. 3. Develop schedule of engineering activities with associated deliverable products. 4. Establish WBS. 5. Document and disseminate plan; include mission statement.
2. Allocation and management of subsystems and requirements	Design functions Discipline functions	1. Consult with project office to establish top-level system requirements, philosophies, and constraints. 2. Assess and compartmentalize systems into subsystems and elements. 3. Determine and allocate performance, cost, reliability, operability, schedule, and TRL requirements to design functions. 4. Acquire and formally allocate discipline criteria. 5. Document and disseminate all requirements.
3. System analysis	Design functions Discipline functions	1. During concept selection phase, define concepts; apply sizing program to evaluate and refine concepts; determine sensitivities; and identify new technologies required for each concept. 2. Develop system parameter matrices and associated uncertainties. 3. Determine system derived requirements and impose discipline derived requirements. 4. Determine system attributes from systems analyses. 5. Assess configuration and subsystems to verify conformance to all requirements. 6. Establish failure modes and perform a risk assessment. 7. Continue analyses throughout the project duration. 8. Document and disseminate results.
4. Integration for balanced design product	Design functions Discipline functions	1. Formally integrate and balance the various design function attributes to satisfy all systems requirements and discipline criteria. 2. Manage conflict among discipline functions and between design functions to resolve all issues. 3. Perform trade studies as required. 4. Manage interfaces and changes. 5. Document and disseminate results.
5. Verification	Design functions Discipline functions	1. Develop verification plan (analysis and ground/flight tests). 2. Audit verification process. 3. Correct anomalies. 4. Document results. 5. Validate system during developmental flight tests. 6. Implement operational plan compatible with the verified system. 7. Document and disseminate verification plans, corrective actions, and operational plans and procedures.

4.3.2.3.1 Task 1—Engineering Design Activity Plan. Initially the type of organizational structure must be determined. The various types are delineated in section 4.1. Subsequently, the details of the formal and informal communication process are set up consistent with the organizational structure selected. This includes the chain of command, electronic communication system and control, formal data reporting, security, and others. Then based upon the compartmentalization, a WBS system must be developed with

associated tasks to support the activities of all the engineering design functions. These WBS designations are then implemented to develop an electronic schedule of engineering activities and the associated deliverable products. An important feature of the schedule is the critical path along with associated uncertainty. When the above is completed, the plan should be documented and disseminated.

4.3.2.3.2 Task 2—Allocation and Management of Subsystems and Requirements. A major focus of the system plane relates to understanding the mission statement and then developing the top-level requirements, constraints, and architecture philosophies. This activity is important and continues throughout the duration of the design process with the greatest intensity initially. The significance of the top-level requirements as they relate to the mission statement and to the vehicle design and operation must be determined by considering nominal conditions in addition to sensitivity and uncertainty analysis. These data will be applied to assess potential impacts from trade-study results. Usually, the top-level requirements are invariant; however, they can be changed if there is cause and there is not a significant compromise to the mission statement.

The system is then assessed in order to compartmentalize it into appropriate subsystems and design functions. Then the system plane in conjunction with the other design planes determines the performance, cost, reliability, safety, operability, and TRL constraints that are to be allocated by the system plane to the other design planes. The system plane must also acquire discipline specific criteria for formal allocation. All these data are then documented and disseminated. Throughout the process, the system plane manages the configuration evolution so that the activities of the various design functions are coordinated. After preliminary design, a baseline is established, and all data are under formal configuration control.

4.3.2.3.3 Task 3—System Analyses. The system analysis pertains to determining performance, cost, reliability, safety, schedule, operability, and TRL design attribute values for the total system along with formal technical integration to resolve conflict in order to achieve a balanced system design. Initially, architectural concepts along with parameter matrices and their uncertainties are determined and then, by applying the sizing program, the concepts are assessed. Trade studies and sensitivity analyses are performed and the concepts are refined to achieve the performance requirements restricted to the constraints and program guidelines. The refined concepts may require new technologies; thus, these must be determined and evaluated. The number of new technologies required to achieve a concept then becomes a factor in the concept selection. As the refined concepts begin to converge, the system parameter matrices and associated uncertainties are matured. Then by applying those input data, systems analyses are conducted to determine the remaining system attributes; i.e., cost, reliability, schedule, and operability along with their uncertainties. Then all these results are applied to assess the architectural concept's attributes in regard to conformance with all the requirements, constraints, guidelines, etc. The results are eventually applied in a decision model to numerically rank the architectural concepts to aid in the concept selection.

After the number of concepts has been narrowed down, risk analyses are performed. The major focus of these analyses is technical, cost, and schedule risk. The failure modes are established as part of the technical risk analysis.

The total system analyses delineated above are continued, and the system attributes refined throughout the design process. The other design functions provide attributes of their subsystems as input to the total system analyses. The objective of the analyses is to improve the quality of the values of the attributes and reduce the uncertainties. These data are applied as technical performance parameters that are used to track

the progress of the design and to make numerous decisions throughout the design process. These results are documented, controlled, and disseminated by the systems design function.

4.3.2.3.4 Task 4—Integration for Balanced Design Product. The system plane facilitates informal and formal technical integration to achieve a balanced design product. The informal integration pertains to the technical integration on the system plane to attain balance among the system attributes. The formal technical integration is between all the design planes and the system plane. The focus of the integration is to obtain a balance of the attributes among the design functions to satisfy all the requirements, constraints, and discipline criteria. To achieve balance, sometimes it is required to manage conflict among design functions and between disciplines to resolve issues that cannot be resolved through informal integration. This may require a multiplicity of changes. The system plane must control and manage all changes as the conflict is being resolved. In addition, it must also control and manage all system interfaces. These interfaces may or may not be part of the conflict resolution. All these data must be documented, controlled, and disseminated by the system plane.

4.3.2.3.5 Task 5—Verification. The system verification activity is the responsibility of the system design function, and it is supported by all of the other design functions and the discipline functions. Initially, verification plans are developed. The verification can be accomplished by analyses, simulation, or test (ground /flight). It is then the responsibility of the system plane to audit the verification process. This is usually accomplished with the other design functions and discipline functions. When anomalies are discovered, corrective action is required. The corrective action can be accomplished by redesign or by requirement changes. The corrective action must be subsequently verified. The results of these activities must be documented and disseminated.

The final verification is obtained from developmental flight tests. If significant anomalies occur, then a corrective redesign is required or an operational constraint is place on the system. These corrective changes are required to be verified. All of these results are required to be documented and disseminated.

4.3.3 Aerodynamic Design Function

The connection between the design process technical integration and the aerodynamic design function is delineated in figure 34. This illustration depicts the relationship between the aerodynamic design function and the other design functions. In addition, it shows the work/information flow process that is supported by key aerodynamic decision gates that are required to develop and assess the aerodynamic attributes. The details of all the above are delineated in this section.
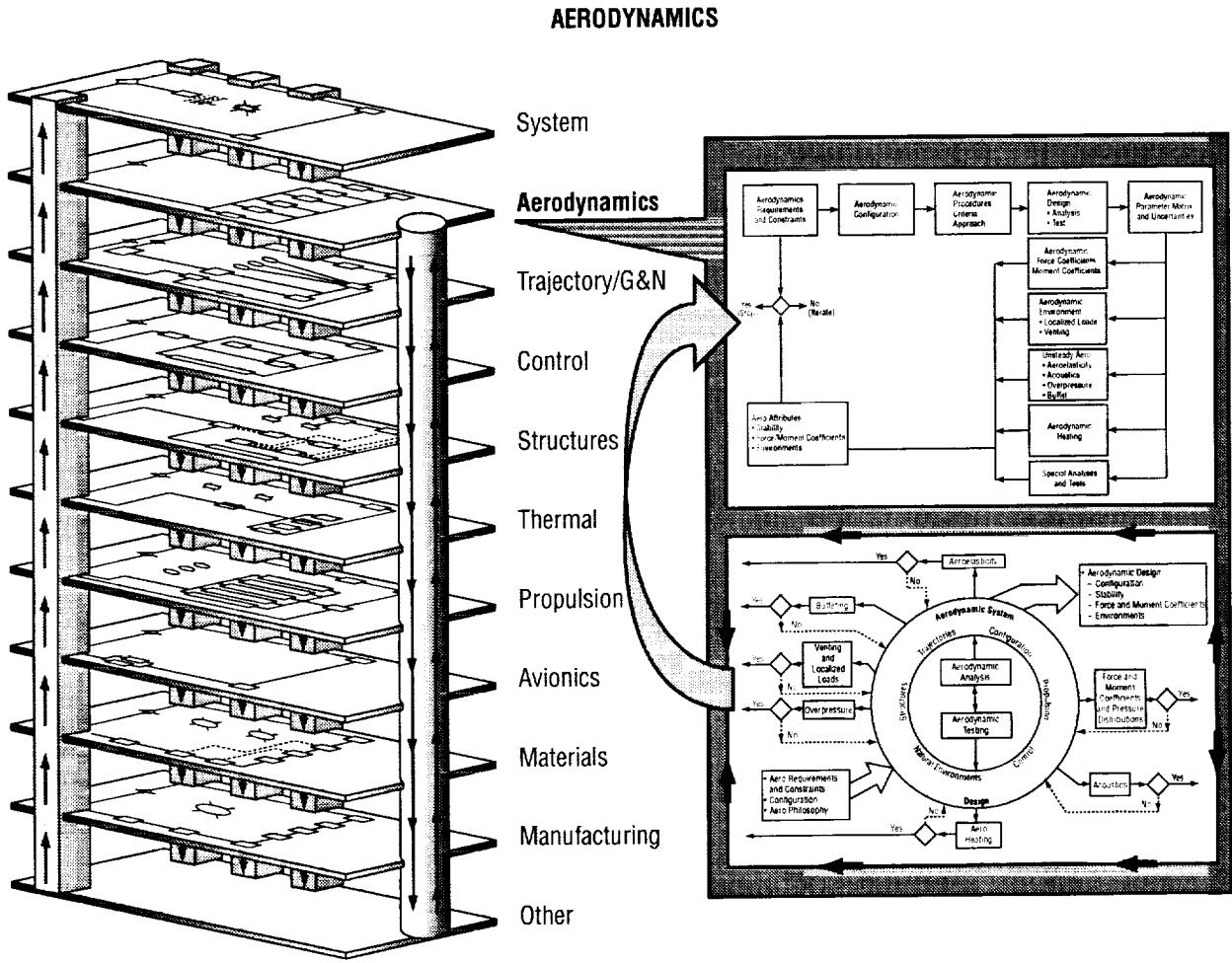
Figure 34. Design process technical integration—aerodynamic design function.

4.3.3.1 Aerodynamic Design Function Plane. This discussion describes the features of the aerodynamic design function delineated in figure 34 and its connection to the stack in figure 26. The aerodynamic design function interacts through informal integration mainly with the trajectory/G&N, structures, thermal, and control design functions. However, the aerodynamic requirements and constraints are allocated through formal integration with the system design function (see fig. 26 and 35). These requirements and constraints include the aerodynamic configuration, cost, schedule, etc. They are assessed with established aerodynamic procedures, criteria, and methods. Subsequently, the aerodynamic design process is initiated where analytic, empirical, numerical (CFD), and test methods are applied to determine the significant aerodynamic parameters and associated uncertainties. Initially, the aerodynamic force and moment coefficients are determined. They are used in the sizing/trajectory program and are continually refined and updated throughout the design process to support system performance analysis. The steady aerodynamic environments are the basis from which localized loads and compartment venting pressures are determined. The unsteady aerodynamic environments consist of determining aeroelastic stability, acoustics, overpressure, ground winds, and buffet design parameters. The aerodynamic heating environment consists mainly of the radiation heat flux from the engine plumes and the convective heat transfer from the external flow over the launch vehicle during ascent and reentry. The plume electron profiles must also be determined. All the aerodynamic parameters and their uncertainties are implemented into the

design process in an iterative manner until there is convergence with the requirements and constraints allocated from the system plane. In some situations the allocated aerodynamic requirements and constraints are modified to achieve overall balance. This can occur when all other disciplines are formally integrated by the system plane or when the physics of the situation dictates. Eventually, the aerodynamic design attributes must satisfy the requirements and constraints. This is delineated with the gate shown in figure 35. Finally, the aerodynamic parameters and their uncertainties are verified in flight experiments.
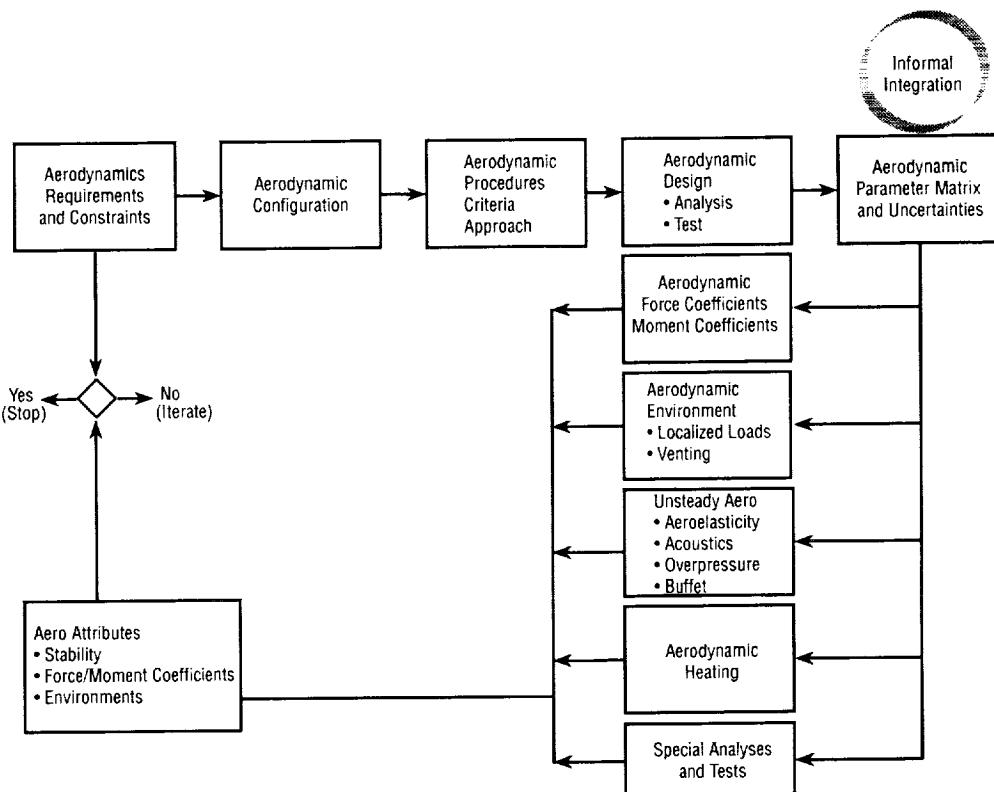
Figure 35. Aerodynamic design function plane.

The aerodynamics parameters and induced environments design process flow diagram from reference 2 is shown in figure 36. It can be seen that there is a direct correlation with figure 35. The focus of aerodynamics design function shown in figure 35 is to illustrate formal and informal technical integration, requirements and constraints, procedures and criteria, parameter matrix and associated uncertainties, major design functions that are accomplished by the aerodynamic discipline along with associated connectivity, and the output design attributes. The focus of the aerodynamic design process shown in figure 36 is the aerodynamic discipline activities along with the corresponding requirements, inputs, outputs, connectivity, and products. The NxN diagram of reference 2 (Appendix A) is representative of further delineation of the inputs and outputs associated with the aerodynamic design process.

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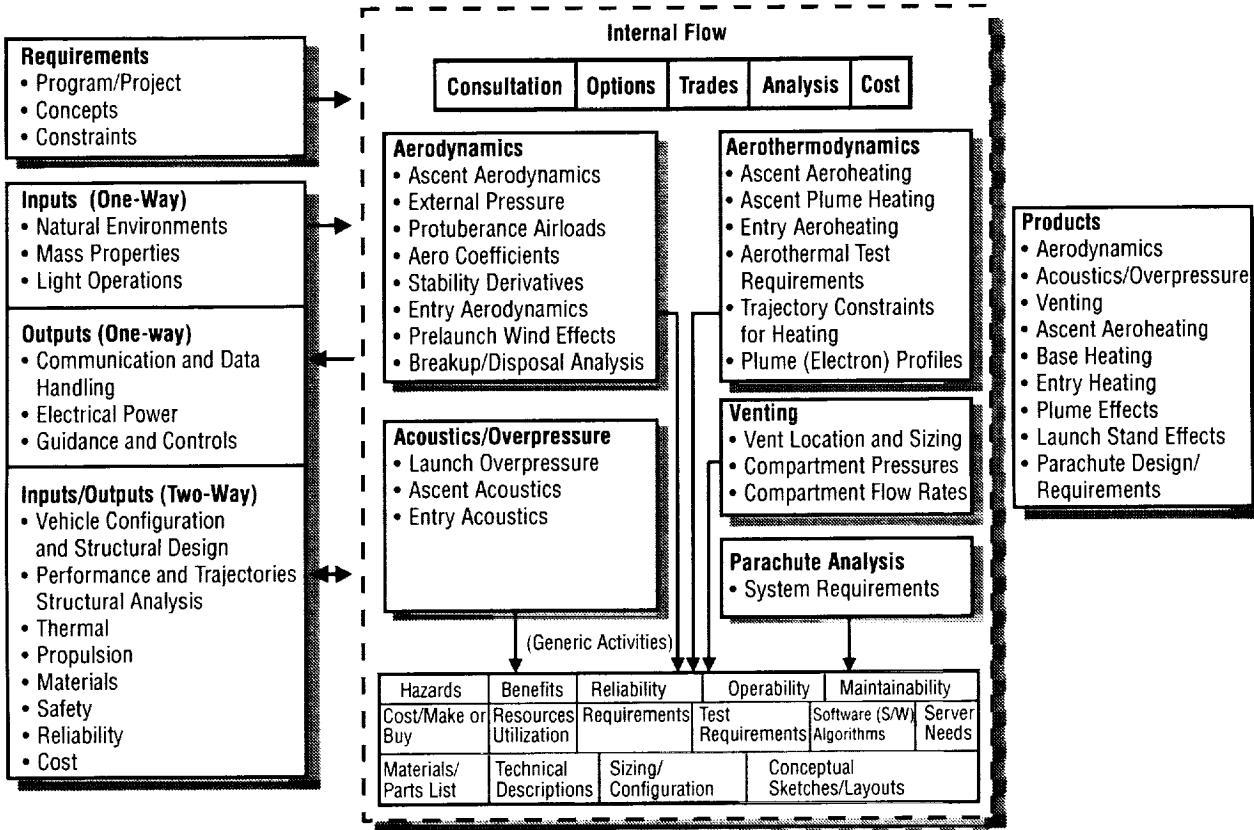
Figure 36. WBS 2.3—aerodynamics and induced environments.[2]

These inputs/outputs show the correlation with other design functions, and they represent the product flow of figure 26. The corresponding tasks are shown in table 2. These tasks are related to accomplishing specific aerodynamic design objectives. The tasks associated with figure 35 are the allocation of requirements, aerodynamic design, and verification. These tasks are further discussed in section 4.3.3.3.

Table 2. WBS 2.3—aerodynamics and induced environments task description.[2]

Inputs	Tasks	Outputs
•Projected ground rules and goals •Launch pad geometry •Preliminary design out emold line •Ground and ascent wind profiles •Atmospheric models •Launch stand ambient temperatures •Protuberance geometry •Engine placement geometry •Ascent trajectory sets (altitude, velocity, α, β histories) and engine operating conditions •Entry trajectories •••Airflow history to inlet •Trajectory constraints •••Mach transitions •Structural deflections •Heating constraints ••Wall/surface temperatures •Control weights, centers of gravity •Engine dimensional and operational characteristics •Turbine exhaust definition •On-pad effluent definition •••Rocket based combined launch (RBCC) exhaust conditions •••Forebody inlet performance requirements •••Transition mach number •Vehicle integrated OPS concept and requirements •Hazard analysis •Failure mode effects analysis inputs •••CIL inputs	3.4.1 Aero design consultation 3.4.2 Generate ascent aerodynamics 3.4.3 Generate external pressure distributions 3.4.4 Generate protuberance airloads 3.4.5 Generate aero coefficients 3.4.6 Generate aero stability derivatives 3.4.7 Generate vehicle/stage entry aerodynamics 3.4.8 Determine vent size and location requirements 3.4.9 Determine compartment pressures 3.4.10 Calculate compartment flow rates 3.4.11 Generate ascent aeroheating histories 3.4.12 Generate ascent plume heating histories 3.4.13 Generate entry heating histories 3.4.14 Determine aerothermal test requirements 3.4.15 Specify trajectory constraints for heating 3.4.16 Generate launch overpressure environments 3.4.17 Generate ascent acoustics environments 3.4.18 Generate entry acoustics environments 3.4.19 Determine prelaunch wind effects 3.4.20 Determine parachute system requirements 3.4.21 Perform breakup/disposal analysis 3.4.22 Generate plume electron profiles Tools: • Computer codes: CEC/TRAN72, SPF/2, SIRRM, RAMP2, RAVFAC, BLIMPJ, MOC, SPP, LANMIN, MINIVER, Various CFD codes, etc. • Wind tunnel data • Historical ground and flight test data base	•Pressure vent sizes and locations •Moldline update including airframe/engine design •Vehicle ascent aerodynamics •Heating indicators ••Vehicle/stage entry aerodynamics •Engine inlet flowfield definition •External aerodynamic pressure distributions •Compartment pressures •Protuberance airloads •Acoustic/overpressure definition •Fluid dynamic loads (buffering) •Ascent aero heating histories •Entry aero heating histories •Compartment flow rates •Plume heating environments •Guidance and control instrumentation locations •Airloads on propulsion elements •••Engine installed thrust •••Forebody pressure recovery and flow field history •Aerothermal test requirements •Plume electron profiles •Ascent and descent pressure distributions •Heating and pressure instrumentation requirements •Sonic boom overpressure •Test requirements to include instrumentation

Key: • ELV, reusable launch vehicle (RLV), and RBCC
        •• RLV and RBCC
        ••• RBCC only

4.3.3.2 Aerodynamic Gates. The decision gates associated with the aerodynamic design function are shown in figure 37. It can be seen that the inputs are from the system plane and the aerodynamic discipline, plus there are interactions from other design functions. The outputs are the aerodynamic design attributes, and they must satisfy the system requirements on the aerodynamic design function plane. This is shown with the gate in figure 35. The decision gates shown in figure 37 relate to specific aerodynamic design needs and requirements; e.g., force and moment coefficients, acoustics, heating, etc. The data related to each gate are determined by aerodynamic designers via discipline analyses and testing. During this process, the aerodynamic designer must also be aware of the overall system requirements of cost, reliability, TRL, etc. The aforementioned data are the aerodynamic parameters and induced environments. Each of these quantities is determined in an iterative fashion. As the aerodynamic configuration begins to converge, metrics for the various gates also converge. The metrics are determined through formal technical integration of all the relevant design functions. These metrics then become the design targets or requirements for the aerodynamic designer. As the design proceeds, some of the metrics may change because of unforeseen impacts. This can result in another design subiteration. When all the gates are satisfied, the aerodynamic design is complete. The aerodynamic design is finally validated with data obtained from flight experiments. Operational constraints or a delta redesign may be required if the flight data indicate a serious operational impact.

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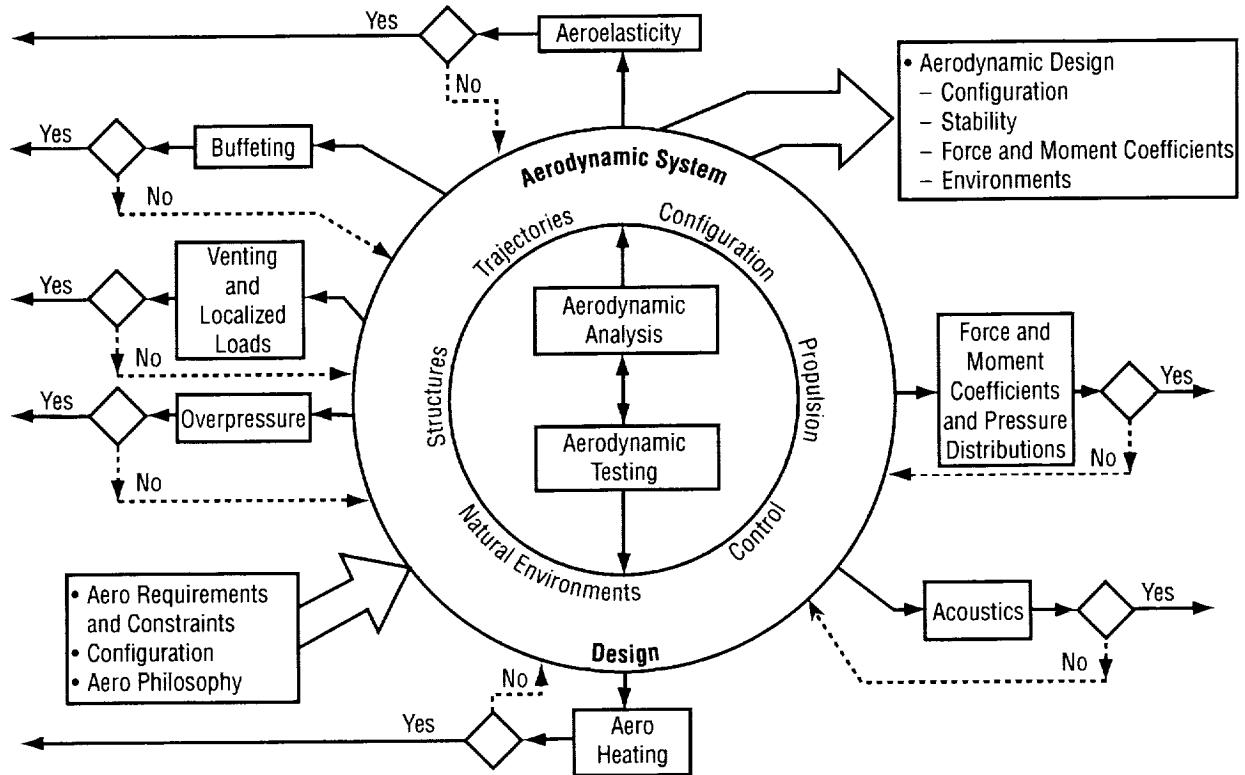
Figure 37. Aerodynamic design function gates.

4.3.3.3 Aerodynamic Design Tasks. The aerodynamic design function begins with the determination of the aerodynamic forces and moments to be used in the trajectory analysis and with the determination of the acoustic and blast overpressure environments to be used for environmental impact assessment. As the design matures, more and different aerodynamic parameters are needed for other aspects of launch vehicle design (see fig. 35). These parameters and their uncertainties are determined in an iterative fashion through the design process and continually matured. A summary of the aerodynamic tasks is shown in table 3.

4.3.3.3.1 Task 1—Requirements Determination and Allocation. This activity is accomplished by the aerodynamics design function with the support of the system design function and other design functions and disciplines as shown in table 3. In addition to performance, the overall vehicle aerodynamic configuration is determined from many factors, with cost and operational considerations being significant. The aerodynamic design procedures and approaches are then established along with various design criteria. Specific metrics are determined for the decision gates. These metrics can change as more knowledge is acquired about the configuration and when additional constraints evolve from other design functions. Eventually, the metrics converge, and they become the targets for the aerodynamic designer. At this point the metrics are maintained at the system level and are under configuration control. Initially the technical integration is formal, but as the vehicle design advances, it becomes predominately informal until the aerodynamic attributes satisfy the requirements. These final attributes flow upwards to the system plane; i.e., formal integration. There are some aerodynamic parameters that are not allocated. The configuration and the associated physics (e.g., plume radiation heating, ignition overpressure, and others) determine these parameters.

Table 3. Primary tasks for aerodynamic design function.

Activities	Interactions	Tasks
1. Requirements determination and allocation	System Control Trajectories Propulsion Structures Thermal Natural environment	1. Acquire allocated requirements and constraints from system and interact, formally and informally, through allocation process. 2. Obtain definition of configuration. 3. Establish procedures, criteria, and approaches. 4. Setup discipline specific criteria as the metrics for decision gates. 5. Communicate through formal and informal integration process.
2. Aerodynamic design	System Control Trajectories Propulsion Structures Thermal Natural environment	1. Develop aerodynamic models to determine force and moment coefficients and steady aero environments. 2. Develop models to determine unsteady aerodynamic and heating environments. 3. Establish all input data and determine aerodynamic design. – Provide aero parameter matrix and uncertainties. 4. Communicate with interacting disciplines to resolve unacceptable conditions. Resolve informally if possible. 5. Formally integrate aero attributes. 6. Document attributes.
3. Verification	System Control Trajectories Propulsion Structures Thermal Natural environment	1. Perform aerodynamic tests to verify force and moment coefficients and steady aero environments. 2. Perform speciality tests to verify unsteady aerodynamic and heating environments. 3. Update all input data and refine aerodynamic design data base using test data. – Refine aero parameter matrix and uncertainties. 4. Communicate with interacting disciplines to resolve unacceptable conditions. Resolve informally if possible. 5. Formally integrate aero attributes. 6. Update documented attributes. 7. Validate aerodynamic design data base during developmental flight tests.

4.3.3.3.2 Task 2—Aerodynamic Design. The aerodynamic design is accomplished by the aerodesigner with continuous formal and informal technical integration interactions with the appropriate groups as shown in table 3. Initially, all of the steady, unsteady, and heating aerodynamic parameters and their uncertainties are determined empirically from databases. Usually the estimates of all these quantities are conservative. As the configuration converges, more accurate determinations of the parameters are achieved via mathematical/numerical modeling and wind tunnel testing. The formal and informal technical integration continues in order to ensure that the aerodynamic attributes do not cause conflict or adversely affect the attributes of the other design functions. All unacceptable conditions are required to be resolved. After resolution is achieved, the aerodynamic attributes are formally integrated with the system design function. Finally, the significant aerodynamic features and the aerodynamic attributes are documented.

4.3.3.3.3 Task 3—Verification. In order to ensure that all requirements and constraints are addressed, the verification activity is achieved with full cognizance of the appropriate groups as shown in table 3. Tests of the final (flight) configuration are accomplished to validate the already published aerodynamic parameters and determine the uncertainty associated with those parameters. Tests are also accomplished to determine parameters that are questionable and where the associated uncertainty is unknown.

After all testing is completed, the aerodynamic attributes (i.e., parameter matrix and associated uncertainties) are reassessed and refined. Then those results are informally integrated with the appropriate design functions. Subsequently, the results are formally submitted to the systems design function for final assessments and documentation. If there is conflict, it must be resolved at the system level. This could lead to a redesign or to an operational constraint. When all of the aforementioned is completed, the aerodynamic design database is augmented with all the newly acquired configuration dependent data.

The final validation is achieved during the developmental flight-test phase of the program. The flight-test data are compared to the aerodynamic attributes that are documented by the systems design function. If serious differences occur, there must be a redesign or an operational constraint must be enforced.

The tasks delineated in table 2 from reference 2 correspond to the discipline specific tasks associated with the aerodynamic design function. A comparison to table 3 indicates that the tasks are complementary. It can be seen from table 3 that the emphasis is associated with allocation of requirements, aerodynamic design, and verification; and these are design function specific activities.

System

Aerodynamics

Trajectory/G&N

Control

Structures

Thermal

Propulsion

Avionics

Materials

Manufacturing

Other
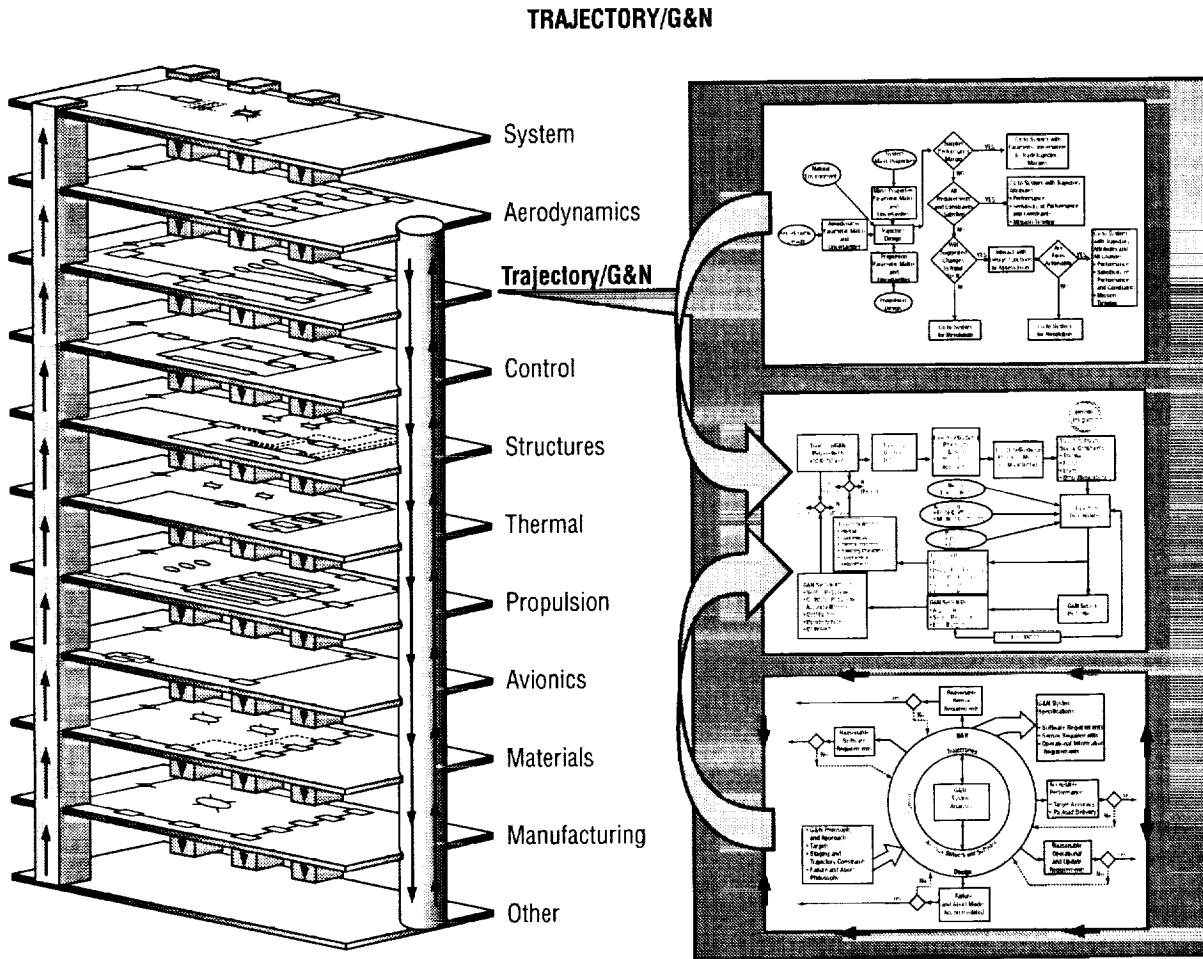
Figure 38. Design process technical integration—trajectory/G&N design functions.

4.3.4 Trajectory/G&N Design Functions

The connection between the design process technical integration and the trajectory/G&N design functions are delineated in figure 38. The illustration depicts the relationship between the trajectory/G&N design functions and the other subsystem design functions. In addition, it shows the work/information flow processes that are supported by key trajectory/G&N decision gates that are required to develop and assess the trajectory/G&N attributes. The details of all the above are delineated in this section.

4.3.4.1 Trajectory/G&N Design Function Plane. The trajectory/G&N disciplines closely interact, and their design functions are shown together in figure 39. Trajectory design in this description encompasses payload performance and includes the design activity that determines what basic vehicle mass and propulsion characteristics are needed to achieve the desired pounds to orbit. The fundamental performance requirements are payloads to specified orbital targets to which are added vehicle constraints such as limits on acceleration, loads, thermal, dynamic pressure (flutter), etc. The additional complication of abort targets, separation targets, or reentry/recovery targets must be included as intermediate points on the trajectory if the system requires them. An initial definition is made of the trajectory and guidance

approach, and the philosophy and pertinent parameters, including their uncertainties, are identified. Trajectory optimization programs are used to determine trajectories that optimize the appropriate objective function and constraints. Initially, this is done deterministically with simplified models to establish basic feasibility, then with increasing fidelity, incorporating appropriate parameter uncertainties. Moment balance constraints are included for asymmetrical configurations. In early conceptual design, trajectory determination uses simplified representations of propulsion, aerodynamics, mass, winds, and air density.
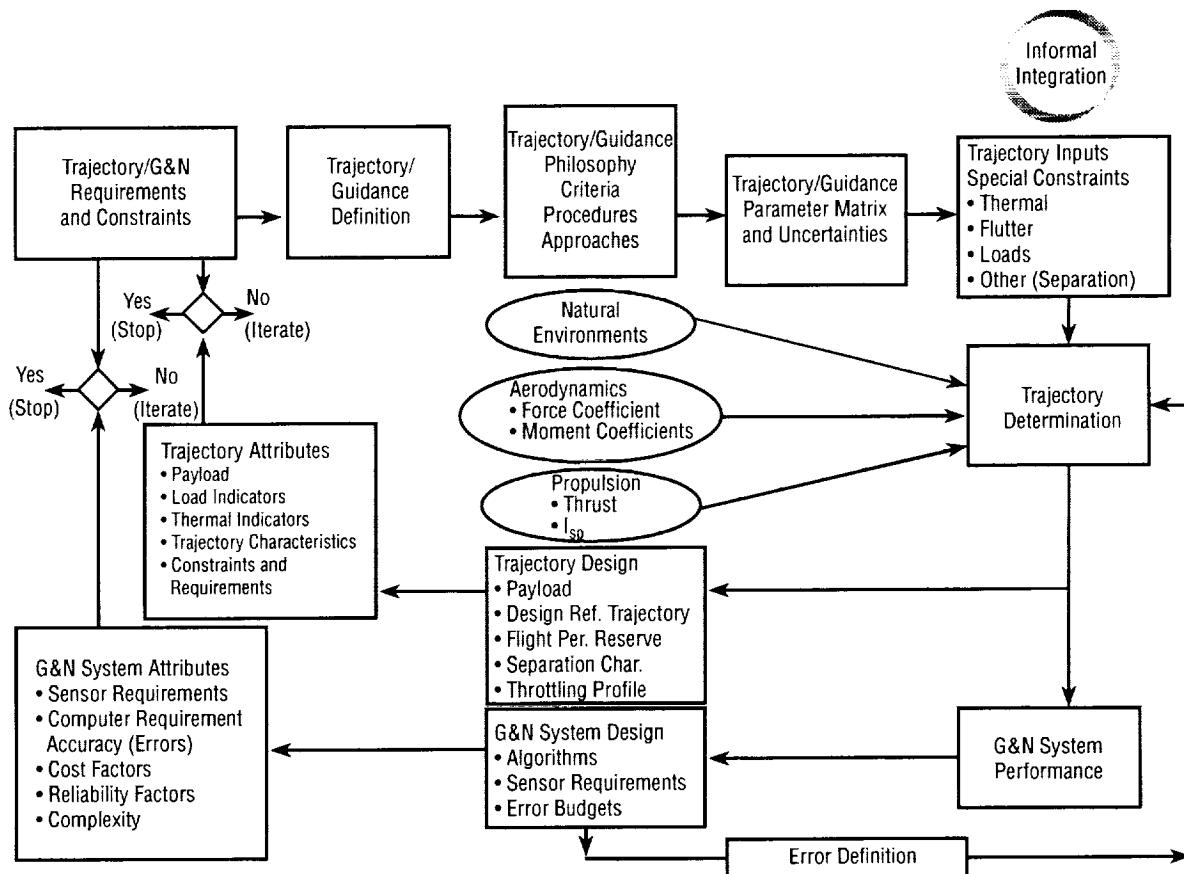
Figure 39. Trajectory/G&N design function plane.

Achieving desired payload to orbit with adequate performance reserves usually requires iteration of vehicle parameters with the system. The trajectory definition, constraints, and system parameters are iterated until the attributes are satisfactory. As the vehicle design process proceeds, trajectory design follows the successive refinement approach experienced by the other design functions and subsystems. It uses improved definitions of the vehicle and environment models to define trajectories (time histories of flight mechanics variables), performance, and performance reserves to higher fidelity. Both nominal trajectories and dispersed design trajectories are developed; the latter represent time-consistent trajectories that produce maximum expected values of certain variables such as loads or aerodynamic heating. Analysis using dispersions also produces performance sensitivities (partial derivatives), flight performance reserves, and fuel bias definition.

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The performance and trajectories process flow diagram and WBS task chart from reference 2 are reproduced in figure 40 and table 4, respectively. The process flow is consistent with the flow diagram of figure 39, with the former emphasizing inputs/outputs and connectivity, and the latter emphasizing the iterative comparison of requirements and attributes to achieve convergence. Outputs are indicated for payload performance and trajectory time histories, both nominal and dispersed. The NxN diagram of reference 2 (Appendix A) is representative of further delineation of the inputs and outputs associated with the performance and trajectories design function process. The tasks given on the WBS chart are expanded in more detail in section 4.3.4.3.
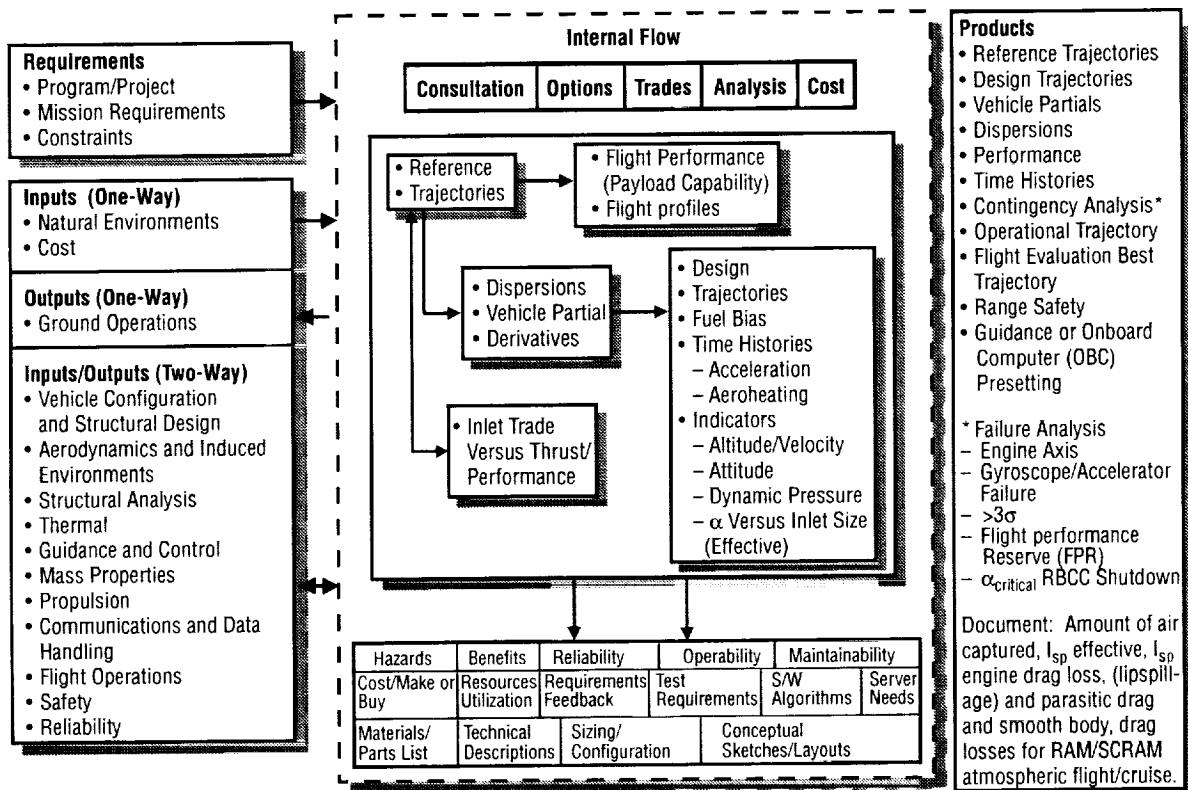
Figure 40. WBS 2.2—performance and trajectories design process flow diagram.[2]

The G&N system design follows a pattern more similar to other design functions in that a tentative G&N configuration is hypothesized and then analyzed to determine its performance. In specifying sensor and algorithm requirements, close coordination is maintained with avionics specialists to obtain adequate performance at acceptable cost and complexity. Uncertainties (errors) determined from the analysis are fed back to the trajectory analysis as inputs to margin and reserve determination. The tentative G&N system is iterated until its attributes satisfactorily meet requirements, or else requirements relief is sought from the system plane. G&N system analysis and design activities shown in figure 39 are combined with the control system activities in reference 2. The G&N process flow and WBS from reference 2, therefore, are included in the figures in section 4.3.5.1.

Table 4. WBS 2.2—vehicle performance and trajectories task description.[2]

Inputs	Tasks	Outputs
•Mission definitions •Initial performance •Vehicle coordination system •Launch pad geometry •Project ground rules and goals •Redundancy requests •Preliminary design concept and database •Range safety constraints •Atmospheric model •Ascent wind models •Launch pad environments •Engine alignment tolerances •••Vehicle geometry drawing •Vehicle ascent aerodynamics •Heating indicators ••Vehicle/stage entry aerodynamics •Engine inlet flow field definition •Engine installed thrust throughout trajectory •Qα, Qβ constraints and structural load indicators ••Wall/surface temperatures •Heating rate or temperature indicators •Autopilot definition •Guidance system inputs •••Modified autopilot to reflect a control law for airflow to inlet •Control surface mixing logic •Control weights and current weights	3.2.1 Perform trade studies on trajectory/ configuration options 3.2.2 Develop nominal trajectories 3.2.3 Develop design trajectories 3.2.4 Assess vehicle sizing, mass properties 3.2.5 Evaluate vehicle performance 3.2.6 Develop abort scenarios and trajectories Tools: • Software—Dynamic simulations, program to optimize simulated trajectories (POST)	•Staging requirements •Propellant requirements •Number of engines •Performance updates •Entry propellant weight •Ascent trajectory sets (altitude, velocity, X, β histories) and engine operating conditions ••Entry trajectories •••Airflow history to inlet •Trajectory constraints •••Mach transitions •Loads trajectory data •••Ascent, cruise, loading requirements •Reference trajectories and time histories •Max Q •••α, airflow •••Ascent, cruise, landing requirements •Propellant load versus time •Burn times •Residuals at main engine cutoff, etc. •Vehicle mass versus time •I_{sp} (flow rates) •Usable propellant requirements •Flow rates •System dispersions •••α inlet •••Derived air volume •Antenna range data •Launch mission rules •Vehicle breakup and disposal analysis •Launch commit criteria •Launch corridor •••Landing corridor •Abort alternate mission analyses •Event timelines

Key: • ELV, RLV, and RBCC
        •• RLV and RBCC
        ••• RBCC only

4.3.4.2 Trajectory Gates. Trajectory design is driven by top-level payload performance and targeting requirements, along with constraints which limit the acceptable trajectories to those satisfying assumed system limitations such as staging conditions, maximum dynamic pressure, maximum load or thermal indicators, abort targets, etc. Working with appropriate other disciplines, the trajectory designer identifies pertinent parameters and their uncertainties and produces optimal constrained trajectories, both nominal and dispersed, to identify the distributions of trajectory performance variables. The trajectory designers work closely with specialists from structures/mass properties, aerodynamics, and propulsion, especially in the early design stages to iterate the basic variables of the vehicle in order to attain performance requirements with acceptable margins, considering parameter variations. Trajectory decision gates are shown in figure 41. Indicated gates consider three possibilities: (1) Surplus performance margin (unlikely), where the system plane is provided the excess margin for other tradeoffs; (2) neither surplus nor shortfall, where performance, sensitivities, and timelines are provided to the system plane without further iteration;and (3) performance shortfall. In the third case, collaboration with the above design functions

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attempts to find an achievable fix for the problem within the respective requirements and constraints. If successful, an output like the second case is made, but, if unsuccessful, the issue goes to the system plane for relief or rebalance of requirements and constraints.
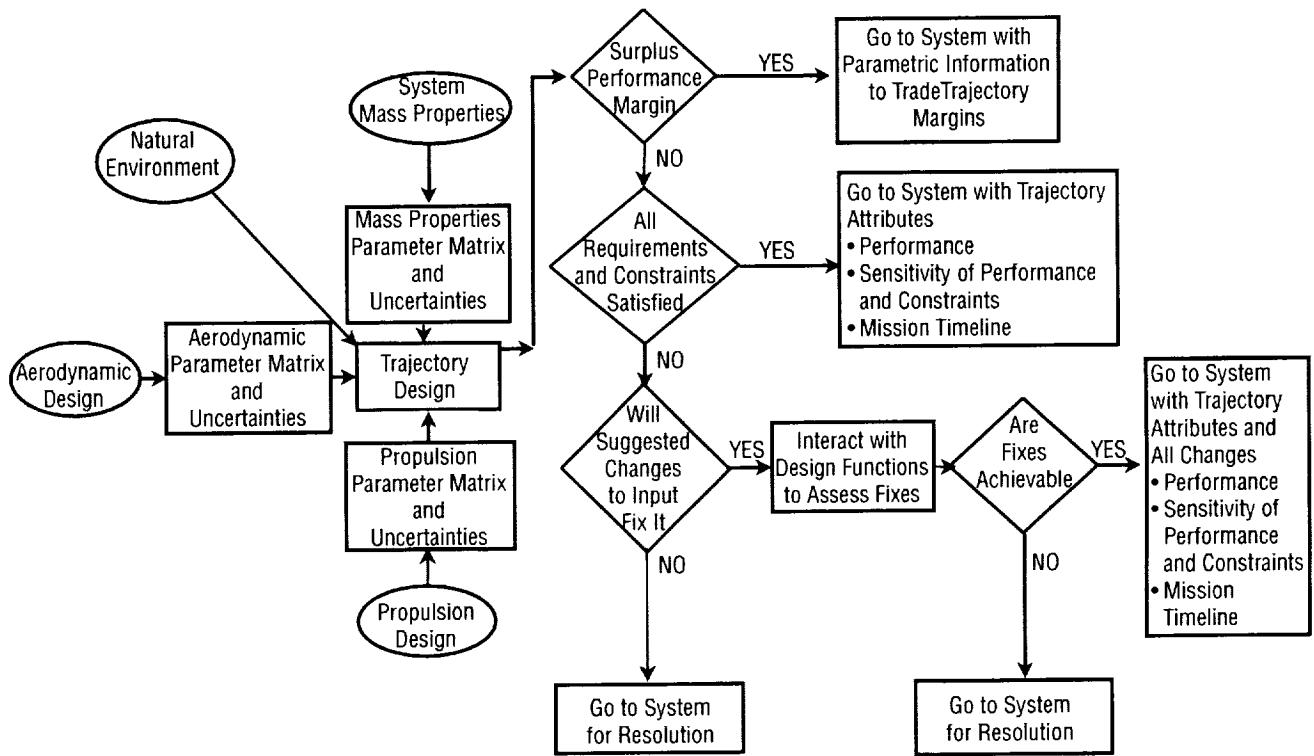
Figure 41. Trajectory design function gates.

4.3.4.3 Trajectory Tasks. The trajectory/performance design function is a part of the earliest conceptual feasibility activities. It iteratively matures its output through the design process and continues to perform mission-specific trajectory/performance determination in the operational phase. The primary responsibility is to determine the trajectory time histories that maximize payload performance subject to all pertinent constraints and to identify payload performance and margins, flight performance reserves, and fuel bias. The multiplicity of constraints on a typical launch vehicle that evolve concurrently with and as a part of design make trajectory design a highly interactive and iterative process. Task summaries are shown in table 5.

4.3.4.3.1 Task 1—Requirements Determination and Preliminary Performance Estimates. In the early part of conceptual design, the trajectory design function (referred to as "trajectory") is a central element of concept feasibility screening. Working as part of a small group, trajectory obtains the vehicle fundamental concept, operating philosophy (e.g., abort accommodation), top-level payload requirements, and constraints from the system plane. Initial estimates of weight, drag, thrust, I_{sp}, and any special environmental conditions are obtained from their respective design functions and disciplines. Using historical information, or by discussion with other disciplines, preliminary constraints are generated. Then, using

Table 5. Primary tasks for trajectory design functions.

Activities	Interactions	Tasks
1. Requirements determination and preliminary performance estimates	System Mass properties Propulsion Aerodynamics Natural environment	1. Obtain fundamental concept, operating philosophy (e.g., abort accommodation), and top-level payload requirement and constraints from system. 2. Obtain initial weight estimate, drag estimate, thrust and I_{sp} estimates, and any special environmental input from the respective design functions. 3. Run simplified trajectory program with initial inputs to obtain performance (including appropriate margins). 4. If desired performance not obtained, work with small group of representatives of other design functions to trade basic system descriptors (listed in item 2) to converge to a solution acceptable to all parties. 5. If trades are major, or if convergence cannot be attained, take trade information to system for decision or requirement/ constraint change.
2. Detailed payload performance determination	System Mass properties Propulsion Aerodynamics Thermal Natural environment	1. As concept matures, perform detailed trajectory simulation and payload determination, maintaining close coordination with pertinent other design functions. 2. Although information is more detailed and interaction somewhat more formal than activity 1, interact with other design functions on sensitivity and trade data to converge to acceptable solutions. 3. Interface with system to provide sensitivity, trade, and margin information for possible adjustments to requirements, constraints, and allocations.
3. Design reference trajectories	Aerodynamics Thermal Structures (loads) Natural environment	1. Obtain from thermal and loads disciplines indicator functions of trajectory variables, and calculate indicator values with each trajectory run within the trajectory/system/environment parameter space. 2. Work with each respective discipline to select its design reference trajectory from the total set, representing a time-consistent trajectory which maximizes the appropriate indicator. Provide these to the disciplines as analysis simplification tools. 3. Continue to consult with the disciplines as the design matures to make any necessary adjustments to the design reference trajectories.
4. Verification	System Aerodynamics Natural environment Propulsion Structures	1. Develop high-fidelity simulation to accommodate test-verified models. 2. Obtain test-verified models of major contributors to trajectory/ performance, such as propulsion system characteristics, structural mass, etc. 3. Using this simulation, verify trajectory design over range of expected parameters and conditions. 4. Obtain final verification from flight test.

these initial inputs with a quick turnaround program, estimated payload performance and margins are determined. If desired performance is not obtained, the trajectory design function works with other design functions and disciplines to trade basic system descriptors (the inputs listed above) to converge to a solution acceptable to all parties. If the trades are major or if convergence cannot be attained, trade information is provided to the system plane for screening decisions or revision to requirements/constraints.

4.3.4.3.2 Task 2—Detailed Payload Performance Determination. Similarly to other design functions, trajectory accommodates increasingly detailed descriptions of vehicle and environmental parameters as the design progresses. The vehicle and environmental models include nominal and dispersed (uncertainty) parameters obtained from the propulsion, structures, and aerodynamics planes, and from the natural environment group.

Likewise, performance requirements and system constraints are refined. The constraints which are imposed on trajectory shaping and engine throttling derive from numerous other disciplines and include—

- State vector orbital targets
- Intermediate staging states dictated by clearance, recovery, and disposal of stages
- Structural loads (represented by load indicators)
- Maximum dynamic pressure
- Maximum acceleration
- Aerosurface hinge moment limits
- Aeroheating (represented by thermal indicators)
- Abort targets and limits, if pertinent
- Communication and range safety constraints
- Etc.

Trajectory identifies and updates these constraints through interaction with the other respective design functions and disciplines.

Detailed trajectory optimization programs are used to determine trajectory and throttling time histories, payload performance, and flight performance reserves/fuel bias to accommodate variations in vehicle and environmental parameters. Sensitivity data are derived to guide trade studies and point the direction of design improvement. Informal trades are made among the design functions and disciplines to converge to acceptable solutions. The trajectory plane interfaces with the system plane to provide sensitivity, trade, and margin information for possible adjustments to requirements, constraints, and allocations.

A cycle is complete when trajectories, dispersions, and margins meeting requirements have been determined for a comprehensive set of constraints and vehicle/environmental parameter values with variations. Validity and appropriateness of the input data, constraint definition, and program fidelity should be queried and brought to satisfaction.

4.3.4.3.3 Task 3—Design Reference Trajectories. Design reference trajectories are generated as a means of simplifying the loads and thermal analysis/design process. Since it is impractical to include all statistically-varying parameters independently in loads and thermal analysis, it is useful to develop reference trajectories that represent the trajectory parameter set which maximizes (to a statistical measure) loads or aeroheating. These design reference trajectories then serve as nonlinear time-consistent bases for detailed loads or thermal analyses (usually linearized) that include the remaining larger set of additional parameter variations.

Trajectory obtains from the loads and aerothermal disciplines indicator functions of trajectory variables and calculates indicator values with each trajectory run within the trajectory/system/environment parameter space. Trajectory then works with each respective discipline to select its design reference trajectory from the total set to a suitable statistical measure. This provides the loads and aerothermal disciplines a time-consistent basis upon which to develop their maximum design cases, considering the large set of remaining variables. Although this approximate approach is used as an expedient for analysis, full-dimensional Monte Carlo check cases run in past programs have confirmed that the approximate approach achieved the desired statistical measure for the systems checked. As the design matures, trajectory continues to consult with the disciplines to make any updates or adjustments necessary to the design reference trajectories.

4.3.4.3.4 Task 4—Verification. Verification of the trajectory and performance design is accomplished with high-fidelity analytical simulations that make use of test-verified models of key components. For example, propulsion system characteristics derived from hot-fire testing and actual structural weights are used in the verification simulation where possible. The vehicle and its environment are modeled in as complete detail as practical. The combined simulation then is used to verify satisfactory trajectory design over the range of expected conditions and parameter variations. Flight test provides the final verification and performance capability.

4.3.4.4 G&N System Gates. In this document, the G&N design function is taken to be the G&N system design synthesis function, as distinct from the hardware/software design function which is assumed to be part of the avionics design function. G&N decision gates are illustrated in figure 42. Primary G&N system interfaces in the design process are with the trajectories, control, and avionics planes. (The avionics interface is for negotiating and specifying sensor and software requirements). G&N also works initially with the system plane to identify the requirements and philosophy which will be allocated from the system plane. Top-level requirements and philosophy as flowed down from the system plane are expanded with greater detail by the G&N specialists to provide the basis and starting point for G&N design. The design process involves the typical synthesize/analyze cycle. Outputs are the G&N system specifications, including algorithms and software requirements, sensor requirements, and operational information requirements; i.e., what mission-specific information will have to be loaded. Before providing the converged outputs, the design must meet the gates of acceptable performance (accuracy, payload delivered), accommodation of required failure and abort modes, and reasonableness of the requirements for sensors, software, and operational information. Close interaction with avionics specialists helps converge and assure the latter requirements are met.
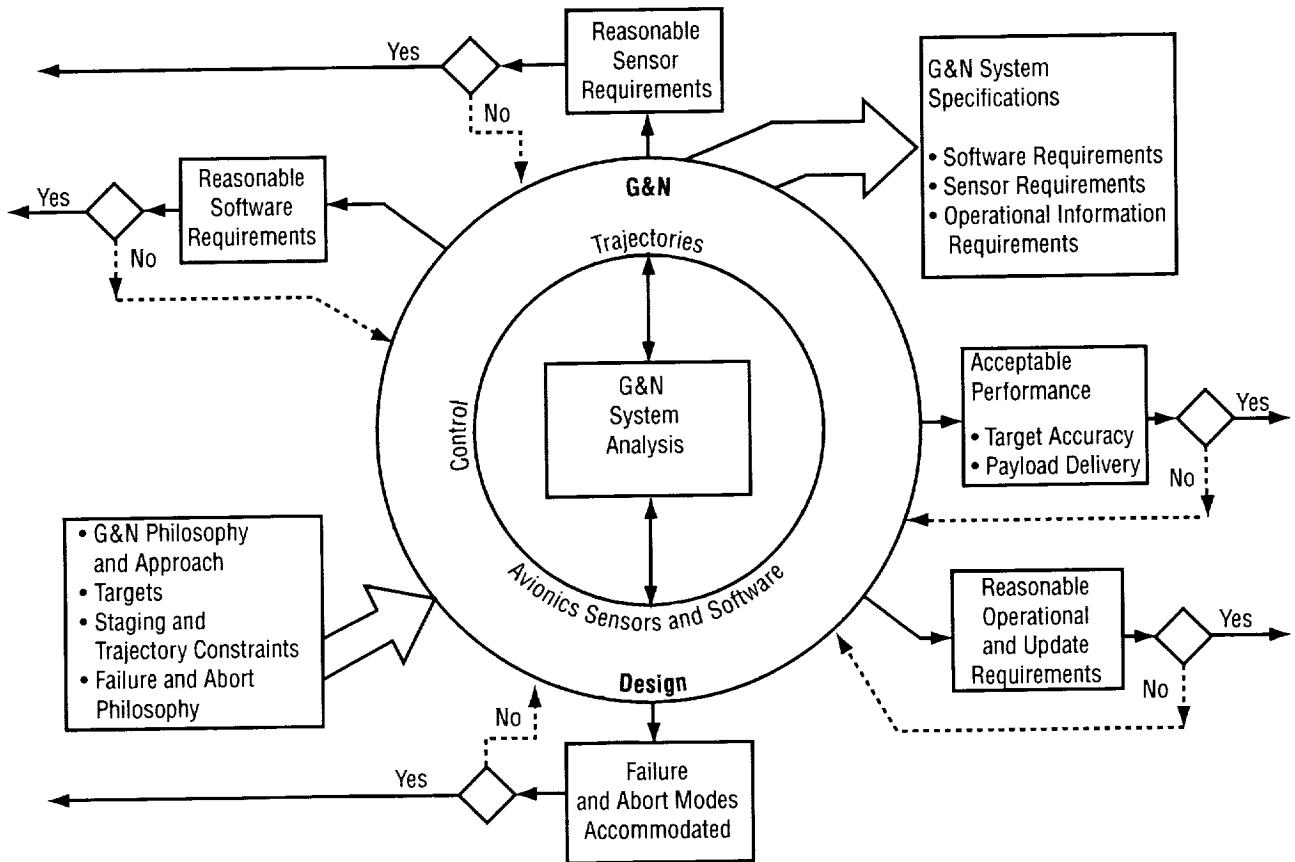
Figure 42. G&N design function gates.

4.3.4.5 G&N Tasks. Tasks for G&N are summarized in table 6. G&N synthesis requires interaction with the systems, trajectory, avionics, and control planes.

4.3.4.5.1 Task 1—Requirements Accommodation. G&N works closely with trajectory in determining target accuracy and payload performance margin requirements and capability. The potential target errors of the G&N system are provided to trajectory as part of the dispersion set that determines performance reserve margins. Stringent accuracy assumptions in this margin drive the G&N system cost and complexity. G&N synthesis balances these conditions to converge on the best design.

Constraints on the vehicle have a major effect on G&N design. For vehicles that require abort capability, abort modes are strong drivers. G&N works with the system and trajectory design functions to accommodate failure and abort modes. A constraint on maximum dynamic pressure may require throttling control that adapts to the specific state conditions. Constraints on the permitted range of engine throttling must be observed.

Another balance that must be achieved is G&N system performance versus the complexity of operational data loads and updates needed to attain the performance for the range of expected missions.

Table 6. Primary tasks for G&N function.

Activities	Interactions	Tasks
1. Requirements accommodation	Trajectory system	1. Work with trajectory in converging to accuracy and payload margin requirements and capability 2. Work with system and trajectory in accommodating constraints such as failure and abort modes, maximum dynamic pressure, etc. 3. With system, determine appropriate balance between performance and complexity of operational data loads and updates.
2. Detailed G&N system synthesis	System Trajectory Control Avionics	1. Perform iterative synthesis/analysis to best balance performance requirements with cost and operational considerations. 2. Maintain close coordination with system and trajectory as requirements mature, with control to define initiation state requirements and to coordinate flight control computer interactions, and avionics for software/hardware requirements (see below). 3. Iterate to satisfaction of requirements and constraints with an adequate balance of performance and cost/complexity.
3. Component and software requirements	Avionics Trajectory System	1. Maintain close working relationship with avionics to keep abreast of hardware/software state of the art. 2. During G&N system synthesis, work with avionics in specifying component and software requirements to provide acceptable performance, cost, complexity, reliability, operability, and maintainability. 3. If performance cannot be achieved with hardware and software that meet avionics attribute allocations, explore performance requirement relief with trajectory and systems. 4. If resolution not obtained, take to system for top-level trades.
4. Verification	Avionics Control Trajectory Propulsion System	1. Develop high-fidelity analytical simulations, modeling system and environment. 2. Using simulation, verify G&N performance over full range of parameter and environment variations. 3. Work with avionics to perform software verify and validate (v&v) and to verify G&N performance in hardware/software test beds. 4. Obtain final verification from flight test.

4.3.4.5.2 Task 2—Detailed G&N System Synthesis. The core activity of the G&N design function is to synthesize a G&N system architecture that best meets the vehicle requirements while satisfying interfacing constraints. It is not the intent of this report to describe in detail the process used by G&N specialists to accomplish this, but to note primary considerations and interactions.

The process is the usual iterative synthesis/analysis cycle, directed toward best balancing the performance requirements with cost and operational considerations. Throughout the process, close coordination is required with the system and trajectory planes as described above, with the control plane to define guidance initiation state requirements and coordinate flight computer cycle requirements, and with the avionics plane for software/hardware requirements as noted below.

Where data and programs have been subjected to critical assessment, satisfaction of requirements and constraints and an adequate balance of performance and cost/complexity determine adequacy of the detailed design.

4.3.4.5.3 Task 3—Component and Software Requirements. One of the main outputs of the G&N design function is a converged set of requirements for G&N sensors and algorithm software which is provided to the avionics plane. Before and during the design process, G&N specialists maintain a close relationship with hardware and software specialists in avionics in order to keep abreast of the state of the art and capability. During system synthesis, G&N works very closely with avionics to specify component and software requirements which both meet system performance requirements and represent acceptable cost, complexity, reliability, operability, and maintainability. The latter set of requirements is captured in the system allocation of requirements to the avionics plane.

If performance cannot be achieved with component hardware and software that meets the avionics plane allocations, G&N explores performance requirement relief with the trajectory design function. If resolution is not obtained, the issue is taken to the system plane for top-level trades or requirements revision.

The process is complete when the sensor component and algorithm software requirements satisfy both the G&N system performance requirements (imposed on G&N) and the cost, reliability, operability, and maintainability requirements allocated to the avionics plane.

4.3.4.5.4 Task 4—Verification. Verification of the G&N system is accomplished primarily with analytical simulations, as augmented with the use of test beds involving flight-type hardware and software. High-fidelity analytical simulations are generated to model the G&N system along with the vehicle and its environment in as complete detail as practical. The combined simulation is run using the full range of expected parameter variations to ensure that satisfactory performance is attained at all operating conditions and system variations. Avionics test beds use flight-type hardware and software with simulated vehicle aspects to confirm the correct functioning of the G&N system as implemented physically (as discussed in the avionics section). Finally, flight test provides the final verification.

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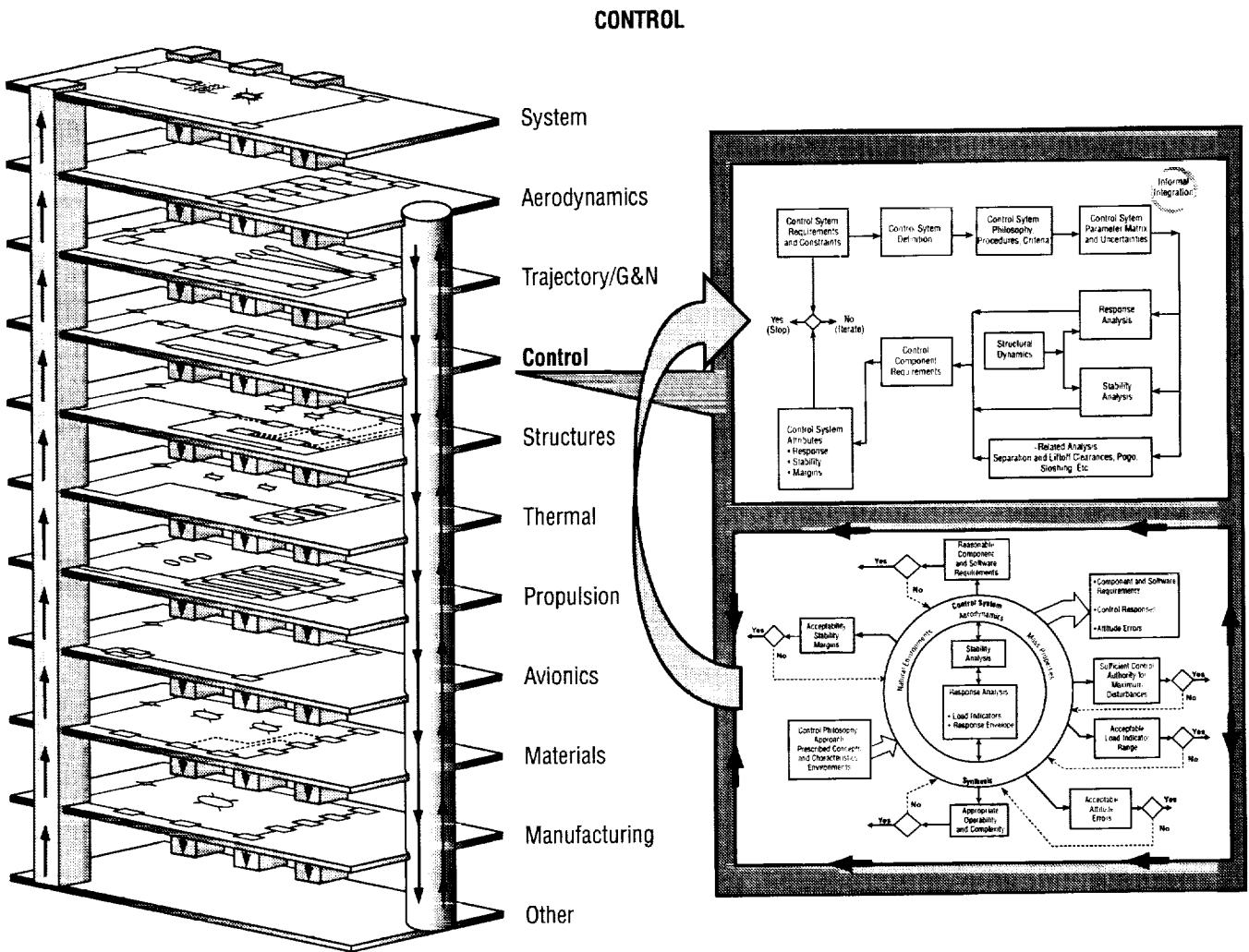
Figure 43. Design process technical integration—control design function.

4.3.5 Control Design Function

As shown in figure 43, the connection between the design process technical integration and the control design function is shown. The illustration depicts the relationship between the control design function and the other subsystem design functions. In addition, it shows the work/information flow process that is supported by key control decision gates that are required to develop and assess the control attributes. The details of the above are delineated in this section.

4.3.5.1 Control Design Function Plane. The control design function as represented on the control plane is illustrated in figure 44. The control design function involves the synthesis of the vehicle control system, specification of the control component requirements, and necessary interactions with other design functions and disciplines. Also involved is determination of vehicular dynamic response and the associated design parameters, including studies of lift-off and separation clearances, pogo, sloshing, etc. First, the requirements and constraints are interpreted into a form applicable to the control system. From experience,

a tentative control system configuration is defined, along with the philosophy, procedures, and criteria that will be employed. The control specialists then identify the matrix of parameters affecting the control system and together with specialists from other disciplines identify by data or judgment the variations (uncertainty distributions) of the parameters. Nominal and dispersed stability and response analyses are run to assess the performance of the tentative design. In some cases, such as structural loads, the acceptability of the performance is determined initially by load indicators, but final acceptability of the refined design is determined on the structures plane.
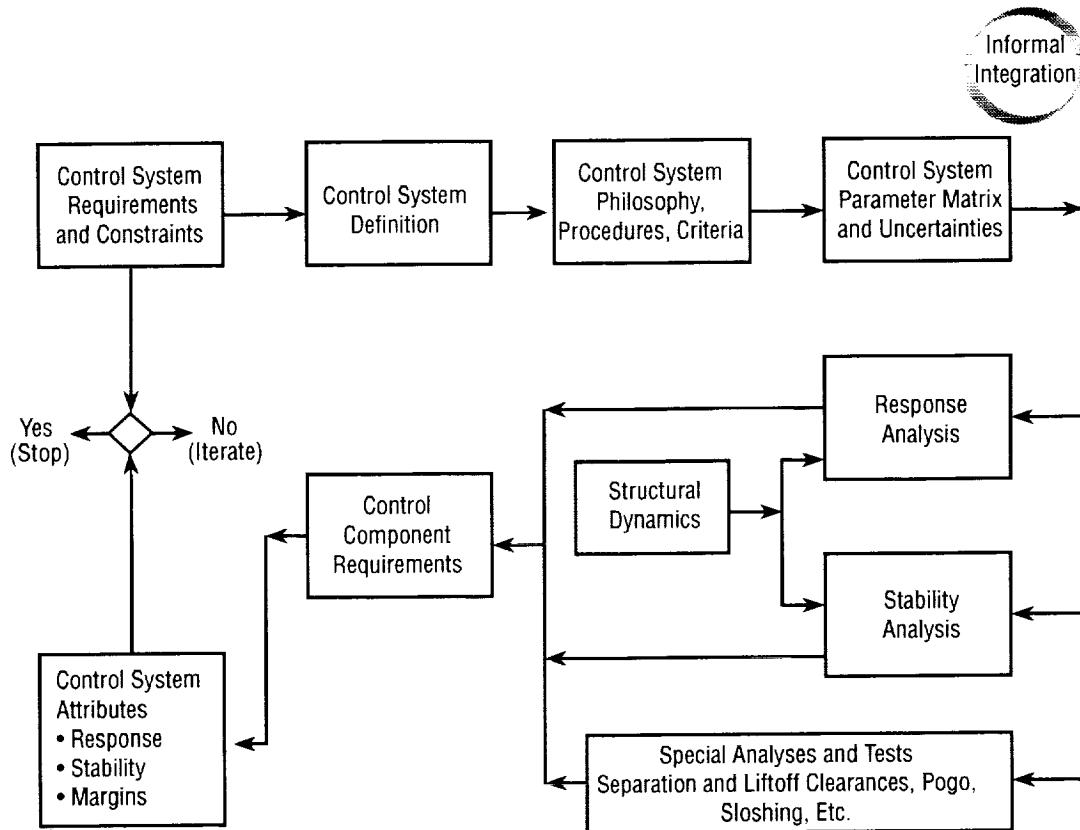
Figure 44. Control design function plane.

Structural dynamics are shown on the diagram as a particularly significant input to the control analyses, but also other design functions and disciplines such as aerodynamics, trajectories, and propulsion are important interactors with control. A close relationship is necessary with the avionics and propulsion design functions that have the responsibility for the control system component hardware and software. The eventual specification of control system component requirements evolves from this close interaction and influences the cost, reliability, and operability attributes of the avionics and propulsion planes. Thus while response, stability, and margins are shown as the control system plane attributes, the attributes of control component cost, reliability, etc., on the avionics and propulsion planes are determined by the control component requirements as converged between the control system specialists and the avionics/propulsion specialists. The tentative control system design is iterated until its attributes meet the requirements and constraints, or relief from requirements is sought from the system plane.

In reference 2, the guidance and control functions are shown combined. The process flow diagram and WBS task chart from reference 2 are reproduced in figure 45 and table 7, respectively. The process flow is consistent with the flow diagram of the control plane, with the former emphasizing inputs/outputs and connectivity, and the latter emphasizing the iterative comparison of requirements and attributes to achieve convergence. The N×N diagram of reference 2 (app. A) is representative of further delineation of the inputs and outputs associated with the control design function. The tasks given on the WBS chart are expanded in more detail in section 4.3.5.4.

As will be addressed later, additional activities of the control design function are to specify design aspects necessary to ensure adequate lift-off and separation clearances, pogo stability, and propellant slosh stability.
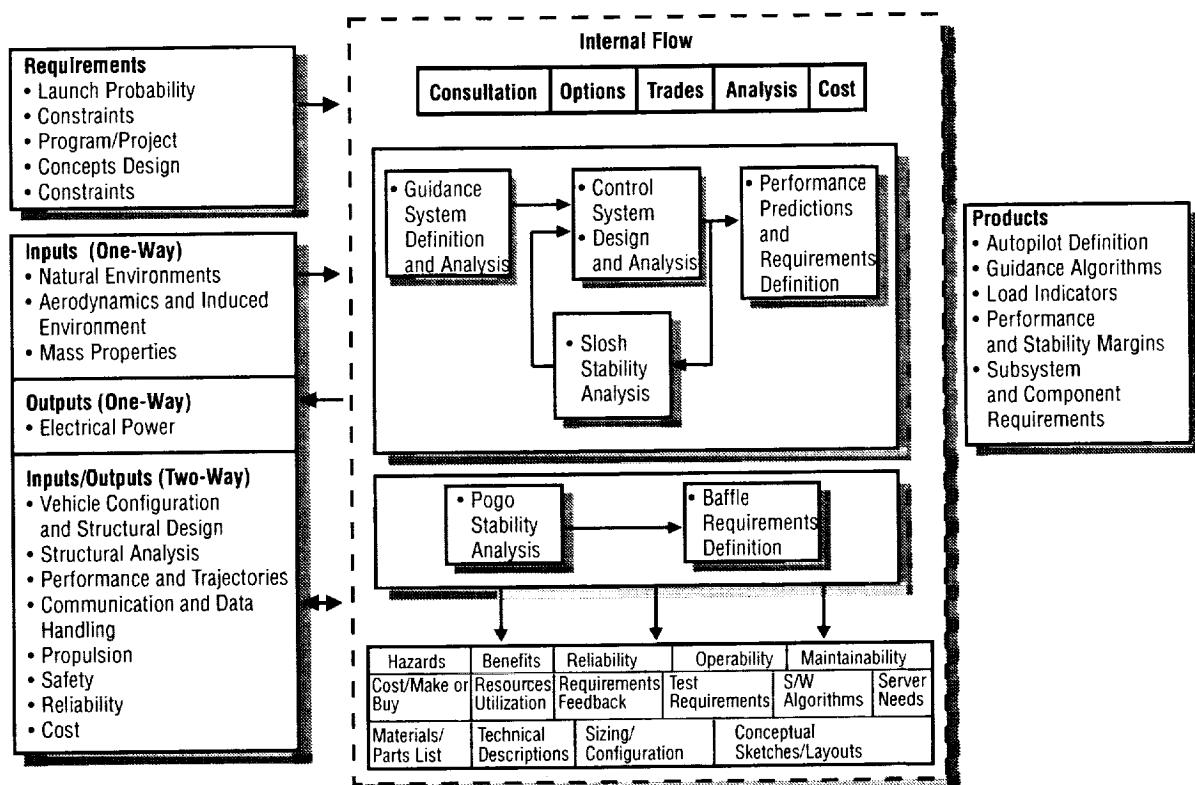
Figure 45. WBS 2.6—guidance and control design process flow diagram.[2]

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Table 7. WBS 3.6.0—guidance and control task description.[2]

Inputs	Tasks	Outputs
•Projected ground rules •Design-to-cost goals •Launch probability requirements •Preliminary design concept and data base •Atmospheric model •Wind models (ground/ascent) •Gust models •Launch pad environments •Overall vehicle dimension •Engine alignment tolerance •Feedline drawings •Vehicle aerodynamics •Guidance and control instrumentation locations •Vehicle flex-body modes •Propellant slosh modes •Propellant feedline flex modes •Qα, Qβ and structural load constraints •Mass properties control plan •Documented control weights •Weights, centers of gravity, moments of inertia •Mass versus time •Thrust vector control (TVC) gimbal capability (degree and rates) •Kinematic analysis •PU system definition •••Inlet airflow constraints for ascent, cruise, and landing •••Air capture transition •Sensor characteristics •Computational characteristics •Antenna types and locations •Hazard analysis •Fault tolerance requirements •Failure mode effects analysis inputs •••CIL inputs •Hardware design, development, testing, evaluation, and production costs •Cost trades	3.7.1 Develop flight guidance and control system strategies 3.7.2 Derive subsystem/component requirements 3.7.3 Determine system performance/margins 3.7.4 Determine induced environments Tools: • General purpose simulations and control system analysis packages such as Matlab and Marshall Systems for Aerospace Simulation (MARSYAS)	•Maximum engine deflection •Control sensor locations •Control surface deflection requirements •Autopilot definition •Guidance system inputs •••Modified autopilot to reflect a control law for airflow to inlet •Control surface mixing logic •Slosh damping requirements •Qα versus Qβ envelopes •Flex-body mode frequency constraints •Vehicle transient response to wind disturbances •Pogo suppressor requirements •TVC requirements •Reaction control system (RCS) requirements •Software requirements •Computer requirements •Sensor requirements •Power requirements for control system •Diagnostics/control logic •Technical descriptions •Test requirements to include instrumentation •Product quantities •Make or buy plan

Key: • ELV, RLV, and RBCC
•• RLV and RBCC
••• RBCC only

4.3.5.2 Control System Gates. Decision gates for the control system design process are shown in figure 46. The control system synthesis process is accomplished by control systems specialists in concert with specialists from aerodynamics, structures, trajectory/G&N, avionics, and propulsion. Inputs to the process include the control philosophy and approach, allocated architecture (concepts and characteristics), and the expected environments. Stability analyses and response analyses are used to determine the performance of synthesized designs. Output of the process is the control system description, component and software requirements for the avionics group, control responses for the loads group and others, and attitude errors for the G&N group. Before a converged set of outputs are made, the control design must pass the gates of acceptable stability margins, sufficient control authority for maximum disturbances, acceptable load indicator ranges, acceptable attitude errors, operability and complexity appropriate to the system, and reasonable component and software requirements. Threshold levels for these gates are determined in collaboration with other disciplines as appropriate. The control design is iterated until the gates can be passed successfully, which is represented in summary on the control plane by the control attributes meeting the control requirements and constraints.
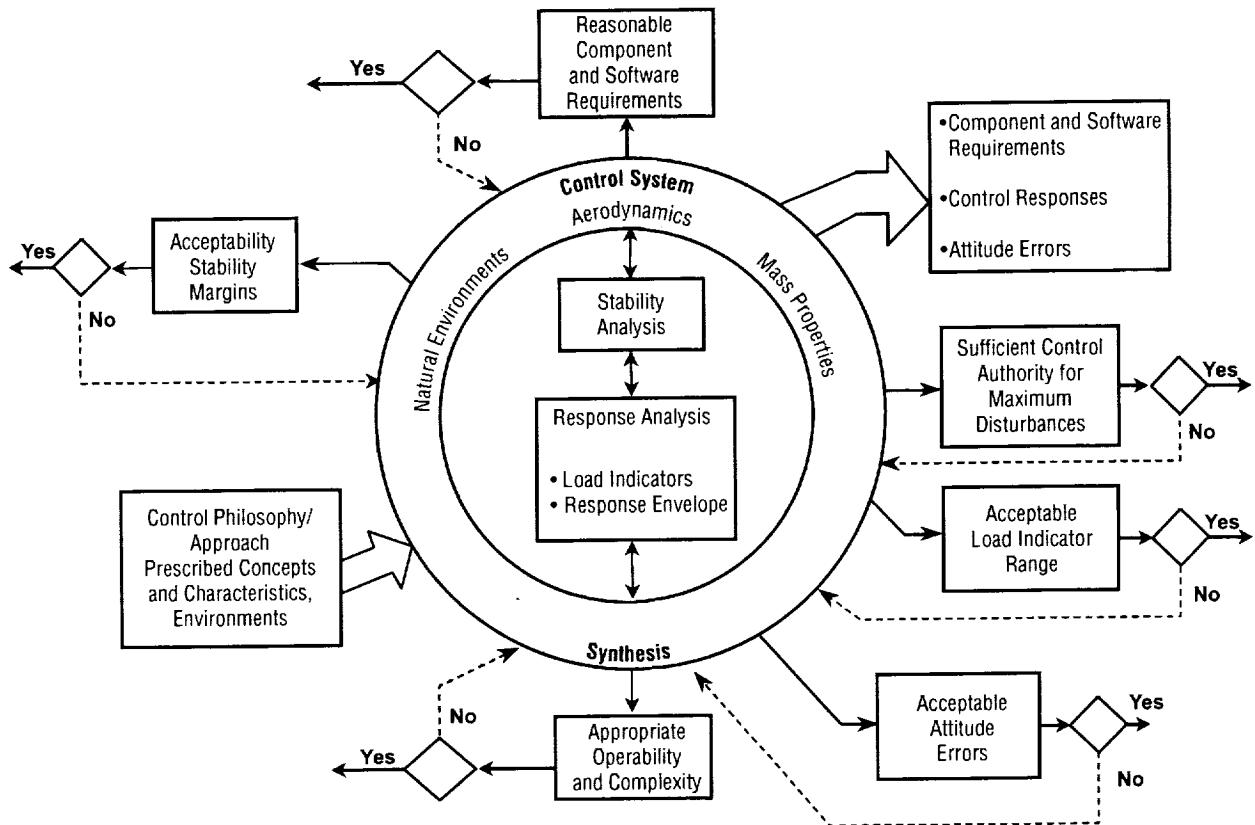
Figure 46. Control design function gates.

Pogo stability is assured by performing stability analyses of the engine/feedline/tank/structural system and specifying requirements for Pogo suppressors if needed to achieve adequate stability margins. Therefore, the Pogo gate (not specifically shown on the figure) is adequate Pogo stability margins.

4.3.5.3 Separation System and Lift-off Clearance Gates. Separation and lift-off clearance analysis and design is an adjunct to control system design and extends to the design of the separation system or, for lift-off clearance, potentially to specification or modification of the launch pad interface (see fig. 47). Dynamic clearance analyses are conducted for tentative separation system designs with pertinent vehicle and environmental inputs. Appropriately, extreme disturbances and parameter variations must be incorporated into the analyses. Separation system decision gates include adequate separation clearance margins and reasonable separation system component requirements at acceptable reliability and cost. When the design converges to meet these gates, the separation system specifications/drawings can be finalized.

Lift-off clearance assurance is obtained through determining adequate lift-off clearance margins by dynamic clearance analysis. This analysis must include appropriately extreme disturbances and parameter uncertainties. Inadequate clearance margins require iterating on the independent variables, predominantly the launch pad interfaces.
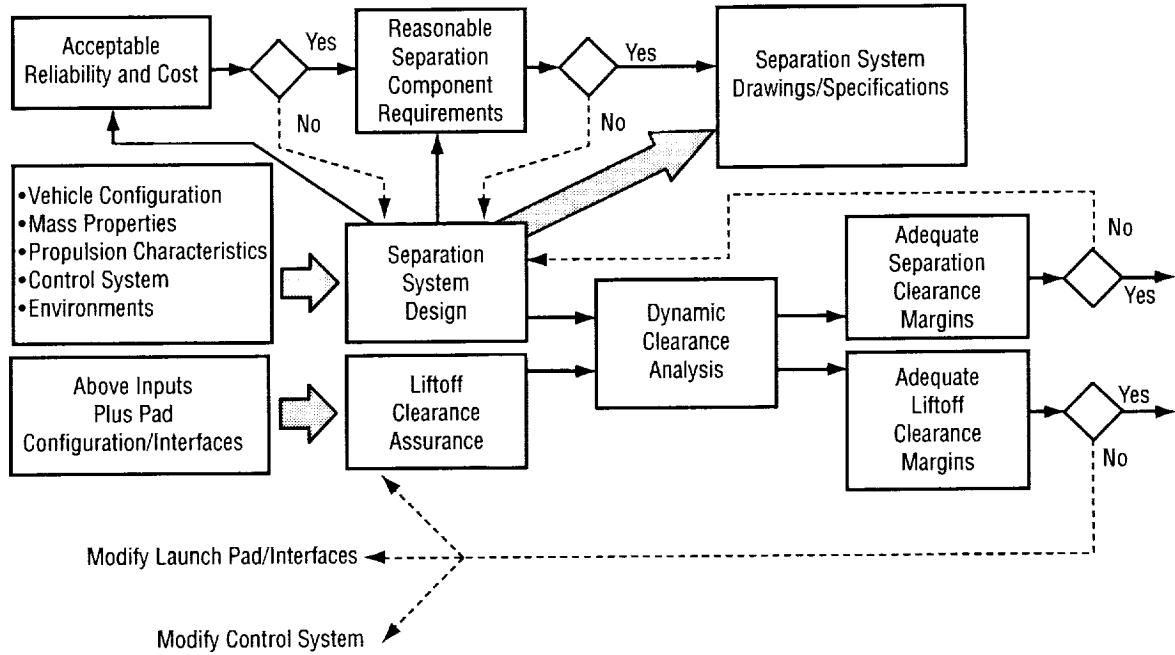
Figure 47. Separation system and clearance gates.

4.3.5.4 Control Tasks. In this report, the control design function is taken to be the control system synthesis function, as distinct from the control hardware/software function which is assumed to be part of the avionics and propulsion design functions. It is assumed that the avionics design function has responsibility for sensors, computers, and software, and that the propulsion design function has responsibility for control effectors; i.e., actuators, reaction control systems (RCS) thrusters, and valving for differential throttling or secondary injection. As will be noted, a very close working relationship must be maintained between the control design function and these two hardware/software design functions in order to achieve a successful design. The main control activities in design are summarized in table 8 and are given below.

4.3.5.4.1 Task 1—Requirements Determination and Allocation. Requirements allocation is a joint responsibility between the system plane, the control plane, and the avionics and propulsion planes. Control and avionics/propulsion planes consult with the system plane in identifying and flowing down the initial requirements to which the control system must be designed. Avionics and propulsion are the design functions for the control system hardware/software and, therefore, are the keepers of the requirements for cost, reliability, maintainability, power usage, etc. Control is the control system design function and, therefore, is the keeper of the requirements for control system configuration and performance. Most of the top-level requirements that are allocated by the system plane fall in the former category (imposed on the avionics and propulsion planes), whereas the requirement imposed on the control plane is to deliver acceptable control performance for the vehicle. Acceptable control performance means acceptable stability, attitude errors, load responses, lift-off and separation clearances, etc. These are requirements that must be given definition by the control design function and are quantified by working interactively with the other design functions.

As the design progresses, if the control system attributes do not meet the requirements and informal iteration among the design functions and disciplines cannot resolve the problem, the attributes and sensitivities are fed back to the systems plane for trades and possible revision of the requirements allocation.

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Table 8. Primary tasks for control system design function.

Activities	Interactions	Tasks
1. Requirements determination and allocation	System Avionics	1. Consult with system to aid in initial requirements allocation. 2. Feed back attributes to system. Provide trade data and consultation for revised allocation if required.
2. Control authority	Trajectory Guidance Aerodynamics Propulsion Natural environment Structural configuration Avionics System	1. Determine wind, trajectory, and thrust disturbances with natural environments and propulsion. 2. Consult with trajectory/guidance to determine acceptable response excursions. 3. Consult with avionics/propulsion/structures to determine reasonable control effector authority limits or trades. 4. For specified control concept and configuration, simulate with appropriate disturbance inputs to determine response excursions as functions of control authority. 5. If response excursions and/or control authority are not acceptable, perform trades in concert with aerodynamics and configuration to improve conditions. Alternatively, revisit items 2 and 3 above. 6. If issues resolved among participants, send attribute and configuration information to system. 7. If issues not resolved, take to system for top-level tradeoffs.
3. Detail control system syntheses	System Trajectory Guidance Structures Propulsion Aerodynamics Avionics	1. Collect and derive requirements from system and interfacing design functions, along with internal design criteria. 2. Perform iterative synthesis/analysis with increasing fidelity, directed toward meeting requirements, constraints, and criteria while balancing performance with cost and complexity 3. Work informally with other design functions to resolve conflicting requirements. If resolution is not obtained, take to system for top-level trades. 4. In addition to synthesized control system design, provide load indicator responses, providing load relief design if required. 5. Interactively determine slosh baffle requirements. 6. Using clearance analysis, determine separation system requirements and launch facility geometrical constraints.
4. Component and software requirements	Avionics Structures Trajectory/Guidance System	1. Maintain close working relationship with avionics to keep abreast of hardware/software state of the art. 2. During control system syntheses, work with avionics in specifying component and software requirements, to provide acceptable performance, cost, complexity, reliability, operability, and maintainability. 3. If performance cannot be achieved with hardware and software that meet avionics attribute allocations, explore performance requirement relief with structures (load indicators) and trajectory/guidance (attitude errors).
5. Verification	Avionics G&N Propulsion System	1. Develop high-fidelity analytical simulations. 2. Using simulation, verify system performance over full range of parameter and environment variations. 3. Work with avionics to perform software v&v and verify control performance in hardware/software test beds. 4. Verify separation and clearance margins using high-fidelity response analysis, incorporating any available test-verified component models. 5. Verify Pogo stability margins analytically, using test-anchored dynamic models of propulsion system and structure. 6. Damping performance of the Pogo suppression system may be confirmed by pulsing during hot firing tests, with and without the suppressor.

4.3.5.4.2 Task 2—Control Authority. An important early activity is sizing the control effectors for sufficient control authority. Effectors are the devices that cause force or torque to be applied to control the vehicle. Effectors may be engine gimbal actuators, aerodynamic control surfaces, engine differential throttling, etc. The range (or existence) of control capability in these effectors needs to be determined early in the cycle since it can have significant effects on the total design. Also, the rate capability of the effector is an important variable.

Working with natural environments and the propulsion plane, control determines maximum wind, trajectory, and thrust disturbances and their appropriate statistical combination to provide a design disturbance set. Vehicle mass and aerodynamics data are obtained from their respective disciplines, along with uncertainties in these parameters. (Note: Historically, problems have occurred in this area. Adequate definition of parameter uncertainties is critical.) Control consults with trajectory and guidance design functions to determine maximum response excursions acceptable to those functions. Control also works with hardware-responsible personnel from the propulsion design function and, in the case of aerodynamic surfaces, aerodynamics/structures design functions to obtain reasonable effector authority range and rate limits and the relationship of authority/rate values to hardware cost and complexity. (In very early design stages, control personnel may make preliminary control authority assessments based on their historical knowledge of the above variables.)

A control system architecture is hypothesized and simulated with the above disturbances and parameter variations to determine response excursions as a function of control effector authority and rate. If response excursions and/or control effector authority/rate are not acceptable, trades are performed in concert with the aerodynamics, structures, and propulsion planes to improve the conditions. Alternatively, the response excursions and effector authority/rate definitions described above may be revisited. If issues are resolved informally among the participants, the control attribute and configuration information is sent to the system plane. If the issues are not resolved, they are taken to the system plane for top-level tradeoffs, reconfiguration, or requirements revision.

When is the control authority determination adequately addressed? At each design cycle, there must be satisfactory definition of inputs, parameters, and their uncertainties. For example, aerodynamic data should have realistically sufficient uncertainties identified based on the data source (analytical, database, wind tunnel tests, etc.) The simulation model should be of appropriate fidelity, including allowances for response lags and unmodeled effects in the system. Margins or headroom should be provided, their magnitude being a function of the fidelity of the configuration definition and simulation. The margins will decrease as the design converges to better definition. For a given design cycle, control authority determination has been adequately addressed when effector authority/rate capabilities which are reasonable in terms of cost and complexity produce acceptable response excursions, while considering, and this is key, uncertainties and margins appropriate to the fidelity of the models.

4.3.5.4.3 Task 3—Detailed Control System Synthesis. The core activity of the control plane is to synthesize a control system architecture that best meets the vehicle requirements while satisfying interfacing constraints. It is not the intent of this document to describe in detail the process used by control specialists to accomplish this, but to note primary considerations and interactions.

In addition to those requirements imposed by the system plane and those derived from interfacing design functions and disciplines, control uses informal design criteria (for example, phase and gain margins) which have the intent of assuring satisfactory stability and response. Input to the process includes the information noted in Task 2 from other design functions and disciplines, plus detailed sensor and actuator characteristics, structural dynamic modes, slosh dynamics, and engine dynamics. The process uses iterative synthesis/analysis with simulations of increasing fidelity as the design cycles progress.

Typically, analyses and simulations are done on multiuse dynamics and control software (e.g., MARSYAS, Matlab, etc.) that accommodates a variety of system models. As the design progresses through finer definition, the model of the vehicle dynamics is expanded to include higher frequency structural modes and slosh modes. The model of the control system component dynamics is expanded to include higher order effects and nonlinearities. These models are used in stability and response analyses to assess the performance of the synthesized control system design.

Wind disturbances may be represented in very early design stages by synthetic wind profiles that have been constructed to represent a high wind or design disturbance. Subsequently, sets of measured winds are used in Monte Carlo analyses to determine the system response in a probabilistic sense.

Along with satisfying internal and external requirements and criteria, the control system design produces load indicator responses to disturbances and dispersions, configuring the system to provide load relief if necessary. Also, it interactively determines slosh baffle requirements and through clearance analyses determines separation system requirements and launch facility geometrical constraints.

Again, adequacy of the detailed design is determined by satisfaction of requirements and adequate margins, where the input and simulation data and its uncertainties have been subjected to critical assessment.

4.3.5.4.4 Task 4—Component and Software Requirements. One of the main outputs of the control plane is a converged set of requirements for control components and software that is provided to the avionics and propulsion planes. Before and during the design process, control specialists maintain a close relationship with hardware and software specialists in avionics and propulsion to keep abreast of the state of the art and capability. During control system synthesis, control works very closely with the avionics and propulsion planes to specify component and software requirements that both meet system performance requirements and represent acceptable cost, complexity, reliability, operability, and maintainability. The latter set of requirements is captured in the system plane allocation of requirements to the avionics and propulsion planes.

If performance cannot be achieved with component hardware and software that meets the avionics and propulsion plane allocations, control explores performance requirement relief with the structures plane (load indicators) and the trajectory/guidance plane (attitude errors). If resolution is not obtained, the issue is taken to the system plane for top-level trades or requirements revision.

The process is complete when the component and software requirements satisfy both the control system performance requirements (imposed on the control plane) and the cost, reliability, operability, and maintainability requirements allocated to the avionics and propulsion planes. Again, appropriate allowances for uncertainties and margins must be included.

4.3.5.4.5 Task 5—Verification. Verification of the control system is accomplished primarily with simulations of two types: (1) Analytical simulations and (2) test beds. High-fidelity analytical simulations are generated to model the control system and the vehicle/environment in as complete detail as practical. The combined simulation is run using the full range of expected parameter variations to ensure that satisfactory performance is attained at all operating conditions and system variations. Avionics test beds use flight-type hardware and software with simulated vehicle aspects to confirm the correct functioning of the control system as implemented physically, as discussed in the avionics section.

Verification of lift-off and separation clearance is done in analytical simulations. Since this can only be done analytically, it is important that sufficient margins are maintained. Pogo stability verification also is done by analysis, using test-anchored dynamic models of the engine and structure. Pogo pulsing during engine hot-fire tests can be used to obtain engine dynamic response information and to show the damping effect of adding Pogo suppression systems. Sloshing and flexible-body stabilization are verified by the best-available analytical models but are not fully validated until flight.
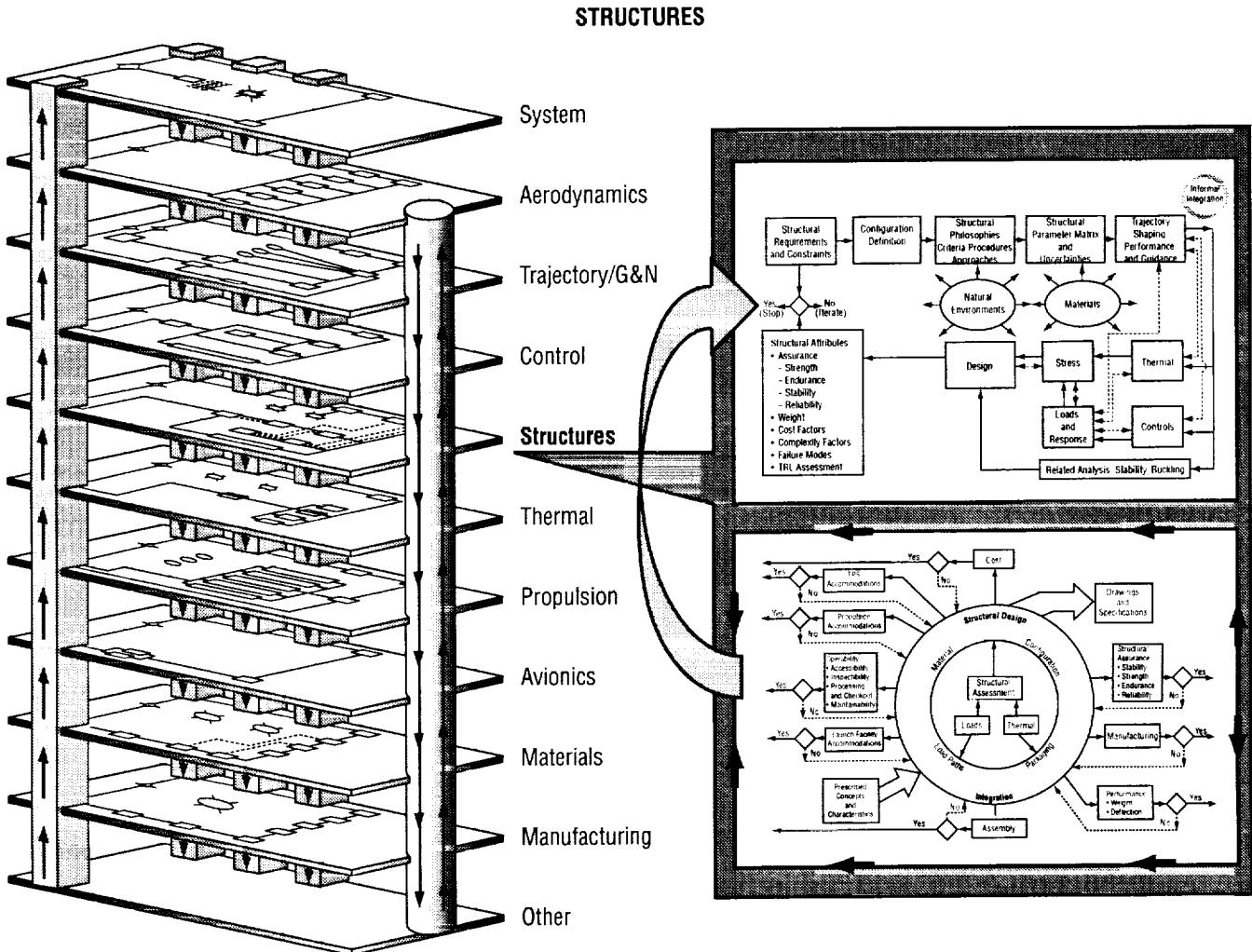
Figure 48. Design process technical integration—structure design function.

4.3.6 Structures Design Function

The connection between the design process technical integration and the structures design function is delineated in figure 48. The illustration depicts the relationship between the structures design function and the other design functions. In addition, it shows the work/information flow process that is supported by key structural decision gates that are required to develop and assess the structures attributes. The details of all the above are delineated in this section.

The structures design function is defined as any design activity involving structural subsystems; e.g., tanks, interstages, thrust frames, lines, ducts, components, etc., and finally the total structural system (vehicle).

4.3.6.1 Structures Design Function Plane. The structures plane in figure 49 shows the information flow among discipline functions required to accomplish the structures system design. The output of this plane is the structures' design and its various attributes. The flow diagram starts with the requirements and the initial configuration, moves through the definition of philosophies, criteria, procedures, and approaches, then establishes the parameters and their uncertainties. The next blocks are the discipline functions which interact with the structural analysis to provide the structural design data. Included are the trajectory, controls, and thermal disciplines. Inputs to the discipline tasks are compatible data inputs from natural environments and materials. The structural analysis discipline functions are loads and response, stress, stability, buckling, etc. All these discipline functions culminate in the structural design discipline which produces the structural design. The discipline functions in conjunction with the design function are fundamental in defining the structural attributes. The integration of the tasks is performed using inputs and outputs from one discipline to the other, as discussed in the following sections. The tasks performed on the structures plane produce results which must be passed through a prescribed set of gates that determines when the design is completed. In cases where gates cannot be met, the structures plane communicates with the system plane to balance out the design.
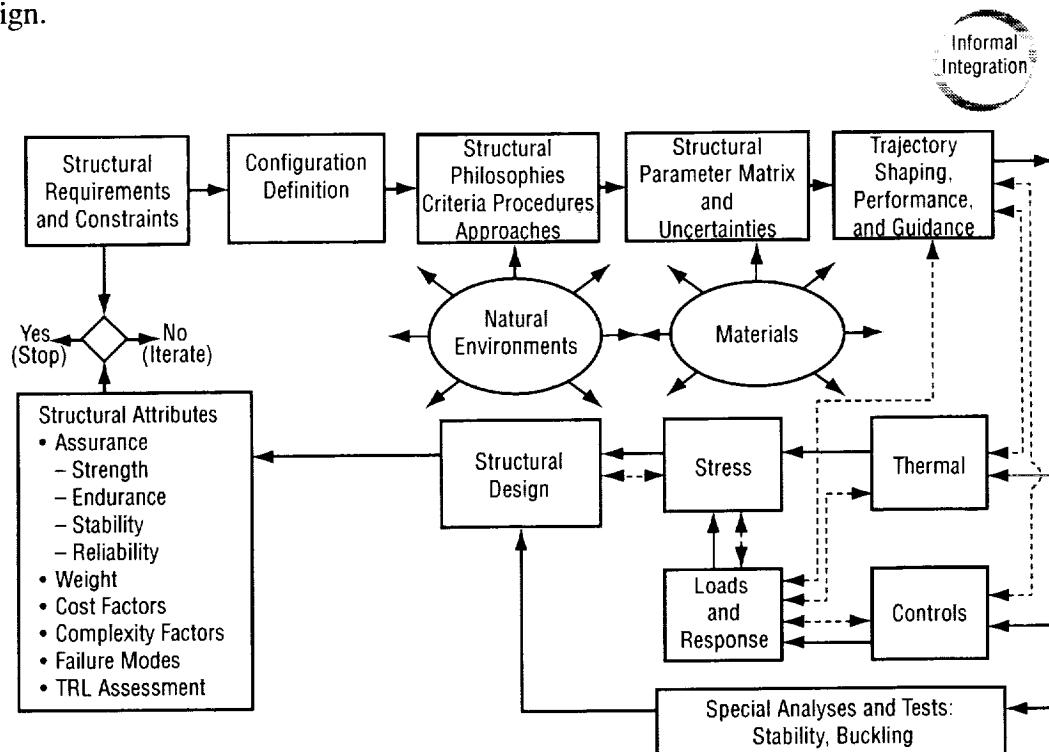
Figure 49. Structure design function plane.

As discussed previously, an N×N diagram has been developed consisting of a matrix of inputs and outputs (see ref. 2 and app. A). Table 9 depicts an exploded scale portion of this diagram, showing the inputs and outputs for structural analysis. Shown are the inputs from thermal and control. Structural analysis outputs are shown horizontally, and structural analysis inputs are shown vertically. For example, structural analysis outputs are flex-body modes, propellant slosh modes, propellant feedline flex modes, and q-alpha and q-beta constraints as input to control, while control provides to structural analysis the inputs of slosh damping requirements, q-alpha and q-beta envelopes, flex-body mode frequency constraints, and autopilot definition.

Table 9. Example expansion of vehicle design N×N diagram.[2]

3.5
Structural analysis
	• Temperature gradient
	design limits
		• Vehicle flex-body modes
		• Propellant slosh modes
		• Propellant feedline flex
		  modes
		• Q*Alpha, Q*Beta and
		  structural constraints

• Structural Temperatures/gradients	3.6 Thermal	

• Slosh damping requirements
• Q×alpha versus q×Beta
  envelopes
• Flex-body mode
  frequency constraints
• Autopilot definition
• Vehicle transient response
  to wind disturbances
		3.7
		Guidance and control

4.3.6.2 Structures Gates. Structural decision gates are shown in figure 50. This figure shows the integration of structural assessment and structural design. The inputs are the prescribed concepts and characteristics. The basic outputs are drawings and specifications. Also shown are the corresponding gates that affect the structural design. For example, structural assurance must meet the criteria for stability, strength, endurance (fatigue and fracture), and reliability. The other gates are clear and left to the reader to interpret. Gate metrics that cannot be met result in either design change which meets the metrics or an involvement of the system plane to rebalance requirements, etc.

The N×N diagram and related write-up separate structural analysis and structural design into separate activities while the structures plane is an integration of both. As a result, the N×N augments with more detail the activities of the structures plane. Figure 51 depicts the structural analysis process. The left side gives the requirements including the discipline criteria. One-way inputs and outputs are defined as well as the two-way inputs and outputs. The middle section of the chart shows the structural analysis tasks and the flow. The loads analysis is central to combining outputs from vibroacoustics and dynamic analysis. The loads output is input to the stress analysis which is then the input for the life or durability analysis. The products of structural analysis are shown on the right side of the chart. Other internal flows are shown including vehicle configuration, options, cost, etc.
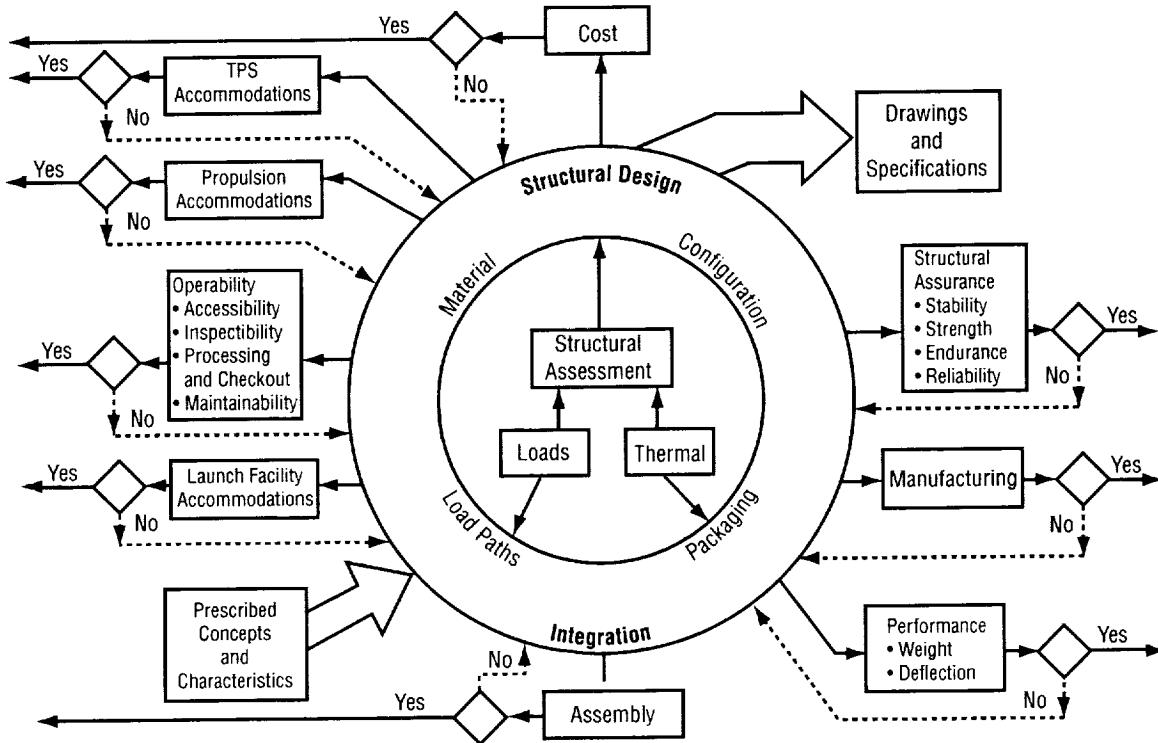
Figure 50. Structure design function gates.
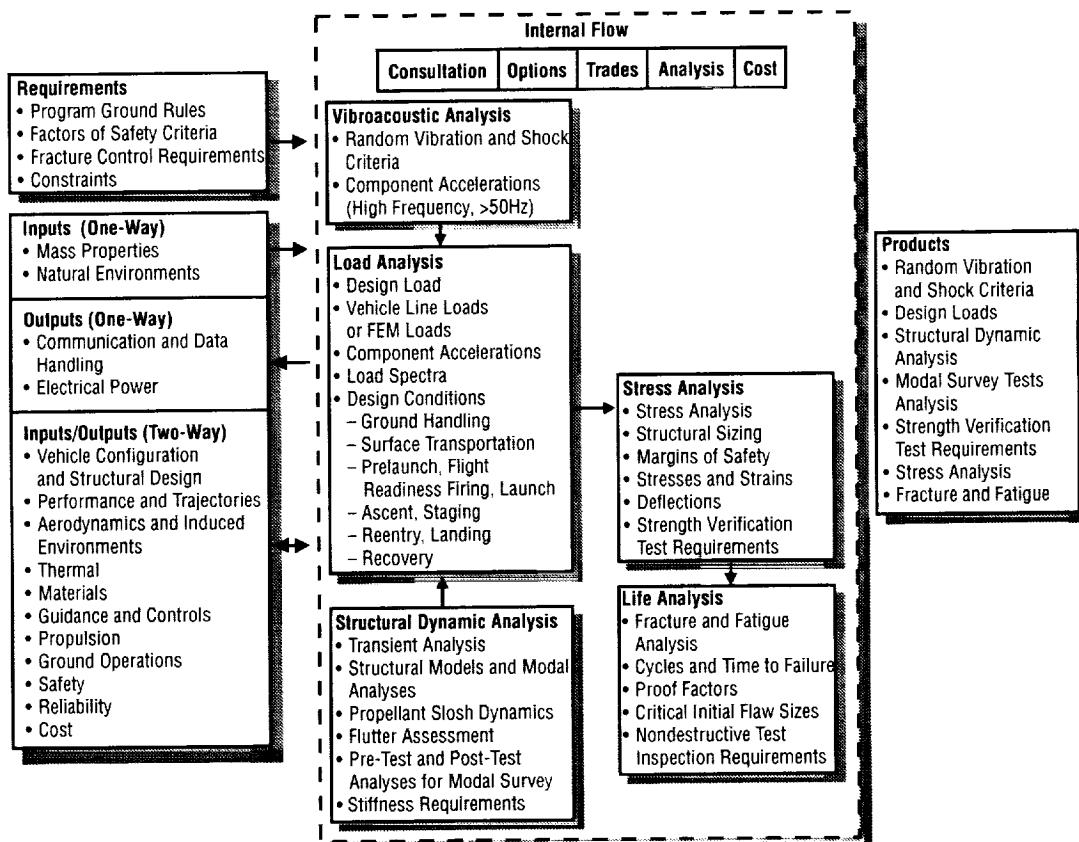
Figure 51. WBS 2.4—structures analysis design process flow diagram.[2]

The structural design flow chart, figure 52, shows the structural design activity and has the same format as the structural analysis flow chart. Structural design deals with component geometry, interfaces, subsystem layout, etc. The major products are the design specifications and the drawings.

Requirements
- Program/Project
- Concepts
- Design
- Verification
- Constraints

Inputs (One-Way)
- Natural Environments

Inputs/Outputs (Two-Way)
- Performance and Trajectories
- Materials
- Manufacturing
- Guidance and Controls
- Mass Properties
- Thermal
- Structural Analysis
- Propulsion
- Aerodynamics and Induced Environments
- Communication and Data Handling
- Electrical Power
- Ground Operations
- Flight Operations
- Safety
- Reliability
- Cost

Internal Flow

Consultation	Options	Trades	Analysis	Cost

Vehicle Configuration
- Subsystems
- Interfaces
- Moldline
- Structural Element Function

Structural Design
- Component Geometry
  - Construction Type
  - Dimensions and Tolerances
  - Mass and CG
  - Cross-Section Properties
- Interfaces
  - Mechanical
  - Datums
- Subsystem Layout
  - Subsystem Placement
  - Line Routing
  - Access Panels
  - Vent Ductwork
- Holddown/Release Mechanism
  - Staging
  - Active Systems
  - Passive Systems

Hazards	Benefits	Reliability	Operability	Maintainability	
Cost/Make or Buy	Resources Utilization	Requirements	Test Requirements	S/W Algorithms	Server Needs
Materials/Parts List	Technical Descriptions	Sizing/Configuration	Conceptual Sketches/Layouts		

Products
- Vehicle Configuration
- System Layout
- Construction Type
- Detailed Drawings
- Structural Mass
- Subsystem Layout
- Structural System Description
- Functional Requirements
- Vehicle/Pad Interface
- Transportation Requirements
- Verification Requirements

Figure 52. WBS 2.1—vehicle configuration and structural design process flow diagram.[2]

The NxN diagram is a complement to the structures plane, providing more details of tasks shown on the structures plane. The structures plane diagram shows the linkage between structural design, structural analysis, and the system plane. The tasks provided in reference 2 can be correlated to the task details given in section 4.3.6.3 which follows.

Reference 2 delineates the WBS tasks with inputs and outputs as shown in tables 10 and 11.

Table 10. WBS 2.4—structural analysis task description.[2]

Inputs	Tasks	Outputs
•Projected groundrules and goals •Factors of safety criteria and fracture control requirements •Launch platform finite element model •Ground and ascent wind models •Vehicle geometry •Vehicle/pad interface geometry •Holddown/release mechanism definition •Structural details •Component installations •Shock sources •External aerodynamic pressure distributions •Compartment pressures •Protuberance airloads •Acoustic/overpressure definition •Fluid dynamic loads (buffeting) •Structural temperature and gradients •Slosh damping requirements •Q-alpha, q-beta envelopes •Flex-body mode frequency constraints •Autopilot definition •Vehicle transient response to wind disturbances •Weights, centers of gravity, moments of inertia •Ignition and shutdown thrust transients, timing •Steady state thrust oscillation •Ullage pressure and tank fill heights versus flight time •••RBCC exhaust/thrust •••Forebody inlet •Material properties •Material allowables •••Material selection consultation •••TPS design definitions •Material thermal (required/expected) •Drawings for flight GSE •Launch sequence timelines •Vehicle integrated OPS concept and requirements •FMR and LMR •Hazard analysis •Fault tolerance requirements •System and component reliability allocation and estimation •Failure mode effects analysis inputs •••CIL inputs	3.5.1 Vibroacoustic analysis 3.5.2 Load analysis 3.5.3 Structural dynamic analysis 3.5.4 Stress analysis 3.5.5 Life analysis Tools: • Commercial software—NASTRAN, ABAQUS, ANSYS, PATRAN • In-house software—dynamic loads analysis programs, NASGRO, bolt strength analysis software • In-house vibration data base	•Structural sizing, margins of safety •Loads and deflections •Propellant slosh baffle sizing •Q-alpha, q-beta constraints and structural load indicators •Temperature gradient design limits •Vehicle flex-body modes •Propellant slosh modes •Propellant feedline flex modes •Q-alpha, q-beta and structural load constraints •Structural analysis of lines and brackets •Establish dynamic envelop of feedline ••••Aft/forebody structures •• Life limit •Vibroacoustical design criteria •Review of battery cell design (pressure vessel) •Structural failure modes •Failure propagation logic development •Test requirements to include instrumentation

Key:　• ELV, RLV, and RBCC
•• RLV and RBCC
••• RBCC only

Table 11. WBS 2.1—vehicle configuration and structural design task description.[2]

Inputs	Tasks	Outputs
•Projected groundrules and goals •Production and ground OPS •Critical interfaces •Subsystems definitions •EPA and OSHA constraints •Environmental OPS constraints •Preliminary design concept and data bases •Staging requirements •Propellant requirements •• Entry propellant weight •Pressure vent sizes and locations •Structural sizing and margins of safety •Loads and deflections •Propellant slosh baffle sizing •Cryogenic insulation sizing •Active thermal control system sizing •Temperature and propellant sensor locations •Maximum engine deflection •Control sensor locations •Control surface deflection requirements •Mass properties data—weight; e.g., inertias •Propellant inventory •Propulsion system layout •Tank internal pressures •••Forebody moldline (iterate required air volume) •••Staging requirements •••Propellant requirements •Material allowables •••Material selection consultation •••TPS design, thermal materials required •Packaging volumes required •Electrical power system (EPS) component details •Access requirements •••Turnaround, launch, and landing facilities •Vehicle integrated OPS concept and requirements •On-orbit flight OPS •• Landing gear drawings •Fabrication parameters •Range safety requirements •Hazard analysis •Fault tolerance requirements •Reliability estimates •Failure mode effects analysis inputs •••CIL inputs •System-to-subsystem reliability, allocations Hardware design, development, testing, evaluation, and production costs •Cost trades	3.1.1 Configure vehicle 3.1.2 Layout 3D structural model 3.1.3 Determine suitable construction type (e.g., truss, isogrid, etc.) 3.1.4 Select appropriate material 3.1.5 Calculate structural member sizes 3.1.6 Analyze crosssection moments of inertia 3.1.7 Determine structural component mass and CG location 3.1.8 Assess provisions for clearance and access 3.1.9 Locate subsystems 3.1.10 Route subsystem lines 3.1.11 Produce detail drawing for manufacturing shop 3.1.12 Design structural components 3.1.13 Identify shock sources 3.1.14 Specify critical dimensions 3.1.15 Establish suitable manufacturing tolerances Tools: • Commercial software—CAD platform and translators, EMS • In-house software—optimization design codes	•Engine alignment tolerances •Vehicle geometry and structural details •Feedline drawings •Component weight estimates •Parts list •Cross-sectional properties •Line routing zones •Pressurant bottle locations •••Preliminary air column •••Profile •Power return thru structure •Component installation •Verification requirements •Transportation requirements •System definition and design description document •Holddown release mechanism •Hazard analysis inputs •Schematics •Failure mode effects analysis inputs •••CIL inputs •Technical descriptions •Test requirements to include instrumentation •Production quantities •Make or buy plan inputs

Key: • ELV, RLV, and RBCC
    •• RLV and RBCC
    ••• RBCC only

Table 12. Primary tasks for structures design function.

Activities	Interactions	Tasks
1. Requirements determination and allocation	Mass properties System Control Trajectories Materials Propulsion Aerodynamics	1. Consult with system to obtain operations philosophy, constraints, cost, mass fraction, etc. 2. Obtain initial configuration definition. 3. Provide to systems the discipline peculiar criteria for formal/legal application. 4. Develop discipline specific verification requirements. 5. Setup allocated requirements, discipline specific criteria, etc., into the metrics for decision gates. 6. Flow up derived requirements to system.
2. Loads analysis	Trajectory Control Aerodynamics Materials Thermal Propulsion Avionics Propulsion	1. Setup describing equations (models) of the system (separate sets are required for the various mission events such as transportation, liftoff, max "g," max "q," separation, etc.). 2. Develop all input data, configurations, environment, etc., and execute loads analysis. 3. Work with trajectory, control, etc., to resolve excessive load conditions. Resolve informally, if possible. 4. Consult system to resolve remaining loads issues, constructing derived requirements such as load relief controls. 5. Input loads to stress and design. 6. Work with propulsion, aerodynamics, and avionics to accommodate packaging and special requirements in the design. Continue to work trades and balancing activities. 7. Insure that cost, reliability, and operations are a part of the design trades and metrics.
3. Structural capability determination	Loads Thermal Materials Aerodynamics	1. Determine strength margins, fatigue margins, fracture control requirements, and structural stability margins. 2. Coordinate with design and loads to informally resolve undesirable margins. 3. Consult systems for trades and requirements changes to resolve remaining margin issues. 4. Continue to work with design to resolve issues and concerns through design changes.
4. Structural design	Loads Thermal Materials Stress	1. Using system requirements, loads, thermal, and stress perform detail design, outputting configurations (geometry), materials, specifications, drawings, etc., to serve as baseline of next iteration. 2. Continue to work with stress, thermal, and systems to upgrade design to accommodate requirements change, reduced margins, and issues. Provide trade date and recommendations to program on issues.
5. Verification	Testing Loads Thermal Stress	1. Work with stress, loads, and thermal to determine test facility requirements, test condition, instrumentation, and data system requirements. 2. Work between disciplines to evaluate results. 3. Flowup anomalies to system for design changes or changes in operational constraints and procedures. 4. Final structural validation achieved in development flight tests.

Structural analysis and structural design are shown separately, whereas these activities are integrated herein.

4.3.6.3 Tasks. The top-level tasks of the structures plane are shown in table 12. They are divided into five categories: (1) Requirements determination and allocation, (2) loads analysis, (3) structural capability determination, (4) structural design, and (5) verification. For each category the interactions are shown along with the corresponding tasks.

4.3.6.3.1 Task 1—Requirements Determination and Allocation. Task 1 is a joint task between the system plane and the structures plane. The system goal is to take the total system level requirements, compartmentalize them, and allocate them to the planes. In this case, typical requirements allocated to the structures plane are:

- Weight
- Geometry constraints
- Cost
- Operations constraints
- Schedule.

The structures design function works with the system design function to properly accomplish this allocation task.

The discipline groups develop a second set of requirements that are technical criteria. These are approved and levied by the project and controlled or managed by the disciplines. Typically in structures there is a detailed set of these criteria, documented officially by NASA for general use as legal requirements. Generally, the criteria are too comprehensive and must be tailored by the disciplines, the system, and the project. Typical examples are strength criteria, endurance criteria such as fatigue and fracture, criteria for loads analysis, vibroacoustics, and attachment methods.

Included in these criteria are not only safety factors but also verification requirements such as static and dynamic test, qualification and acceptance criteria, parameter variation ranges, and traceability. Gates include not only meeting requirements given in the criteria documents but validation of models, data accuracy, etc. If the model is wrong, the accuracy of the input data is immaterial. Therefore, all models must be verified.

Finally, during the design and development process, derived requirements will evolve and can become part of the legal requirements. Examples of derived requirements are requirements for load relief control, slosh baffles, day-of-launch wind biasing, launch constraints, etc. In each case the design must accommodate the new requirements. The total set of structures requirements (allocated requirements, derived requirements, and formal discipline criteria) becomes the gate acceptance criteria (metrics) that determine if the structural design is acceptable and complete. The specifications and design attributes from the structures design plane are provided to the system and other design function planes. Obviously, some of these specifications and attributes result in constraints for the other planes that place limitations on their application and interaction with the structures design.

4.3.6.3.2 Task 2—Loads Analysis. Utilizing inputs from (1) configuration, (2) natural environment, (3) aerodynamics, (4) materials, (5) thermal, (6) trajectory, (7) control, and (8) propulsion; the external load environments are determined. For efficiency and ease, the loads analyses are performed separately for the various mission events involving (1) transportation and handling, (2) lift-off, (3) max q, (4) max g, (5) separation and staging, (6) docking, (7) reentry, and (8) landing and recovery. These inputs are also addressed in the NxN diagram, process flow, and WBS charts. Tables 10 and 11 define the WBS tasks with inputs and outputs (products) which include the load analysis. Table 12 defines the total structural analysis tasks, including inputs and outputs, with the load analysis being one element. The tasks in these three tables are compatible. The other design activities are covered in the subsequent tasks. Structural models, both rigid body and dynamic, must be developed for each event, describing the plant characteristics. These models are then combined into appropriate system models with all the environmental inputs, constraints, etc., and a response analysis is run to determine the combined loads. These must be defined in some statistical or quantifiable manner accounting for variations and unknowns. These results along with other data become the input to the next task.

During this process, if excessive loads exist, then the load specialist works informally with other disciplines in an attempt to resolve the issue. Can aerodynamics be altered? Are the variations of key parameters too conservative? Are the criteria too conservative? Can the wind model be changed? Are dynamic tunings creating a problem, requiring detuning?

Occasionally, the issues cannot be resolved informally. In this case the issue is carried to the system plane where trades and balances are accomplished across the subsystems, design functions, etc. For example, the configuration shape may be altered to change the aerodynamics. In order to reduce loads, yet maintain an acceptable system, criteria can be changed as well as design levels of parameter uncertainties and their combinations.

Achieving the acceptable loads set requires that the loads specialists not only communicate and understand in depth their specialty, but that they have an understanding of the interacting disciplines. Together they must clearly define requirements for the needed input data. For example, they must specify the needed resolution of the aerodynamic coefficient matrix, pressure distribution spatial resolution, and critical locations requiring higher fidelity resolution. The interactions with other disciplines are very important and complex. They include but are not limited to the following:

- Trajectories—definitions of the flight path and angles
- Control—the control logic, control gains, and the dynamic responses
- Interfaces—definition of mechanism envelopes, constraints required for separation, docking, etc.
- Material—materials properties definition as a function of operational environments
- Aerodynamics—definition of the aerodynamic and acoustic environments.

The detail of the load process, technically and computationally, is not a part of this report. Other documentation (see bibliography) adequately covers those details. What is key here is an understanding of the metrics for deciding when the job is finished and how the models, data, etc., are validated. Uncertainty factors are normally used on loads until the model/data verification/validation are accomplished. This validation pertains also to both the stiffness and mass distribution of the models.

4.3.6.3.3 Task 3—Structural Capability Determination. This task is concerned with determining the structural capability using the loads and other induced environmental inputs such as thermal. The capability assessments include at least the following:

- Strength
- Ductility
- Fracture
- Fatigue
- Stability
- Deflection/interference
- Attachment capability (welds, fasteners, bonds, etc.)
- Vibroacoustic capability.

Very specific formal criteria are levied for each of these areas and must be met or a waiver approved. These criteria in general are the means of defining margins for the various predicted failure modes. If they are not met, then the same process, informal and formal, as discussed under loads is employed. There are four main interactions/interfaces for the stress functions: loads, thermal, materials, and facilities. The loads and thermal disciplines define the environments including accelerations, delta P's, etc. The materials discipline defines the materials properties as a function of operational environments. Assembly and launch facilities define interfaces, constraints, etc.

The activities on the structures plane require understanding load paths and stress variations and concentrations. As a result not only must the specialist understand the many various computerized tools such as finite element codes, thermal codes, grid codes, graphic codes, etc., but must be able to analyze by hand special cases of structural response and evaluate them with respect to criteria and specifications.

The structural analysis function and the structural design function are highly interactive. There are, in general, two avenues open if the criteria are not met: (1) Change the design to accommodate the environments or (2) reduce the environments (loads) as discussed under loads. As a result, communications between loads, design, and stress are tightly knitted. Many problems can be solved informally among the three groups; however, some critical trades must be made through the systems plane due to the high complexity of the interactions which require tests and compromises.

4.3.6.3.4 Task 4—Structural Design. Structural design is one of the most complex tasks in developing a launch vehicle. It requires strong interactions with all other disciplines, subsystems, etc., and the designer must be the structural design integrator. This dictates that the designer has not only an indepth understanding of design (load paths, functions, materials, attachments, etc.) but also an understanding of the supporting disciplines, subsystems, elements, etc. Parts standardization knowledge, as well as accepted design approaches, is also important. Materials selection is a key choice in design. All the margins are driven by materials selection, as is mass fraction, weight, etc. The structural design tasks are suboptimized tasks in that the design is driven by constraints and interface requirements as well as loads and thermal and many other tasks. As each design cycle is approached, the previous design cycle configuration is refined. In each new cycle, all problems raised in the previous cycle are accommodated or challenged on the systems plane against other requirements, criteria, and disciplines. In general the final decision must be approved at the system level.

Not only must the design tasks accommodate loads and thermal, but, also, they must accommodate design considerations of the following other factors:

- Cost
- Performance—mainly weight; structural efficiency
- Operations—processing, check out, accommodation, accessibility
- Propulsion—thrust frames and element location, lines, ducts, engines, etc.
- Avionics—accommodation of electrical components, sensors, and actuator
- Pyrotechnics—location and security
- Manufacturing and assembly—design to accommodate and optimize
- Launch facilities—interfaces, accessibility, etc.
- TPS—structural design provides the support for the TPS
- Packaging—structural design provides location and support for components, etc.
- Materials—material characteristics required.

The design process is further complicated by the wide choice of materials from composites to metallics; shapes, particularly shapes of tanks and fairings; stabilization techniques such as orthogrid, ring stringer, etc.; and manufacturing approaches such as welding, casting, powder metallurgy, etc. The wide choice of attachment approaches such as welding, rivets, adhesives, bolts, etc., is also a major consideration. Additionally, cost considerations greatly complicate the design process. All have impacts on structural margins and weights.

The design is complete when all the decision gates are satisfied. Those gates include the top-level requirements, structural assurance, subsystems accommodations, and other significant design considerations as shown in figure 50. The top-level requirements are met with appropriate cost, weight, mass fraction, etc. The structural assurance is achieved when all the stability criteria and structural margins are satisfied. All subsystems and interfaces such as TPS, propulsion, avionics, and launch facility must be accommodated efficiently. Finally, the design must meet the gates of acceptable manufacturing, assembly, and operations. When all these gates are met, the drawings and specifications can be finalized.

4.3.6.3.5 Task 5—Verification. Verification of structural systems is one of the key tasks of assuring a launch vehicle is ready to fly. The verification process ensures first that the structures meet or exceed the requirements/specifications and, second, that the operational constraints/procedure are adequate to ensure structural integrity. The verification is a combination of analysis, similarity, and testing. Structural testing is the preferred approach; however, due to the cost of structural testing and the maturing fidelity of structural analysis, analysis is used in special cases in lieu of testing. Protoflight testing of structures is another viable option which incurs a small risk to flight hardware but validates the structure to loads slightly greater than limit. The missing link is quantification and understanding of critical failure mode margins. The philosophy of protoflight testing is "Test the hardware to a specific margin above the largest expected flight load (usually 5 percent), correlate the analytical model to that load, update the model, then use the updated model to predict margins." Structural verification is, therefore, a combination of similarity, testing, and analysis.

a. Similarity.

Verification by similarity is valid where a similar structure has been verified by test and the similarities can be quantified. In general, this technique is used when two or more of the same articles are built. In the case of components which must pass environmental testing at both the qualification/ verification level and acceptance level, only one article of a family (i.e., common valves) is qualification tested, thus qualifying the others by similarity. Acceptance tests, however, must be performed on all articles. These environmental tests include acoustic, vibration, and thermal. Since it is expensive and schedule critical, vibration environments (criteria that are acoustically driven) cannot always be verified by acoustic tests. Two techniques are used to verify these criteria: (1) Data bank scaling of similar structures that have been tested and (2) statistical energy analysis (SEA).

b. Testing.

As stated previously, testing is the preferred method of verifying the structure; however, cost and schedule many times prevents testing. Structural testing occurs at the part, component, subsystem, and system levels. Structural testing has several major categories:

- Component qualification and acceptance (vibration, acoustics, thermal/vacuum)
- Dynamics
- Strength
- Stability
- Aeroelasticity (flutter, divergence, etc.)
- Fatigue
- Proof (fracture)
- External loads
- Pressure.

Testing is accomplished to meet specifications, and traceability must be shown between the requirements and the test results.

Coupon tests are conducted by the materials discipline establishing the materials characteristics in the following areas:

- Ultimate strength
- Yield strength
- Fatigue life
- Fracture
- Environmental compatibility.

Where required, these tests must include temperature and environmental effects.

Component qualification and acceptance testing was discussed under similarity.

Dynamic tests are required to validate the dynamic model for control system design, Pogo suppression, aeroelasticity, and loads. Models are corrected and updated based on the tests, then used by the above mentioned disciplines to perform their design and verification analysis. The test hardware must simulate or duplicate the dynamic characteristics of the system. Mass simulators can be used for components whose frequencies are outside the frequency range of the basic modes. Also, too many dynamically tuned or closely spaced component frequencies can contaminate the basic modal data, making it hard to get accurate data. Judgment must be used as to which are important. Sensitivity analysis helps quantity this judgment. Dynamic tests must consider boundary conditions, excitation methods and locations, instrumentation, modal goodness criteria, data collection, and evaluation systems. Testing boundary conditions in general are either fixed, fixed hinged, or free-free. Excitation methods are single-point random, multi-point random, sine sweep, sine dwell, and impulse. Model assurance criteria are used for mode selections from the test for modal correlation. These range from frequency accuracy to modal cross correlation, etc. Dynamic testing verifies the dynamic stiffness and mass distribution assumed by the analytical modeler.

Strength verification applies the external loads environment, verifying the analytical model's static stiffness assumptions and the critical load paths. If the structure is tested to failure, margins are verified along with critical failure modes. As discussed previously, if protoflight test is used, the structure is tested to limit load plus some margin below yield. The correlated/updated model is then used to predict margins.

Aeroelastic testing establishes flutter margins. This is accomplished as an integrated structures/aerodynamic wind tunnel test. The structures discipline must design the scaled wind tunnel model to have the appropriate scaled modal frequencies required to predict flutter.

Proof testing takes advantage of fracture data, establishing that no flaws are present which will lead to failure in a prescribed mission lifetime. Proof pressure testing is used extensively for pressure vessels and rotating machinery.

c. Analysis.

Verification by analysis is becoming an acceptable approach in today's environment. There are two basic approaches used for verification by analysis: (1) Models are benchmarked or correlated using tests (in particular protoflight test) and then used to predict structural failure modes and margins and (2) larger design safety factors are used to cover model uncertainties. Models/analysis also play a key role in test verification, predicting the test response, instrumentation utilization, loads application, etc.

Structural verification uses the above three approaches (similarity, testing, and analysis), either independently or interdependently. Structural verification is complete when the requirements have been met. If requirements are not met, three options exist: (1) Redesign, (2) waive requirement, or (3) implement operational constraints and procedures.

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System

Aerodynamics

Trajectory/G&N

Control

Structures

Thermal

Propulsion

Avionics

Materials

Manufacturing

Other
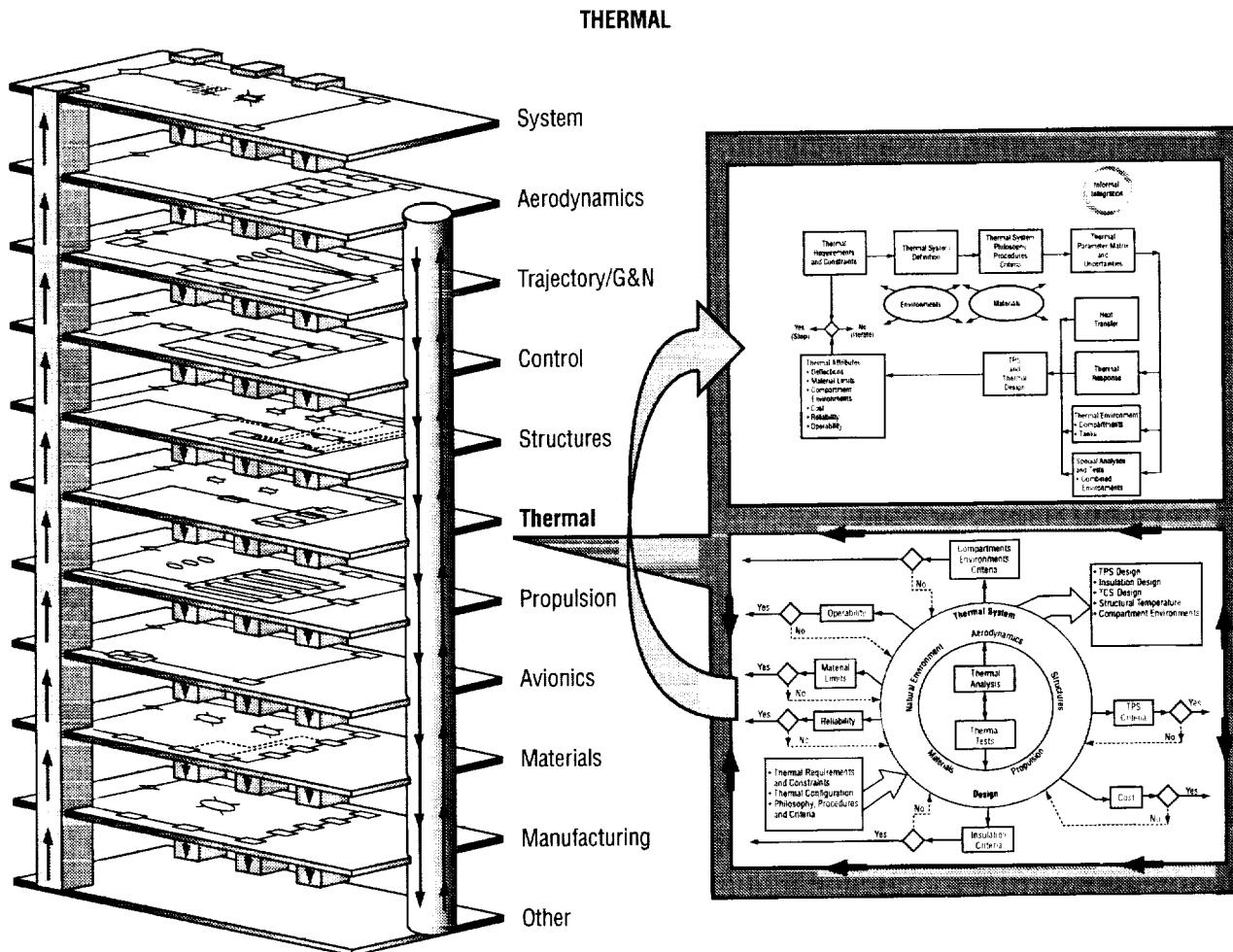
Figure 53. Design process technical integration—thermal design function.

4.3.7 Thermal Design Function

The connection between the design process technical integration and the thermal design function is delineated in figure 53. The illustration depicts the relationship between the thermal design function and the other design functions. In addition, it shows the work/information flow process that is supported by key thermal decision gates required to develop and assess the thermal attributes. The details of all the above are delineated in this section.

The thermal design activity is fundamental to the vehicle design and its operational success. It consists of determining the thermal environments (with input from aerothermal), predicting the heat transfer, achieving the thermal designs, and providing verification. The thermal design activities provide design of insulation, TPS, and component and compartment TCS's. These systems provide the desired thermal states for structures, propellants, components, payloads, and crew. An important function is providing structural temperatures for stress fields for fracture, fatigue, and deflection.

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4.3.7.1 Thermal Design Function Plane. The thermal design plane is shown in figure 54. It depicts the thermal design flow and various interacting discipline functions. The design process flow starts with requirements and the thermal system definition. Following these are the thermal system philosophies, procedures, and criteria. As in the other planes, the parameter matrix and uncertainties are developed by the discipline functions in conjunction with the system plane. The major discipline functions shown are heat transfer, thermal response, and thermal environments for such things as compartments and tanks. Outputs from these activities, as well as inputs from other disciplines, become the inputs for the TPS and TCS design. More details of the tasks are in later sections. The attributes of the thermal design are compared to requirements. If they meet the requirements, the design is complete; otherwise design iterations occur. If the design iterations cannot solve the problem, then the system plane becomes involved with trades and balances to achieve overall convergence.
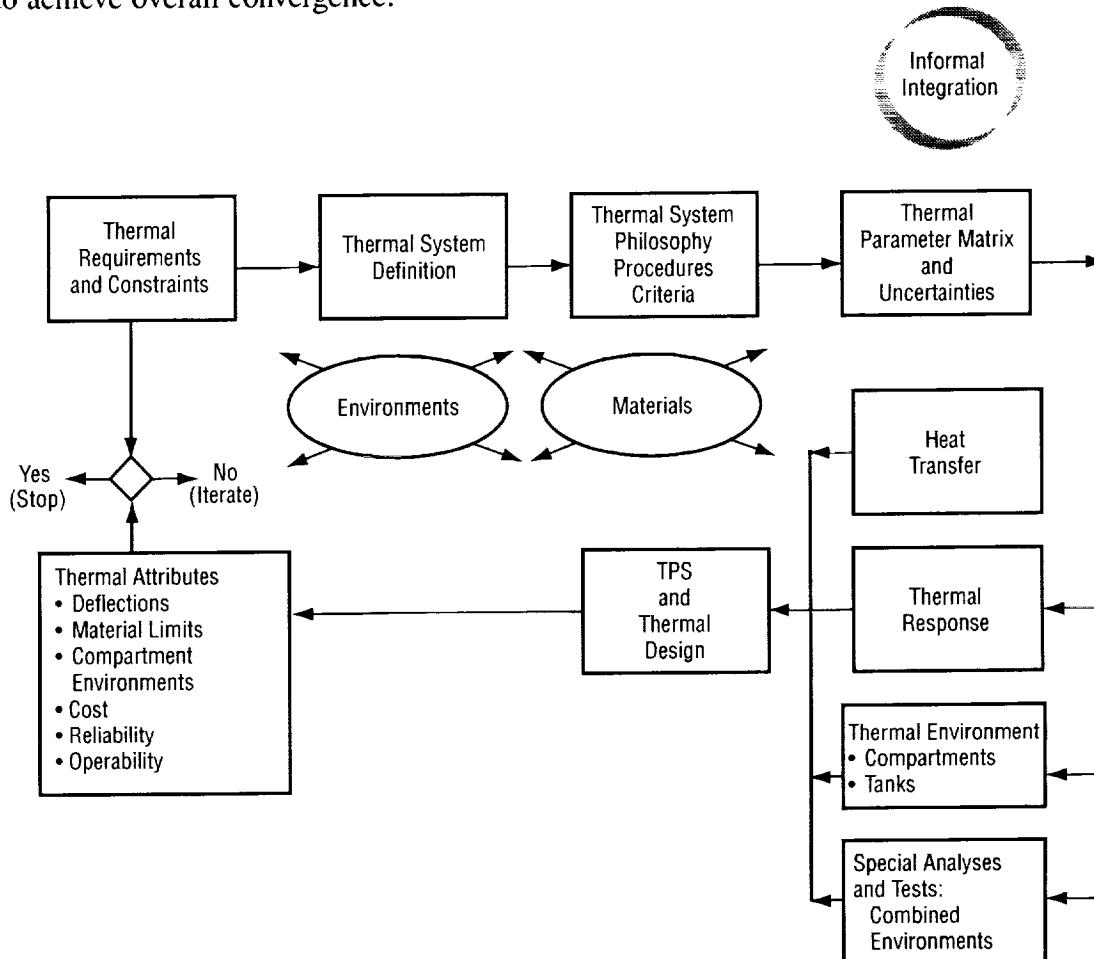
Figure 54. Thermal design function plane.

The thermal process flow from reference 2 is shown in figure 55. External inputs are shown as requirements, one-way inputs and outputs, and two-way inputs/outputs. These are the details of what is illustrated on the thermal design plane. The process flow represents the details of the discipline flow of the thermal design plane (shown as heat transfer, etc.). Depicted are the analysis tasks, thermal design data, and thermal design areas. The NxN diagram of reference 2 (Appendix A) is representative of further delineation of the inputs and outputs associated with the thermal design function. More detailed discussion is provided in the following paragraphs.

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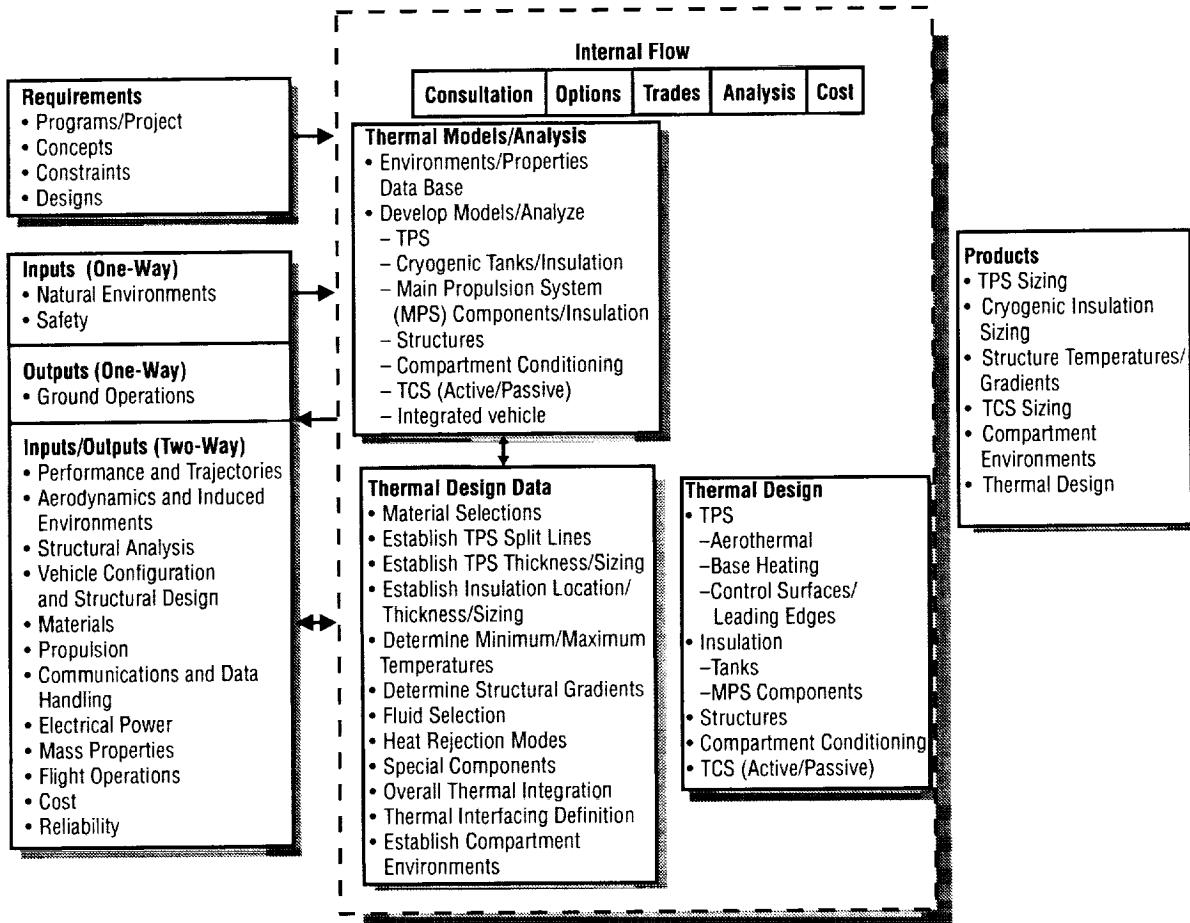
Figure 55. WBS 2.5—thermal design process flow.[2]

4.3.7.2 Thermal Gates. The decision gates for the thermal design process are shown in figure 56. All these gates must be satisfied to produce the design of TPS, insulation, and TCS and to output structural temperatures and compartmental environments.

The thermal design must pass not only the performance gates (margins and sensitivity) but also the discipline gates such as structural integrity. Thermal design is complicated in that it must protect from plume and aero heating, condition propellants (tank insulation), and provide thermal environments for components and crew. Interactions with other disciplines are a fundamental part of meeting the thermal gates. If the gates cannot be met through informal design interactions, the system plane is used to make trades and balance requirements. Foremost in the thermal gates is that the thermal model must be shown to have the accuracy required to predict thermal characteristics. Other gates include acceptable cost, reliability, and operability.
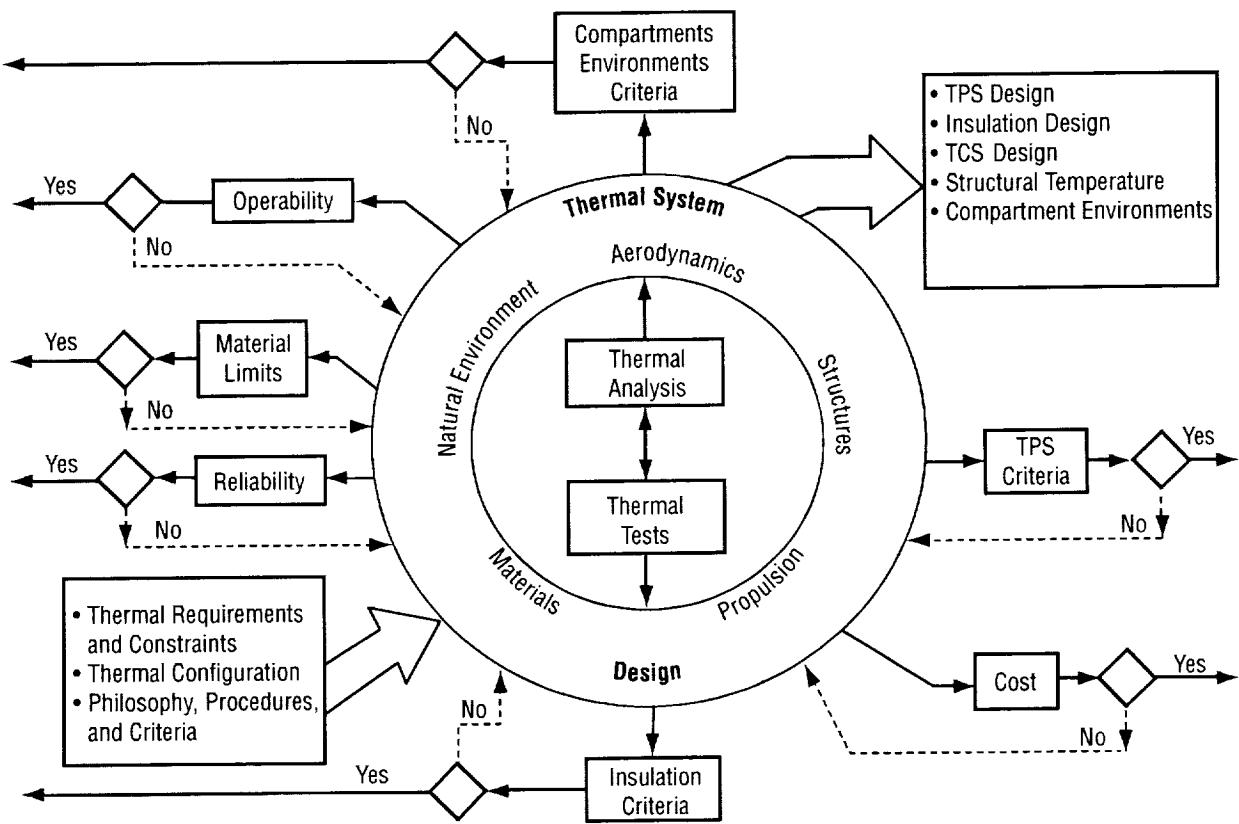
Figure 56. Thermal design function gates.

4.3.7.3 Tasks. The thermal WBS tasks from reference 2 are shown in table 13. These tasks delineate the discipline tasks depicted on the thermal design plane, figure 54.

Shown in table 14 are the top-level thermal design function tasks including the activities, the interactions, and the tasks. This task matrix is provided to illustrate primary technical interacting activities discussed in the following paragraphs.

4.3.7.3.1 Task 1—Requirements Determination and Allocation. Task 1 is a joint activity with systems and other design functions to jointly define and allocate the systems and thermal requirements and criteria for thermal design application. As a part of this activity, a preliminary definition is made of the thermal system. Associated with this are the design philosophy, parameter definition, and uncertainties.

Table 13. WBS 2.5—thermal design task description.[2]

Inputs	Tasks	Outputs

•Projected groundrules
•Design-to-cost goals
•Preliminary design concept and data base
•Launch pad environments
•Configuration details, materials, dimensions
•••Ascent, cruise, loading requirements
•Ascent aeroheating histories
•Entry aeroheating histories
•Compartment flow rates
•Plume heating environments
•Temperature gradient design limits
•Mass properties control plan
•Documented control weights
•Weights, centers of gravity, moments of inertia
•Ground hold conditions
•Heat load requirements for propellant conditioning
•Chill down requirements
•Engine configuration
•Engine operating characteristics
•Engine thermal requirements
•Material thermal properties
•Material allowables
•••Material selection consultation
•••TPS vehicle interface definition
•••Material thermal required
•Thermal design limits
•Sensor characteristics
•EPS operational environment requirements
•Vehicle integrated OPS concept and requirements
•Hazard analysis
•Fault tolerance requirements
•Failure mode effects analysis inputs
•••CIL inputs
•Hardware design, development, testing, evaluation, and production costs
•Cost trades
	3.6.1 Review Phase A results
	3.6.2 Establish properties data base
	3.6.3 Analyze thermal design concepts
	    – TPS
	    – Cryogenic insulation
	    – Compartment thermal assessment
	    – TCS (active/passive)
	    – MPS
	3.6.4 TPS sizing
	3.6.5 Cryogenic insulation sizing
	3.6.6 TCS sizing (active/passive)
	3.6.7 Compartment thermal environments
	3.6.8 MPS thermal sizing
	
	Tools:
	• Commercial software—SINDA and PATRAN
	• In-house software
		•Temperature sensor locations
		•• Wall/surface temperatures
		•Heating rate or temperature indicators
		•Heating constraints
		•• Wall/surface temperatures
		•Structural temperatures and gradients
		•TPS sizing (aerothermal/base heating)
		•Cryogenic insulation sizing
		•Active TCS sizing
		•Component weight estimates
		•Parts list
		•Propellant condition
		•Temperature time history
		•Pressure
		•Chilldown of engine
		•Temperature and heating loads
		•Structural temperature requirements
		•Thermal environment
		•Thermal environment for EPS
		•Power requirements for thermal control system
		•Structural temperature requirements
		•Subsystem definition and design description document
		•Environments and loads definition
		•Materials type
		•Technical descriptions
		•Test requirements to include instrumentation
		•Production quantities
		•Make or buy plan

Key: • ELV, RLV, and RBCC
     •• RLV and RBCC
     ••• RBCC only

4.3.7.3.2 Task 2—Thermal Analysis. Task 2 utilizes Task 1 requirements and preliminary definition in conjunction with the design reference trajectory and the predicted external thermal environments to calculate the heat transfer, thus the temperature of the structure. The task evolves into three distinct analysis areas:

• Thermal environments considering radiation, convection, and conduction for the compartments and tanks, as well as human environments, payload conditioning, etc.
• Heat transfer characteristics
• Thermal response of the system to the thermal environment.

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Table 14. Primary tasks for thermal design function.

Activities	Interactions	Tasks
1. Requirements determination and allocation	Mass properties System Aerodynamics Propulsion Trajectories Structures	1. Consult with system to obtain operations philosophy, constraints, cost, etc. 2. Obtain definition of configuration. 3. Provide to systems plane discipline peculiar criteria for formal/ legal application. 4. Develop thermal verification requirements. 5. Develop thermal requirements into gate matrices. 6. Flow up derived requirements to system.
2. Thermal analysis	Aerodynamics Propulsion Structures Trajectories	1. Set up describing equations for each of the separate subsystems and mission events. 2. Develop all input data and execute various thermal analysis. 3. Work with interacting disciplines to resolve anomalies, etc. 4. Consult with system to resolve remaining issues. 5. Insure that cost, reliability, etc., are included in trades, etc.
3. Thermal system design		1. Using system requirements, thermal analysis results, etc., design the TPS outputting design specifications to serve as the baseline for the next design iterations or for verification. 2. Using system requirements, thermal analysis results, etc., design the TCS outputting design specifications to serve on the baseline for the next iteration or for verification.
4. Verification	Test Trajectories Stress	1. Work with interacting disciplines to determine test facility requirements, test conditions, instrumentation, and data system requirements. 2. Work between disciplines to accomplish verification test. 3. Work between disciplines to evaluate results. 4. Flow up anomalies for resolution and operational procedures definition. 5. Final thermal verification achieved in development flights.

These data become the inputs for thermal design of TPS, life support systems, payload conditioning, and compartments, and for structural design to account for thermal effects. Thermal effects on structure include stresses, deflections, and materials property changes. Execution of this task requires close communications with the trajectory, materials, structures, propulsion, avionics, and aerodynamic design functions. This interaction includes both input data and output data. For example, the propulsion system may use a regenerative-cooled nozzle or an ablative nozzle where each requires special analysis. The regenerative-nozzle analysis includes flow circuits, boundary layers, film coefficients, heat transfer, etc. The ablative nozzle analysis combines heat transfer, gas dynamics, pyrolosis, materials, erosion, etc., to determine thermal/materials characteristics.

4.3.7.3.3 Task 3—Thermal System Design. This task is responsible for the design of the various thermal systems. These designs include at least the following:

- TPS and insulation for propellant conditioning
- TPS for aerodynamic and plume heating
- Life support thermal environment system
- Payload conditioning
- Ablative nozzles
- Regenerative and passively cooled nozzles
- Solid rocket motor insulation and heat protection
- Compartment and component thermal conditioning (includes avionics components).

Thermal design interfaces with the other design functions and with systems. These exchanges are both formal and informal. As the design evolves, the gates for completion are a combination of the performance and the specialist's criteria. For example, structural margins for strength, fracture, and fatigue (influenced by temperature) must be met. The performance gates usually have to do with the resulting thermal environments and/or materials limits. Cost and operability are additional gates. Special gates exist for the special systems such as life support and ablative nozzles. The system, the design function, and the disciplines determine these special gates.

Usually, thermal gates are worked informally with the various disciplines. If the informal approach cannot achieve an adequate design, then the system design function must provide the appropriate balance to achieve the best design. Engineering judgment plays a central role in the balancing act.

4.3.7.3.4 Task 4—Verification. Thermal verification generally is achieved using tests. These tests are for both components and subsystems. The tests are designed to duplicate the environments. As a result many thermal verification tasks must be accomplished in thermal vacuum chambers. Other tests include wind tunnel and hot-gas facility testing for aeroheating and propulsion plume impingement and solid rocket motor hot-fire test beds for solid rocket motor (SRM) components.

Designing and conducting high-fidelity ground component and subsystem tests are essential to the verification process. Proper boundary conditions and environments must be ensured. All tests as with all models are approximations; therefore, the test limitations must be well understood and challenged. Verification, therefore, requires the following:

- Environments definition
- Component definition
- Test constraints and fixtures
- Instrumentation and data systems requirements
- Test conduction
- Test data evaluation
- Correlation of analysis to test data.

The verification of the thermal design is achieved when the analysis and hardware test data meet the requirements. Final verification can only be accomplished during developmental flight testing. It is very important that the development flights have proper instrumentation and data systems.
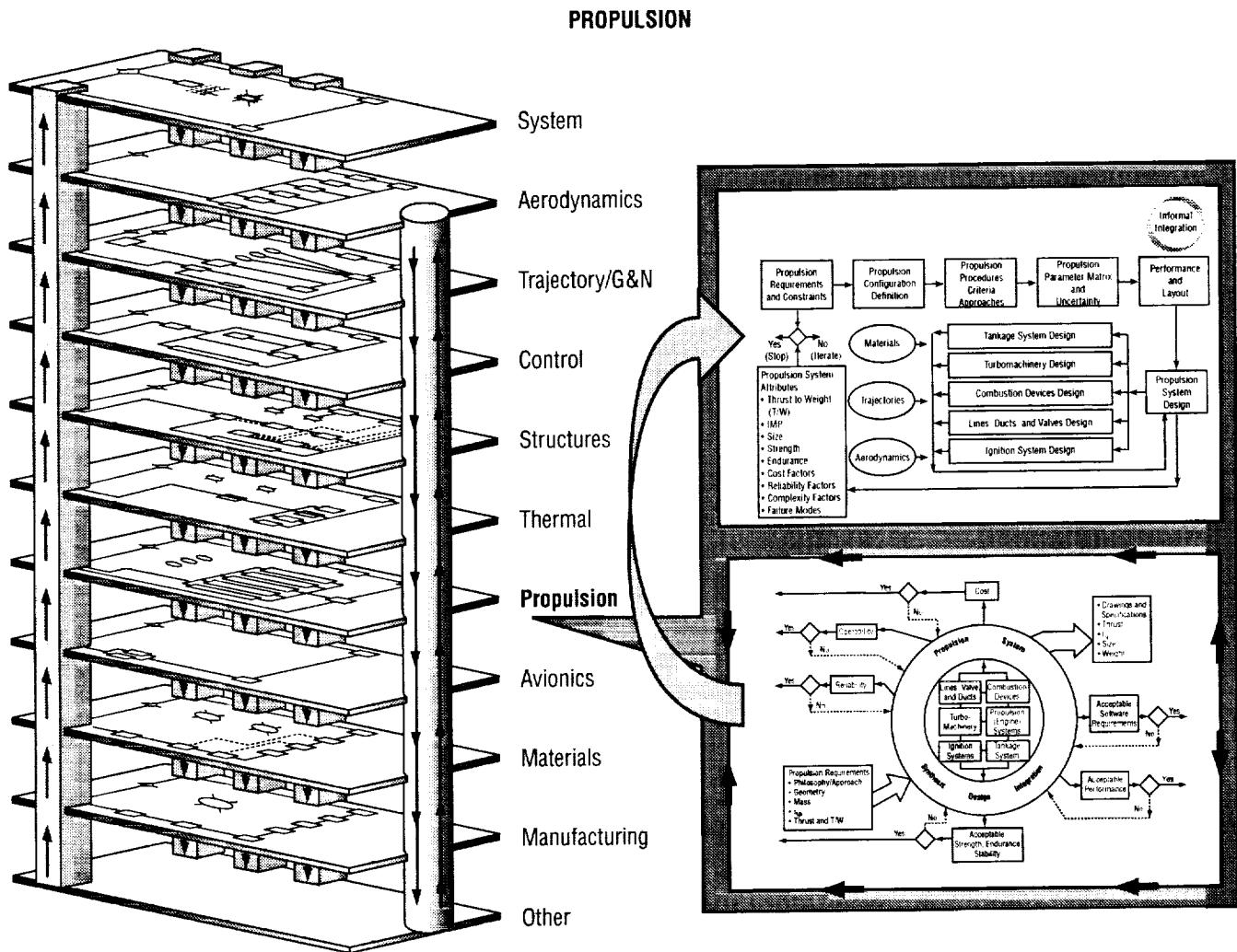
Figure 57. Design process technical integration—propulsion design function.

4.3.8 Propulsion Design Function

The connection between the design process technical integration and the propulsion design function is delineated in figure 57. The illustration depicts the relationship between the propulsion design function and the other design functions. In addition, it shows the work/information flow process which is supported by key propulsion decision gates that are required to develop and assess the propulsion attributes. The details of all the above are delineated in this section.

(Note: Design of the propulsion subsystem is a complex process in itself, involving numerous subsystems and specialties. This report does not describe the propulsion design process in detail but provides a top-level overview to show its relationship and interaction with the total vehicle design using a liquid engine system as an example.)

The design of the propulsion system is strongly coupled with the structural design as well as the flight mechanics (trajectory, control response, etc.). The interrelationship between these design areas is very complex. Vehicle design can be characterized as putting a given payload into a specific orbit by achieving minimum dry weight with a highly efficient propulsion system. The propulsion system converts chemical, etc., energy into thrust, pushing the vehicle and payload into the desired orbit. Choice of the energy conversion system (liquid engine, solids, etc.) and energy source clearly has a strong influence on the structural system. Coupled together, they determine the flight mechanics system. Vehicle design from the performance standpoint is, therefore, concerned with three focus areas: (1) Structural (dry mass) efficiency, (2) propulsion system efficiency, and (3) management of losses (nonideal effects).

4.3.8.1 Propulsion Design Function Plane. The top-level propulsion system (for a liquid engine example) design function is illustrated in figure 58. This figure shows as separate activities the design of the engine subsystems and/or elements. These are turbomachinery, combustion devices, lines, ducts, valves, ignition system, and the engine system. Each of these propulsion subsystems requires its own design including all of the interactions of the supporting discipline functions. The propulsion design process would be comparable to the design process presented in this report. This top-level chart is provided because of the strong interaction between the propulsion system and the rest of the launch vehicle.
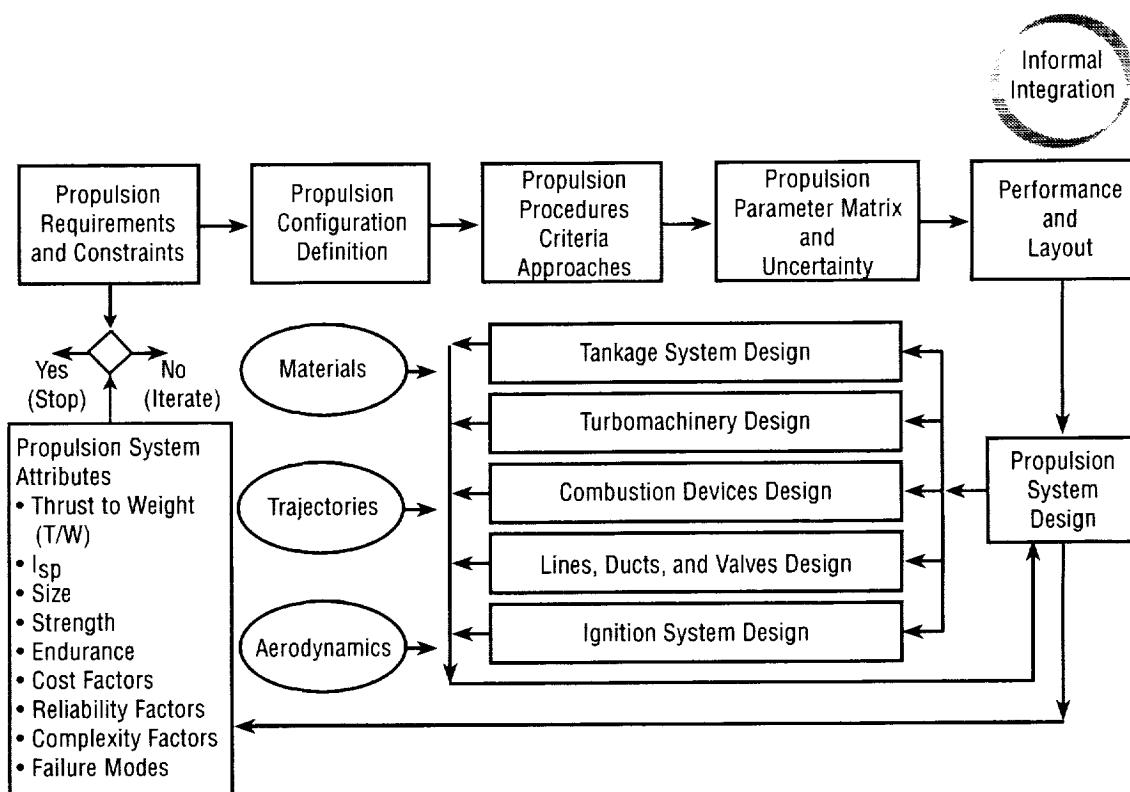
Figure 58. Propulsion design function plane.

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This strong interaction results in many trades and balancing of the attributes of the propulsion system and the other design functions of the vehicle such as trajectory, structures, and control. These design functions are heavily involved also in the system trades which balance requirements and performance attributes. For example, there may be a trade between the amount of payload to orbit and the size of the propulsion and structural systems, with the associated cost.

The process starts, as it has for each of the other planes, with requirements definition and allocation, then proceeds to the parameter matrix definition, then to design the system, subsystems, etc. Section 4.3.1 discusses this generic process.

Figure 59 from reference 2 shows the inputs, outputs, requirements, and products, as well as a limited process flow. The process flow only shows the activities supporting structural design and trajectory design. The detail designs of the propulsion system and its subsystems are not shown; however, they are required to generate the data for the activities shown. It is assumed that these complex activities are accomplished in designing the propulsion system. The propulsion system entry on the NxN diagram from reference 2 (app. A) follows the same pattern shown previously.
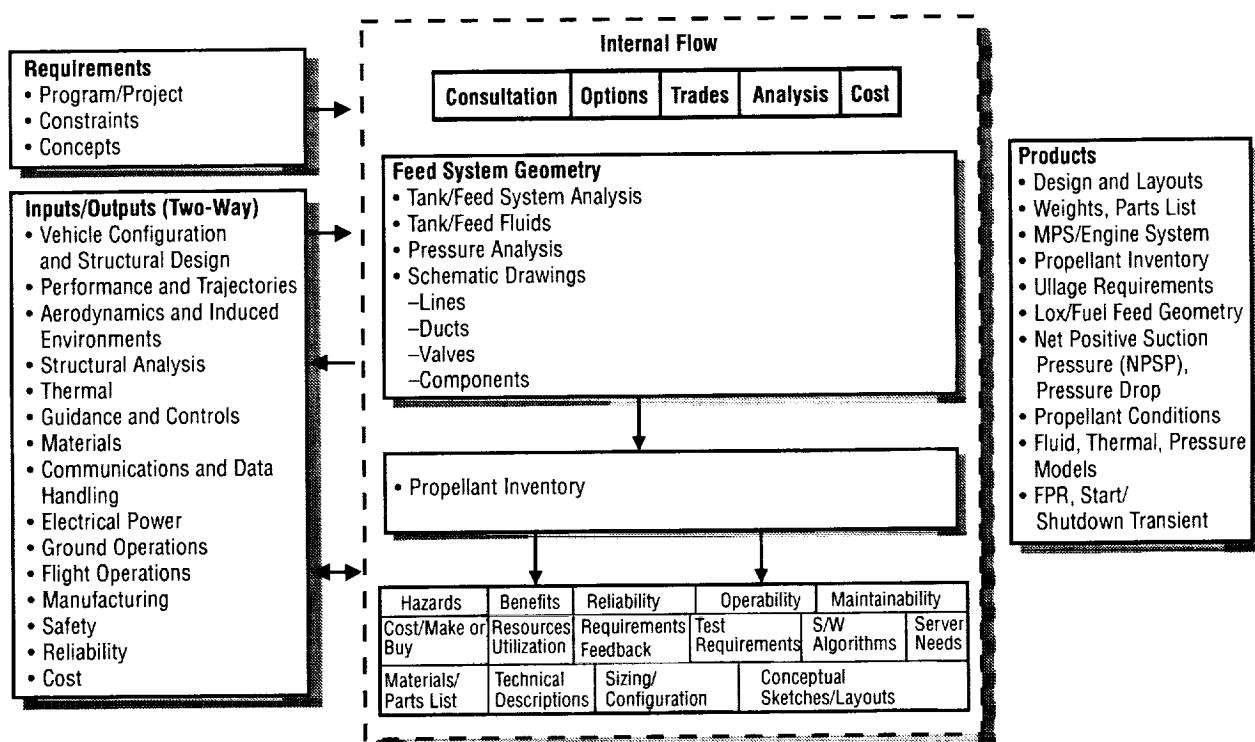
Figure 59. WBS 2.8—propulsion system design process flow diagram.[2]

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4.3.8.2 Propulsion Gates. Figure 60 illustrates the propulsion system decision gates. The gates the propulsion system must meet include I_{sp}, thrust, thrust to weight, and volumetric constraints, as well as the normal discipline gates associated with the discipline functions. Examples are control system stability, turbomachinery stability and vibration, thermal, structural strength, and durability, as well as other pertinent gates associated with propulsion system design.
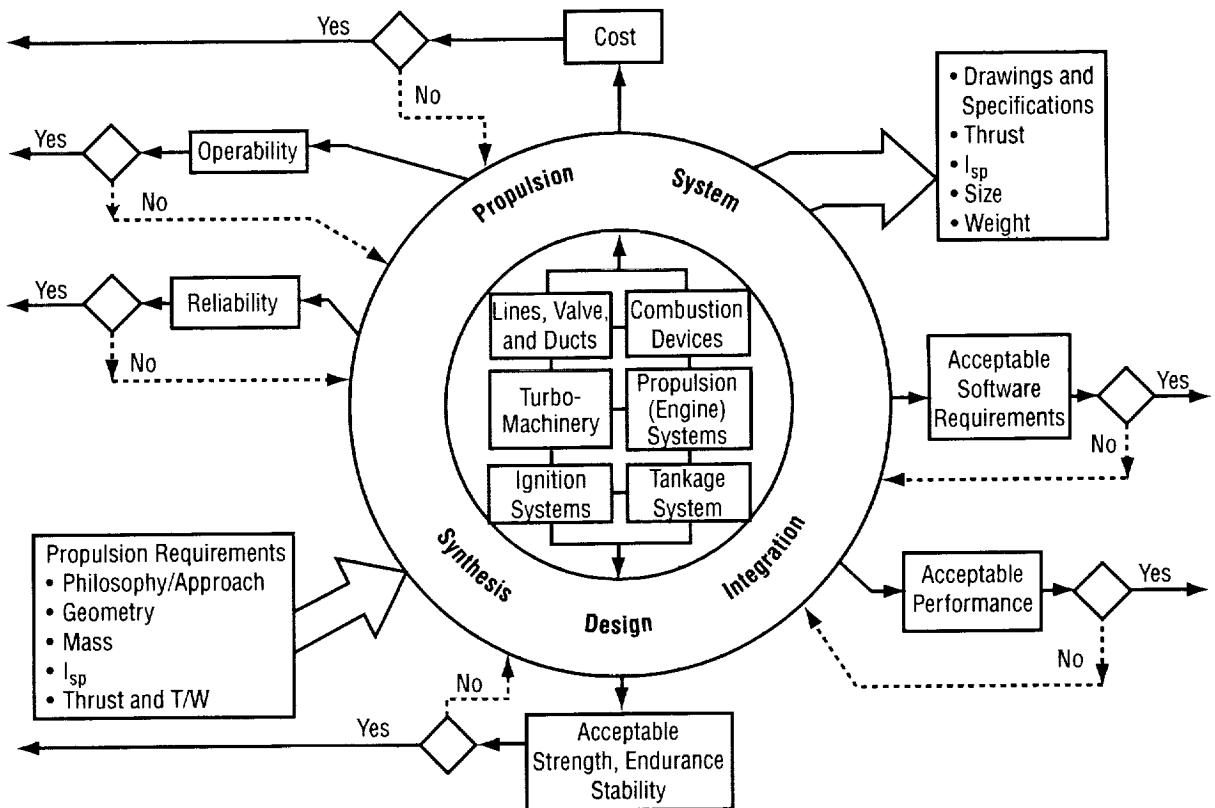
Figure 60. Propulsion design function gates.

The propulsion decision gates include first and foremost the engine performance, which is its ability to efficiently convert chemical energy into propulsive energy (thrust) at the level required to meet the vehicle performance. Implied in this statement are the additional factors of weight, thrust to weight, volume, etc. The engine system must also meet cost, reliability, and operational requirements. In addition to these performance and program requirements, the propulsion system, its subsystems, elements, and components must meet all the discipline requirements such as strength, fracture, fatigue, thermal, etc. Additional thoughts on these gates are in section 4.3.6.2. The major point to remember is that there are many crucial trades between the propulsion system and the rest of the vehicle that result from attempting to meet their respective gates. It should be remembered that the propulsion system provides the energy to achieve orbit. In achieving this requirement, it dictates much of the structures design. For example, the liquid propellant tanks and lines transfer the chemical potential energy to the engines that produce thrust that transmits through thrust frames back to the tanks, etc., to achieve vehicle kinetic energy. Thus, the propulsion system greatly influences the dry weight (mass fraction) of the system. The vehicle cannot

weigh too much or it is too costly. Its geometry cannot be too expansive or, again, operations and cost are too high. Reusable systems also require well-defined, efficient, and effective maintenance and refurbishment characteristics. All these become part of the propulsion system gates and tasks.

4.3.8.3. Propulsion Tasks.

4.3.8.3.1 Task 1—Requirements Determination and Allocation. The propulsion system WBS from reference 2, table 15, is limited to a set of tasks that interact with the other vehicle design functions. There are many tasks required to design the propulsion system and produce the inputs for the tasks defined in table 15. They include design of the engine system, turbomachinery, combustion devices, and engine components. The discussion in the following paragraphs will briefly discuss these tasks. At top level, technical integration tasks are shown in table 16. As with the other design planes, the charts show the general activities, the interactions, and the tasks.

Propulsion system design, as all other design functions, starts with an interaction with the systems plane to determine and allocate requirements to the propulsion plane. Because the propulsion system is composed of many subsystems and elements, these top-level requirements must then be distributed and allocated to the propulsion subsystem levels; for example to turbomachinery and combustion devices. The subsystem requirements are modified by the engine concept selected; e.g., staged combustion versus a gas generator system. In addition, there is a strong interaction from the materials, manufacturing, and structure planes.

In the discussion that is to follow, it is assumed that the propulsion system has been chosen and that the trades and sensitivity data generated to make the selection are available along with the preliminary configuration definition (i.e., staged combustion cycle, liquid hydrogen and oxygen propellants, etc.). This information, along with the above allocated requirements, starts the design process.

Propulsion system design to some extent follows the same compartmentalization approach discussed previously. Subsystems include engine systems, line and ducts, valves, turbomachinery, combustion devices, nozzles, control, etc., each requiring its own design specialties. Key disciplines are rotordynamics, fluid dynamics, thermal, stress, dynamics, fatigue, fracture, combustion, etc. Not only must the propulsion system meet all its engine specific gates but must satisfy the vehicle-imposed requirements. Since the propulsion system ends up influencing a large percentage of the total structural system, this interface is very important. Propellant tanks, for example, compose a large volume and weight of the structure, carrying loads as well as propellant and conditioning the propellant in terms of at least temperature and pressure. Propellant utilization is an important part of the design (how, when, etc., the propellants are flowed and managed). This includes the provision for dumping propellant for aborts or removing propellants during extended holds. A major factor in vehicle design is accommodation (location and arrangement) of engines and the transfer of the energy (thrust) efficiently to provide vehicle acceleration. The first task of propulsion system design is, therefore, the requirement determination and allocation, first from the systems plane to propulsion plane, then from the propulsion plane to its various subsystems, etc.

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Table 15. WBS 2.8—propulsion task description.[2]

Inputs	Tasks	Outputs

• Projected groundrules, design-to-cost goals
• Technology requirements (TRL level)
• Engine I/F
• Redundancy requirements
• Programmatic constraints
• Launch pad environments
• Vehicle configuration and tank geometry
• Line routing zones
• Pressurant bottle locations
••• Preliminary air column
••• Profile
• Vehicle mass versus time
• Thrust, acceleration and pressure versus time
• I_{sp} (flow rates)
• Usable propellant requirements
• Axial acceleration
• Dynamic pressures
• Flow rates
• System dispersions
• Wind dispersions
•• Air inlet constraints
••• Derived air volume
• Air loads on propulsion elements
•• Engine installed thrust
••• Forebody pressure recovery and flow field definition history
• Structural analysis of lines and brackets
• Establish dynamic envelop of feedline
• Determine line thickness
••• Aft/forebody structures
• Propellant condition
• Temperature time history
• Pressure
• Chilldown of engine
• Temperatures and heating loads
• Pogo suppressor requirements
• TVA requirements
• RCS requirements
• Mass properties control plan
• Weights, centers of gravity, moments of inertia
• Material compatibility
• Contamination analysis
• Material properties
• Thermal and cryogenic properties
• Temperature limits
• Telemetry capability
• Sensor characteristics
• Availability of power (current, voltage, phase)
• Operational timelines
• Maintainability
• GSE capability
• Vehicle integrated OPS concept and requirements
• Flight timeline
• Fabrication parameters
• Flight safety review of schematic and OPS
• East and west test range interface
• Hazard analysis
• Fault tolerance requirements
• Reliability allocation and estimation
• Failure mode effects analysis inputs
••• CIL inputs
• Hardware DDT&E and production costs
• Cost trades
	3.9.1 Establish baseline feed system geometry
	3.9.2 Analyze tank/feed system fluid, thermal issues
	    – Temperature profiles
	    – Cryo fluid management
	    – Pressure drop, NPSP availability, water hammer
	    – Residuals ullage
	    – Propellant inventory
	3.9.3 Pressurization system sizing and design
	3.9.4 Valves, ducts, mechanisms design, and layout drawings
	3.9.5 TVC components and design
	3.9.6 Propulsion system schematics and layout drawings
	3.9.7 Testing engine/propulsion component
	
	Tools:
	• In-house software
	• Fluid flow models—cryo fluid management thermal models
	• Testing
	• Commercial software—CAD layout/drawing packages
		• Propellant inventory
		• Propulsion system layout
		• Tank pressures
		• Propellant level sensor locations
		••• Forebody moldline (iterate req air volume)
		••• Staging requirements
		••• Propellant requirements
		••• Number of engines
		••• Performance updates
		•• Entry propellant weight
		• Propellant load
		• Engine performance (I_{sp}, thrust)
		••• Expected engine mach transitions
		••• Inlet captive volume
		••• Recovery pressures
		••• α, for inlet airflow as a function of mach number
		••• Mach transitions
		• Engine dimensional and operational characteristics
		• Turbine exhaust definition
		• On-pad effluent definition
		••• RBCC exhaust conditions
		••• Forebody inlet performance requirements
		• Ignition and shutdown thrust transients and timing sequences
		• Steady state thrust oscillation
		• Ullage pressure and tank fill heights versus flight time
		••• RBCC exhaust/thrust
		• Ground hold conditions
		• Heat load requirements for propellant conditioning
		• Chill down requirements
		• Engine configuration
		• Engine operating characteristics
		• Engine thermal requirements
		• TVC gimbal capability (degree and rates)
		• Feedline layout
		• Kinematic analysis
		• PU system definition
		••• Air capture transition
		• Propulsion system drawings and models
		• Component weight estimates
		• Parts list
		• Life limits
		• Instrumentation
		• Uplink/downlink requirements
		• Drive electronics
		• Electrical power requirements
		• MPS checkout and fill
		• Refurbishment/inspection requirements
		• Verification requirements
		• Transportation requirements
		• Subsystem definition and design description document
		• Vehicle controls
		• Power usage
		••• Flight rules
		• Drawings and schematics
		• Hazard analysis inputs
		• Functional failure model
		• Failure propagation logic development
		• Diagnostics/control logic
		• Failure mode effects analysis inputs
		••• CIL inputs
		• Technical descriptions
		• Vendor quotes
		• Test requirements to include instrumentation
		• Production quantities
		• Make or buy plan

Key: • ELV, RLV, and RBCC
        •• RLV and RBCC
        ••• RBCC only

Table 16. Primary tasks for propulsion design function.

Activities	Interactions	Tasks
1. Requirements determination and allocation	Systems Turbomachinery Combustion Valves, ducts Structures Thermal Flow Control Trajectory	1. Work with systems to flowdown requirements to propulsion including thrust, I_{sp}, T/W, geometry, tankage, etc. 2. Work with propulsion subsystems to allocate requirements for design and verification. 3. Provide to systems, discipline peculiar criteria for formal/legal applications. 4. Develop verification requirements for systems as well as propulsion subsystems. 5. Develop metric flowdown for use by design function gates. 6. Flowup derived requirements to system.
2. Engine system design	Flow Thermal Combustion Turbomachinery Control Structures Testing	1. Determine engine performance characteristics flowdown/allocate requirements to subsystems in conjunction with subsystem inputs. 2. Develop propellants, usage requirements, and coordinate with structural airframe design. 3. Establish propulsion systems development and verification ground-test and flight-test program in conjunction with systems plane, propulsion subsystems, and disciplines.
3. Engine subsystem design	Propulsion systems Materials Flow Thermal Manufacturing Testing	1. Design combustion devices to meet vehicle systems and engine systems requirements and discipline criteria. 2. Design turbomachinery to meet vehicle systems and engine systems requirements and discipline criteria. 3. Design lines, ducts, and valves to meet vehicle systems and engine systems requirements and discipline criteria. 4. Develop ground test program/requirements for each subsystem.
4. Verification	Propulsion system Dynamics Stress Thermal Manufacturing Systems	1. Develop facility (test stands) requirements and implement in conjunction with engine system, subsystems, and disciplines. 2. Coordinate hotfire test requirements with engine systems and subsystems and disciplines including instrumentation, data systems, and test profiles. 3. Run ground test program (hotfire) in conjunction with engine system, subsystem, and disciplines, obtaining and coordinating data for development, verification, and acceptance. 4. Develop plans for qualification and acceptance gates with engine systems, subsystems, and disciplines for static and dynamic ground test that includes, at least, flow, modal, fatigue, strength, vibration, and thermal. 5. Run ground test programs (static and dynamic) in conjunction with engine systems, subsystems, and disciplines obtaining and coordinating data for development, verification, and acceptance. 6. Establish the constraints, maintenance, and operations procedures from results of test program. 7. Final propulsion system validation is achieved in developmental flight tests.

4.3.8.3.2 Task 2—Engine System Design. Task 2 takes these requirements/criteria and designs the propulsion system. This design process is very complex. Analytical models are difficult to obtain. As a result, during design and development of liquid propulsion systems it is mandatory that component and systems tests be used to evolve the design. They can range from air- and water-flow simulations to hot-fire component tests as the design evolves. Then, finally, propulsion systems are developed, verified, and accepted in single engine and propulsion system test stands. A major design activity becomes one of determining test profiles, evaluation metrics, acceptance metrics, etc.

The engine system design must combine all of the subsystems/components into a working system. System design is very complex and challenging. How do you start the engine? How do you control flow and mixture ratio? How do you throttle and shut down the engine? A part of this sequence is engine conditioning before start due to the use of cryo propellants and engine conditioning and purging after shutdown. Obviously, part of this design is tying the valves, actuators, igniters, etc., together through a control system. The timing and balance between the propulsion subsystems, components, etc., is very critical to engine operations. Packaging is also a key issue since, in general, volume is a prime design constraint. As a result, the engine system must put all the parts together and ensure that they work. Managing losses such as flow losses is very critical. Matching the propulsion system to the vehicle system is mandatory. Therefore, interaction between the vehicle system and the propulsion system determines the propellant capacity required, flow rate, and pressures to the vehicle system (then structures), as well as the thrust, etc., and derived requirements such as pogo suppression. Thrust and I_{sp} are provided as propulsion attributes to the system and trajectory planes. Aerodynamics and thermal require the nozzle geometry, thrust, etc., to generate aerodynamics (mainly drag) and plume heating environments. Also, in general, the propulsion system provides thrust vectoring for vehicle controllability.

It should be pointed out again that the propulsion system and the vehicle are strongly coupled. Eighty to ninety percent of the vehicle mass is propellant which drives the structural size. The propulsion system provides the power for boosting payloads to orbit. Producing the power causes effects on aerodynamics and vehicle drag. Usually engines are thrust vectored to provide control thrust as well as axial thrust, in addition to the large coupling with launch vehicle system performance. As a result, detailed communication is required between the propulsion system, the vehicle system, and the other design functions and subsystems.

4.3.8.3.3 Task 3—Engine Subsystem Design. The subsystem/component design usually proceeds in parallel. Turbomachinery must move the propellants at a certain flow rate and pressure. As a result the pumps are a high-energy system requiring a large power source to provide the energy to move the propellants. The first set of gates for turbomachinery design is, therefore, its performance in terms of flow rate and pressure. Designing this type of high performance machine introduces the potential for cavitation and other propellant instabilities that can destroy a pump or degrade its performance. These stability margins become a another set of gates. Rotordynamic stability is another design issue requiring not only damping devices but also minimizing the destabilizing forces. Excessive vibration prevention due to unbalance, etc., is another design task. Gates for rotordynamic stability margins and vibration levels are required. The turbine can have the same kind of issues including disk mode instability, flutter of turbine blades, etc., which must be prevented and require gates as well. Bearing wear is also a design issue. The gate on bearings can be a trade between lifetime and maintenance (bearing replacement). In addition to these very complex, dynamic, and thermal issues, the pump is also a pressure vessel (high pressure) and

must meet strength requirements. It also must meet durability requirements that include low- and high-cycle fatigue, fracture, flutter/vortex shedding, acoustics, and creep. The turbomachinery is, therefore, a very complex design problem with a very stringent set of gates from performance, to stability, to strength and durability. There are other gates which must be met, such as weight and cost; however, some trades to balance can be made between subsystems and at the engine systems plane, as well as at the vehicle systems plane.

Combustion devices follow a similar breakout of design tasks and gates. The first task is the energy conversion task (combustion). Due to the shape of the chamber and other factors, combustion instability can occur, reducing efficiency or even destroying the engine. Gates exist for performance as well as stability. Thrust and I_{sp} are the performance gates. Combustion instability is difficult to predict analytically, thus resorting to test. Combustion chambers and devices are subject to flow instabilities, strength, fatigue, and fracture. Large thermal gradients impact the low-cycle fatigue. Gates, usually the typical structure types, are necessary for these areas. All combustion processes create noise which also impacts the fatigue gates. The combustion device design is also complicated by ignition.

Nozzles can be considered a part of combustion devices or a separate entity. They are very strongly coupled with the combustion devices and the overall performance of the system. Basically, the nozzle shape greatly influences the thrust of the engine. At sea level a low nozzle exit-area-to-throat-area ratio is needed to maintain throat stability as a function of power. At vacuum conditions, a large area ratio is required. Most engine nozzle design is a compromise between atmospheric and vacuum conditions, thus a restriction on the throttle (thrust) level is required in the atmosphere. During start up and shutdown, large shock transients are produced. These transients can produce fatigue damage to the nozzle. Nozzle cooling can be passive or regenerative. In the regenerative cooled case, care must be taken to control leakage, particularly if the engine burns hydrogen. Clearly the nozzle design must deal with strength, fracture, and fatigue. These issues are complicated by the large thermal gradients present. The nozzle design must meet weight, dynamic, and performance gates, as well as the typical strength, fracture, and fatigue gates.

Valves, actuators, lines, ducts etc., all follow the same approach. Their design must meet the performance gates, as well as the standard structures and materials gates. Because of materials compatibility issues, especially with hydrogen and other exotic propellants, gates for materials compatibility exist for the design of all engine parts. Stress corrosion can be a problem for some parts.

4.3.8.3.4 Task 4—Verification. Verification of the propulsion system is very complex and costly, due first to the complexity of the fluid flow and chemical conversion systems (combustion devices). Second, the high performance requirements drive structural design, flow design, thermal design, etc., which usually require special verification. Verification is always a combination of analysis, simulation, and test. The tests consist of component and element tests and system hot-fire tests. Not including all the developmental tests, SSME required for certification at the engine system levels 20,000 seconds on each of two engines of hot-fire ground test. Each new engine or refurbished engine must pass a hot-fire ground acceptance test. The engines and hot-fire tests have special instrumentation for adequate evaluation.

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In addition to these engine system tests, the following tests are performed on elements and components:

- Cold flow (water and air)
- Dynamic (model testing, spin-pit testing)
- Proof pressure
- Strength
- Fatigue (low and high cycle)
- Qualification and acceptance
- Vibration
- Thermal
- Material characterization
  - Extreme hot and cold (near melting to cryo)
  - Environments (hydrogen embrittlement)
  - High mean loads.

Key also is the use of simulations where the engine components and elements such as avionics/control, valves, etc., are coupled with a computer simulation of the other functions such as the combustion process. This allows efficient verification of sequencing, coupling, and software.

Analysis with test verified models is used in general to establish propulsion system structural margins such as strength. Many other analysis tasks include extrapolation to flight environments, off-nominal conditions, etc. There are many verifications which are combined test and analysis. These include propellant conditioning that leads to temperature and pressure requirements on tanks and lines, engine conditioning, start sequences, shutdown sequences, and purges.

Verification of the propulsion system is, therefore, very complex as touched on here briefly. The complexity is greatly increased for high performance manned usage. In this case, reliability and safety is crucial, leading to the requirement for safe engine shutdowns and vehicle aborts. The final verification is achieved through developmental flight testing.
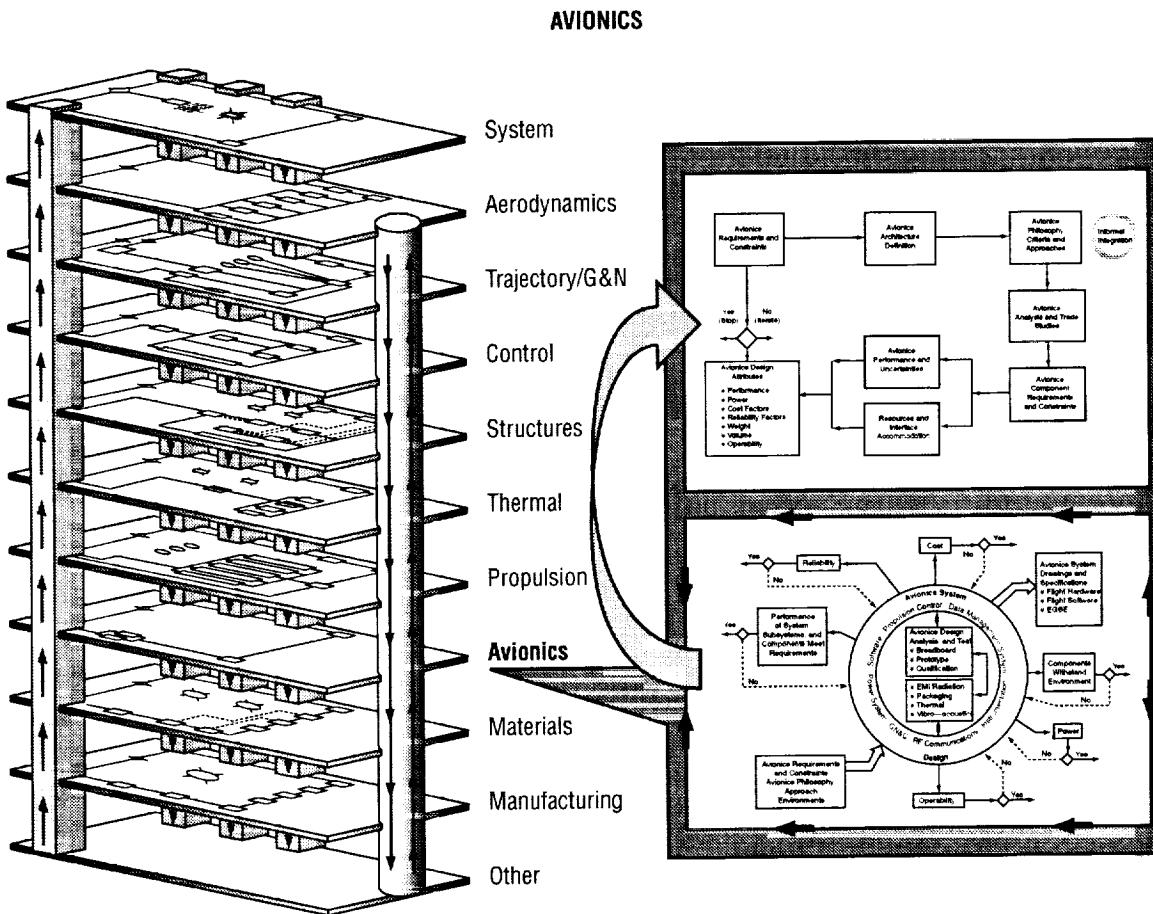
Figure 61. Design process technical integration—avionics design function.

4.3.9 Avionics Design Function

The connection between the design process technical integration and the avionics design function is delineated in figure 61. The illustration depicts the relationship between the avionics design function and the other subsystem design functions. In addition, it shows the work/information flow process that is supported by key avionics decision gates that are required to develop and assess the avionics attributes. The details of all the above are delineated in this section. (Note: Design of the avionics subsystem is a complex process in itself, involving numerous subsystems and specialties. This document does not describe the avionics design process in detail but provides a top-level overview to show its relationship and interaction with the total vehicle design process.)

In this report, the avionics subsystem includes all vehicle electrical and electronic systems, such as GN&C, RF/communications, data management subsystem (DMS) including computers and engine controllers, instrumentation, software, electrical ground support equipment (EGSE), and the electrical power system.

4.3.9.1 Avionics Design Function Plane. The avionics design function includes responsibility for designing the electrical and electronic hardware and software that comprise the avionics system for the vehicle. The avionics system is often considered to be the flight system only. However, both the flight systems and the ground support and checkout systems are included here as part of the avionics design function. Subsystems of the avionics system include GN&C, DMS, RF/communications, instrumentation, software, EGSE, computers, and electrical power. Typical flight hardware components include the vehicle computer, the engine controller(s), the telemetry processor, multiplexers, data storage, antennas, transmitters, receivers, video cameras and processors, instrumentation, sensors, signal conditioners, batteries, cabling, power conditioners, power distributors, rate gyros, and actuator controls. The avionics design function plane is illustrated in figure 62. The avionics design function involves the synthesis of the avionics system to meet requirements in two general categories: (1) Performance of the electrical / electronic systems and (2) resource and interface requirements, including cost, reliability, weight, power use, volume, and thermal conditions. The design of the avionics system involves interactions with disciplines in other design functions including the systems plane. Interaction with the systems plane is vital in determining the requirements for the avionics system. The system plane establishes the aforementioned general categories of requirements. Internal to the avionics design function is the avionics system engineering and integration discipline. This discipline is responsible for understanding the requirements for avionics from the systems plane and deriving the more detailed avionics system requirements. Requirements are allocated and analyses and trade studies are performed. Reliability requirements are considered together with weight, power, volume, and cost to determine the appropriate level of redundancy and redundancy management which is a major driver in avionics complexity. From these requirements, the avionics system architecture is defined. All disciplines within the avionics design function are involved in the architecture definition, but the avionics systems discipline is responsible for assuring that the architecture will meet the overall requirements and constraints. Component requirements and constraints are derived and an electrical, electronic, and electromagnetic (EEE) parts plan is developed.
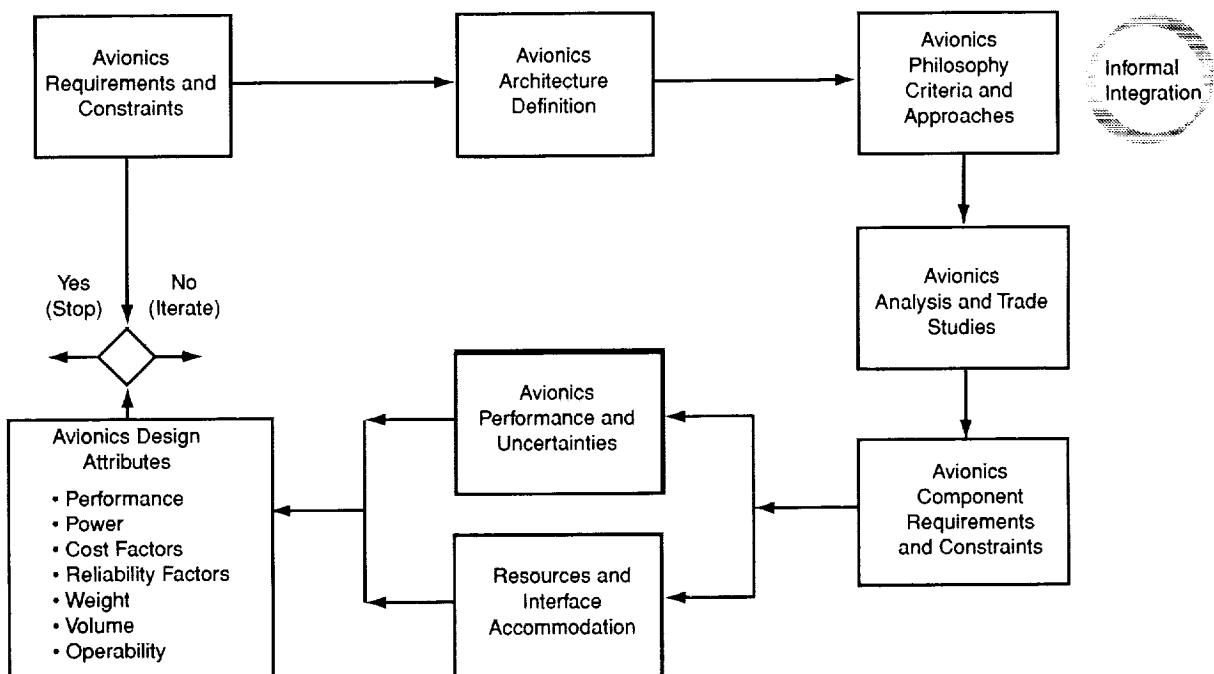
Figure 62. Avionics design function plane.

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An important factor at the time of the architecture definition is the determination of the means and extent of verification of the avionics system. In some cases, verification may begin in an avionics systems testbed or hardware simulation laboratory. Within the testbed, vehicle and engine computer simulations are integrated with the various hardware elements allowing early system testing of the avionics system. This testbed is also used for the important function of verification and validation of the vehicle flight avionics system software. Flexibility is built into the testbed so that all avionics hardware elements do not have to be present at all times. Those hardware elements not present are simulated with computers and software or, in some cases, simple electrical simulations.

The defined architecture provides the basis for preliminary layouts of the various avionics elements. The preliminary layouts are determined from the judgment of the designers as to what hardware will best meet the requirements and the proper division of hardware and software functions. Analysis and, where appropriate, breadboard testing determine the performance and uncertainties of the components. Packaging to accommodate the environments is designed, and estimates are made of the power, weight, volume, and thermal characteristics. The collected attributes of the preliminary design are then compared with the avionics requirements and constraints, and the design is iterated until satisfactory convergence or relief from requirements is sought from the system plane. Make or buy decisions are made on the individual elements of the preliminary design. These elements are built and tested before integrating into the avionics subsystem. Testing as a system may be done in a hardware simulation laboratory. An overall representation of the avionics systems design process and the interactions is depicted in figure 63.
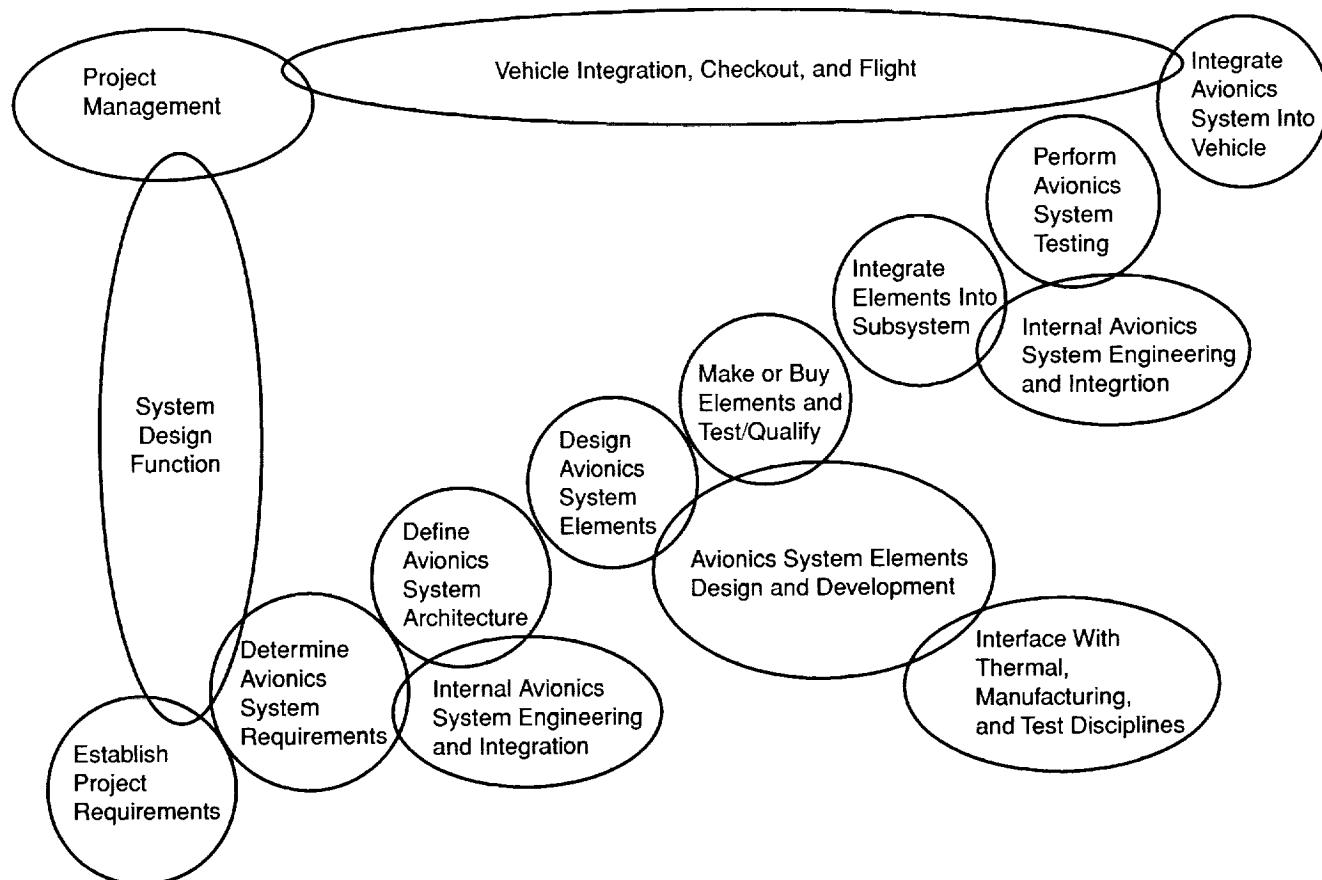
Figure 63. Avionics systems design process interactions.

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A listing of inputs and outputs for the avionics design function process along with discipline activities and products is shown in figure 64. This process flow diagram addresses design considerations for the elements that comprise the total avionics system and is consistent with the flow diagram of the avionics plane. Table 17 is a WBS for the design process for a typical avionics subsystem, the DMS. The WBS chart lists specific tasks that are embedded in the task categories of section 4.3.9.3 and the inputs and outputs of the subsystem design process. The WBS for the other subsystems, including software, would be of a similar nature. Figure 64 and table 17 are an adaptation of the process flow diagrams and task WBS charts of reference 2.

Requirements
- Program/Project
- Constraints
- Concepts

Inputs
- Aerodynamics and Induced Environments
- Structural Analysis
- Materials
- Manufacturing
- Vehicle Configuration and Structural Design
- Performance and Trajectories
- Mass Properties
- Thermal
- Guidance and Controls
- Propulsion
- Ground Operations
- Flight Operations
- Safety
- Reliability
- Cost

Internal Flow

Consultation	Options	Trades	Analysis	Cost

GN&C, Communications, Data Management Subsystem, Electrical Power System, Software, EGSE

- Component Specification
- Make/Buy Evaluation
- Design
- Project Design Reviews
- Parts List
- Schematics
- Test Requirements
- Test Procedures
- Test Reports
- Interface Control Drawings
- Hazard Analysis Inputs
- FMEA Inputs
- Software Requirements
- Software Development and Test Plan
- Software Design Specification
- Software Test Procedures
- Systems Simulation Testing
- Integration and Verification Test Support

Hazards	Benefits	Reliability	Operability	Maintainability
Cost/Make or Buy	Resources Utilization	Requirements Feedback	Test Req'ts/ Procedures	S/W Algorithms
Sizing/Configuration				

Products

Specifications and Drawings For:

- Flight Components
- Flight Software
- GSE
- Ground Support Software
- Instrumentation Program and Component List (IPCL)
- Verification Reports

Figure 64. Avionics process flow diagram.

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Table 17. Data management subsystem task description.

Inputs	Tasks		Outputs

• Avionics system requirements
• Avionics architecture
• IP&CL
• Natural and induced environments
  – Thermal
  – Vibration
  – Radiation
  – EMI
• Materials
• Weight
• Power
• Volume
• Cost
• Verification requirements
• Manufacturing
• Vehicle configuration
• Flight operations
• Ground operations
• Safety
• Reliability
	3.10.3.1
	3.10.3.1.1
	3.10.3.1.2
	3.10.3.2
	3.10.3.2.1
	3.10.3.2.2
	3.10.3.2.3
	3.10.3.3
	3.10.3.3.1
	3.10.3.3.2
	3.10.3.3.3
	3.10.3.4
	3.10.3.4.1
	3.10.3.4.2
	3.10.3.4.3
	3.10.3.4.4
	3.10.3.4.5
	3.10.3.5
	3.10.3.5.1
	3.10.3.5.2
	3.10.3.5.3
	3.10.3.5.4
	3.10.3.6
		Requirements
		  Components
		  Avionics system inputs
		Design
		  Trades and analysis
		  Subsystem design
		  Components
		Documentation
		  Parts list
		  Schematics
		  Released drawings
		Test
		  Test requirements
		  Test procedures
		  Component tests
		  Subsystem tests
		  Test reports
		Subsystem/component GSE
		  GSE trades and analysis
		  GSE design
		  GSE test
		  GSE documentation
		Project/program reviews
			•Subsystem design specifications
			• Flight components specifications
			  – Computer
			  – Command receivers
			  – Data processors
			  – Remote data acquisition units
			  – Storage devices
			• GSE specifications
			  – Subsystem design
			  – Components
			• Released drawings
			  – Test specifications and
			    procedures

The design and development of the avionics software and the EGSE should be an integral part of the avionics design function from the onset. The development of the software requirements requires the interactions of the other design functions through the systems plane. This is evident from consideration of examples of typical functions relegated to the software, such as execution of vehicle and engine control algorithms, receipt, interpretation, and execution initiation of uplinked commands, acquisition of data from on-board instrumentation, and compilation and formatting of instrumentation and operations data for telemetry downlink. Typically, the development of the detailed software requirements may lag the development of the hardware requirements. For example, it may be prudent for the completion and review of the software requirements to coincide with the review of the preliminary design of the avionics system. The EGSE requirements depend on the overall GSE requirements for the vehicle which is a responsibility of the system plane. Typically, there may be requirements for ground power systems and a ground computer system to control and monitor the vehicle ground checkout process. The design of these EGSE systems may be complex and require a process similar to the flight system design process. The ground computer system must have numerous hardware interfaces for meeting requirements for issuing command discrete and analog voltages and acquiring instrumentation data and the vehicle telemetry stream. A user interface system for the EGSE computer must be developed. In some cases, it may be cost effective and technically desirable to achieve some software design commonality in the EGSE computer system and the aforementioned hardware simulation laboratory, particularly in the user interface, the command handling, and the telemetry processing functions.

4.3.9.2 Avionics Gates. Decision gates for the avionics design process are shown in figure 65. Inputs to the process are the avionics philosophy and approach, the environments for the hardware, and performance requirements from the vehicle subsystems that require avionics, such as GN&C, propulsion, thermal, and structures. Interactions with these subsystem design functions are required throughout the design process. Gates for the avionics system fall into three general categories: (1) Performance gates which measure the functional performance of the various avionics subsystems against their requirements; (2) survivability gates which measure the ability of the avionics hardware to withstand its environments; and (3) resource/operational gates which measure attributes such as weight, power consumption, volume, thermal conditioning requirements, reliability, operability, and cost. Functional performance is determined by analysis, simulation, and breadboard, prototype, and qualification testing. Layout and packaging to withstand thermal and vibroacoustic environments lead to units which are environmentally tested, with the packaging design being modified until survivability is demonstrated. Avionics designers are guided by program requirements and resources. The top-level attributes such as cost, weight, power, volume, reliability, and operability are measured against allocated requirements. Once the design has converged to satisfy all gates, the avionics system drawings and specifications can be released, software produced, hardware manufactured, and avionics components and subsystems tested.
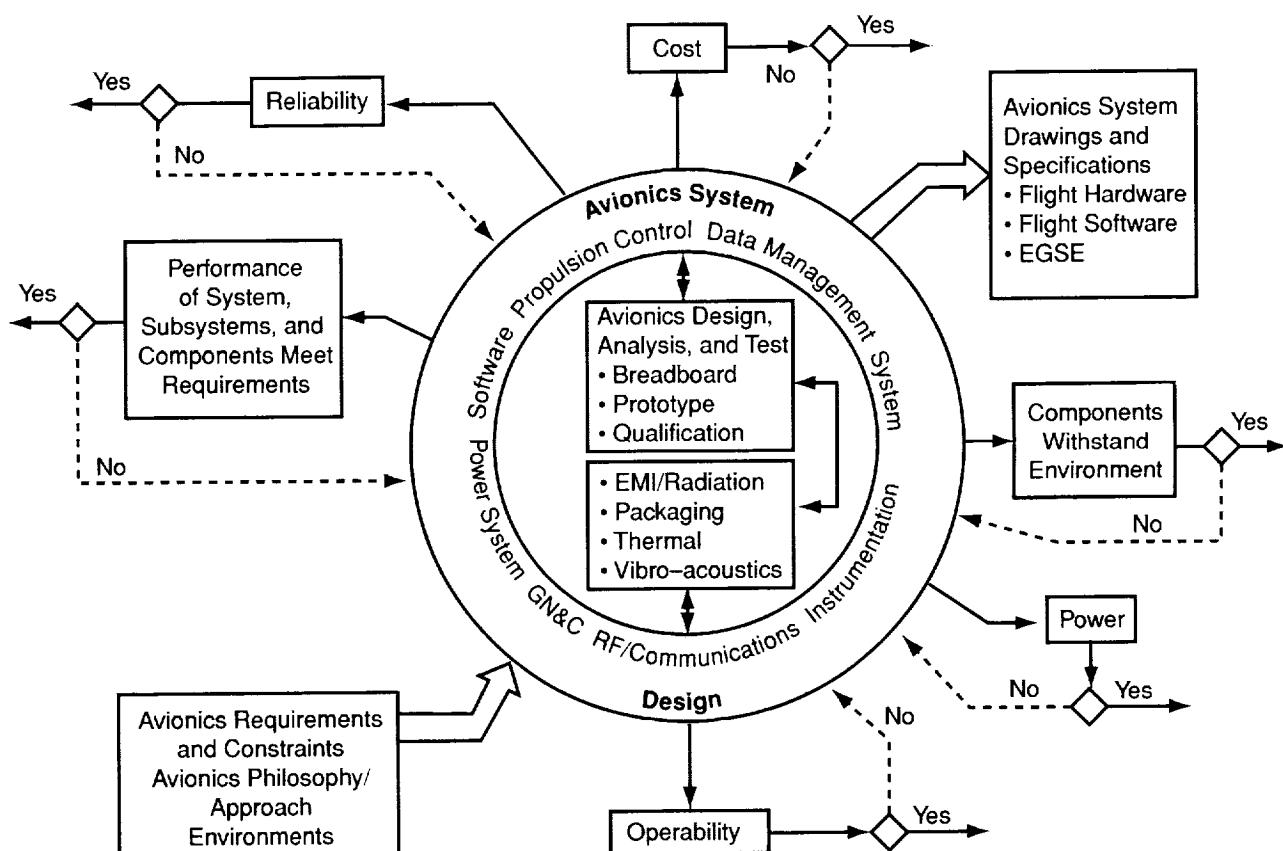
Figure 65. Avionics system design function gates.

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4.3.9.3 Avionics Tasks. The top-level avionics design activities are summarized in table 18 and are described below. The design activities include both flight and ground support equipment.

Table 18. Primary tasks for avionics design function.

Activities	Interactions	Tasks
1. Requirements determination and allocation	System Internal system groups Control G&N Propulsion Thermal Natural environments	1. Consult with system to aid in initial requirements allocation of cost, reliability operability, maintainability, etc. 2. Consult with control, G&N, propulsion, and any internal system group to obtain avionics hardware/software/EGSE performance requirements. 3. Obtain environmental requirements, both natural and induced. 4. Feed back attributes to system and to system groups. Provide trade data and consultation for revised allocation, if required.
2. Avionics architecture	System Internal system groups Control G&N Propulsion	1. Obtain requirements from system and other system groups that specify hardware/software requirements. 2. Identify candidate architectures and component options for flight and ground. 3. Determine redundancy concept. 4. Identify initial make/buy approach. 5. Perform initial top-level assessment of attributes and compare with requirements. 6. Modify architecture as required and iterate requirements if needed to achieve convergence of attributes and requirements.
3. Avionics subsystem design	Internal system groups Control G&N Propulsion Thermal Structures Environments	1. During detailed design, maintain close coordination with system groups that specify hardware/software requirements. 2. For subsystems, including EGSE, and components that are to be made versus bought, perform necessary design steps through concept identification, analysis, breadboarding, component testing, and integrated testing. 3. Develop necessary software from requirements through coding, checkout, and verification and validation testing. 4. Iterate performance and requirements to obtain convergence. 5. Track cost, reliability, operability, and maintainability attributes, iterating with system if not compliant with requirements.
4. Verification	Internal system groups Control G&N Propulsion Thermal Structures Environments	1. Establish a verification plan at early stage of design or procurement. 2. Perform functional verification incrementally as components are developed. 3. Perform qualification testing on flight components. 4. Perform integrated testing of hardware components on integrated test beds. 5. Perform verification in applied environments—vibrations, thermal, vacuum, EMI, radiation, etc.

4.3.9.3.1 Task 1—Requirements Determination and Allocation. This activity is a joint responsibility between the system design function and the avionics design function, working also with the design functions/ subsystems where avionics has responsibility for hardware/software design and implementation. These include all of the avionics subsystems and other appropriate interacting disciplines. As the hardware/software

design organization, the avionics design function is the keeper of the requirements for cost, reliability, maintainability, power usage, etc., as allocated from the system plane. Performance requirements for the avionics components are derived through interaction with the design functions that have the system design responsibility in their respective areas. For example, for control system sensors (i.e., rate gyros, accelerometers, etc.), the sensor range, sensitivity, resolution, bandwidth, and noise requirements are obtained from the control design function after close interaction between avionics and GN&C to converge to the most appropriate set of requirements. Similarly, performance requirements for propulsion instrumentation and avionics components are obtained from propulsion after intensive interaction between the avionics and propulsion design functions. Environmental requirements are obtained from the natural and induced environments groups: radiation, shock, vibroacoustics, and temperature. Avionics interacts with materials in determining the appropriate materials selection.

Avionics consults with the system plane in the allocation of top-level requirements for cost, reliability, and maintainability. Most component performance requirements are derived requirements which flow from the respective organizations which have system design responsibility for that particular subsystem. Meeting the top-level requirement allocation with satisfactory performance usually entails iteration and feedback by avionics with the interfacing groups to converge to a design acceptable to all parties.

4.3.9.3.2 Task 2—Avionics Architecture. Based on initial requirements allocation and interaction with the system groups for the avionics subsystems, avionics identifies candidate architectures and component options directed toward meeting the requirements. Vehicle reliability and failure philosophy requirements, in conjunction with component reliability estimates, drive the requirement for redundancy which is a major factor in the architecture. Initial consideration is given to make/buy options, and a top-level assessment is made, comparing estimated system attributes of performance, cost, reliability, operability, etc., with their requirements. Significant difficulty in meeting requirements may necessitate iterations on requirements with the system and other design functions and disciplines at this stage. When reasonable compliance is achieved with satisfactory margins, detail design begins on the avionics subsystems.

4.3.9.3.3 Task 3—Avionics Subsystem Design. As with other parts of the vehicle, avionics subsystem design is of an iterative nature, entailing steps of greater fidelity and detail. Close coordination is maintained with the systems groups as the hardware/software definition refines. Since the systems groups are also iterating their designs to greater fidelity, requirements may change. Management of margins, primarily from experience base, plays an important role in minimizing requirement iterations.

When the decision is to buy a component, the design function is replaced by detailed specification development, procurement, test, and verification. When the decision is to make a component, design proceeds through concept, simulation, analysis, preliminary design, breadboarding, detailed design, component testing, and integrated testing. The software design goes through a similar process as the hardware. As previously stated, because some of the software detailed requirements are derived during the avionics hardware design process, the software design may not reach maturity as soon as the hardware design. This must be recognized as a factor in the planning and scheduling of the vehicle development.

4.3.9.3.4 Task 4—Verification. The avionics components and the integrated avionics subsystem must be verified for functionality, performance, and compatibility with the environment it will experience. Verification is an iterative process as the flight components and EGSE are developed or procured, making

use of testbeds appropriate to the component or subsystem being tested. Function and performance are checked for the hardware elements over the range of variability that is expected to be encountered. Verification of the capability of the hardware to withstand its expected environments is accomplished by determining correct functioning before, during, and after testing in the pertinent environments—EMI, radiation, vibration, acoustics, thermal, and vacuum. Software is subjected to development, verification, and validation testing, exercising the software with as many combinations of inputs and operating conditions as possible. Depending on factors such as reliability requirements and cost, it may be desirable to subject the software to independent verification and validation testing; i.e., performed by those other than the developing organizations and personnel. Integrated testing of the avionics subsystem is accomplished on testbeds that combine flight-type avionics components with simulated or real interfacing hardware elements. These testbeds may be also used for software testing with both the simulated and real hardware elements. Final validation for both hardware and software is accomplished in flight testing.

4.3.9.4 Avionics Implementation Function. The avionics design function provides the specifications and drawings required for fabricating the avionics hardware and generating the software. The avionics implementation function produces the hardware and software. The hardware specifications and drawings are developed in the design function based on the overall architecture decisions, as well as the philosophy and approach. Depending on these decisions, there may be long-lead procurement items which may need to be initiated soon after the end of the design function or, in some cases, prior to the end. The most common examples of the long-lead items are the highest reliability class of EEE parts. In implementation of the electronic subsystems, a breadboard system may be built and tested in the laboratory. For each subsystem, such as the flight computer subsystem, a unit tester is designed and built. The unit tester provides a stand-alone simulation of all interfaces with the ability to test the basic functionality of the subsystem. The decision may be made to build an engineering model for some subsystems which emulates the flight subsystem in "form, fit, and function." The unit tester for the flight computer subsystem, as well as for some other subsystems, is useful for early software testing. Engineering models of the avionics subsystems may be used for subsystem testing of the design but are also the primary avionics components of the simulation laboratory that are used for avionics system and software testing. Qualification models may be built which contain identical parts and packaging as the flight system. The qualification models are used in the environmental and vibroacoustic testing phase. For one-time flights, the qualification model may become the flight unit which is commonly called protoflight hardware. For a flight vehicle avionics system design to be flown multiple times, the qualification model becomes the basis for the fabrication of the flight systems.

In the design function phase of the software, design specifications are produced. The design specifications contain information such as the overall architecture and design of the software, a breakdown of the architecture into individual software modules, the detailed software-to-software and software-to-hardware interface definitions, the structure of the telemetry and command interfaces, and the definition of the methodology for implementation of the real-time requirements of the software. In the implementation phase, the individual software modules are coded and subjected to development testing. Appropriate groups of modules are integrated and tested. Timing analyses are conducted to ensure that the implementation of the design will meet the performance requirements. Ensuring that the real-time requirements are met in the software implementation is of critical importance. Once development testing is complete, the software modules are integrated and the verification and validation testing phase can begin.

4.3.10 Materials and Manufacturing Design Functions Overview

The design properties of a material system are contingent on the manufacturing processes employed, both in the primary production and secondary shaping and assembly phase. Accordingly, the design functions of materials and manufacturing have been historically linked. Their interdependence in the modern era has been magnified by the rapid expansion in the development of both new materials and new processes.

Composite materials, including metallic, nonmetallic, and combinations thereof, are examples of advanced structural material systems that challenge traditional design methodology. Many such systems require the development of design properties specific to individual component shapes. This differs from most metal alloy systems where the design properties for basic product forms (i.e., sheet, plate, extrusions etc.) are readily available and apply, independent of final component shape. When working with advanced structural material systems, it is often necessary to develop the manufacturing processes concurrent with the component design. The result is a "best fit" compromise between part configuration, weight, cost, and schedule. Assembly processes, such as welding and bonding which alter the properties of a material, also require special attention and clearly delineate the synergistic relationship between materials and manufacturing.

Note: Executing the materials and manufacturing design functions is a complex process in itself, involving numerous disciplines and specialties. This document does not describe the process in detail but provides a top-level overview to show its relationship and interaction with the total vehicle design process.

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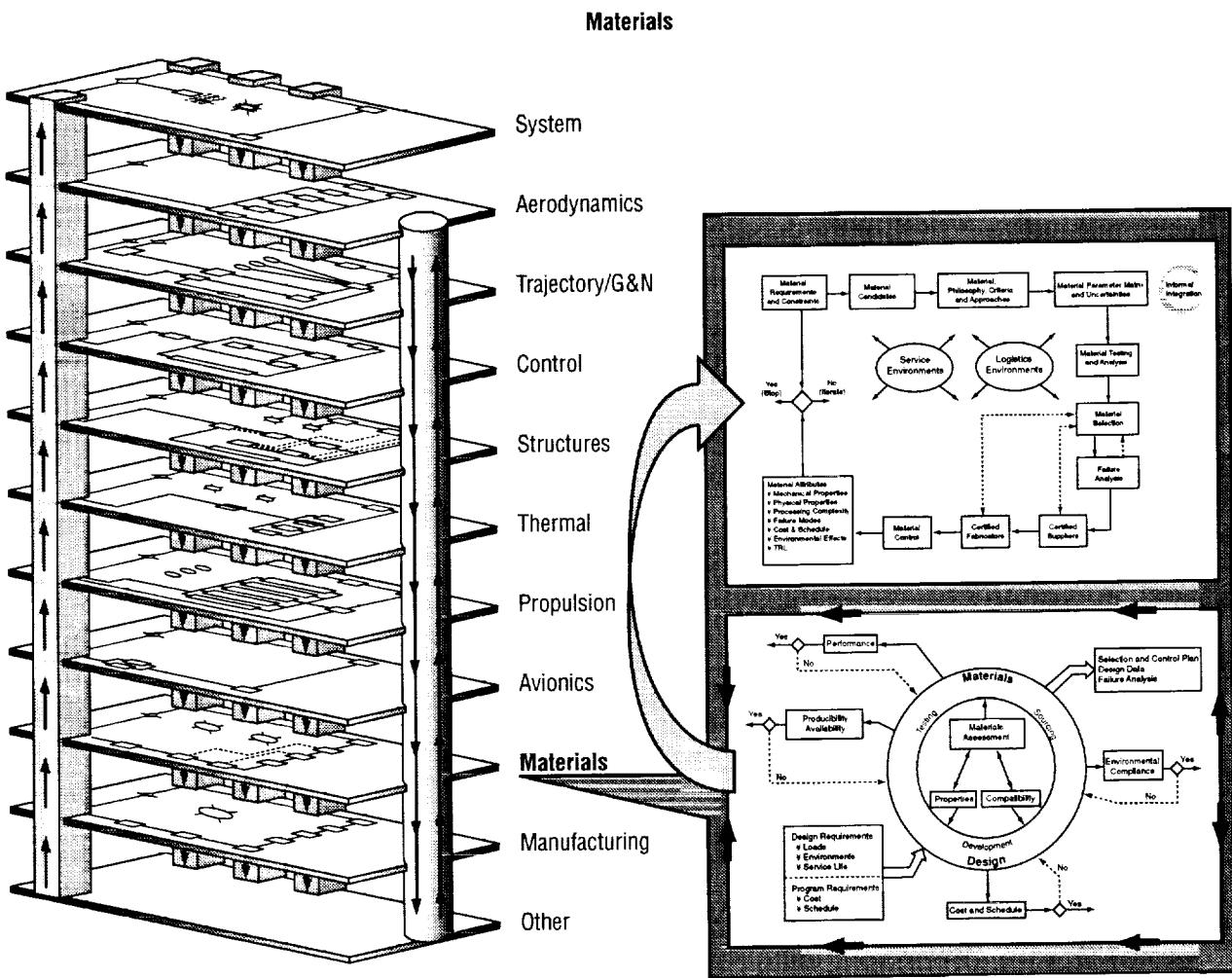
Materials

Figure 66. Design process technical integration—materials design function.

4.3.11 Materials Design Function

Materials is considered a unique function. However, the distinctions between design functions and discipline functions are less rigid in the materials plane than in the more traditional design planes such as structures, propulsion, and avionics. Materials specialists interact directly with hardware designers and analysts throughout the design, development, test, and verification phases. This interaction is enhanced through the evolving integrated engineering environment which facilitates the immediate exchange of information across design planes and between discipline specialists. The relationship between the materials design function and other design functions is shown in figure 66.

4.3.11.1 Materials Design Function Plane. The materials design function plane is depicted in figure 67. The output of this plane is the materials design with all its inherent characteristics for a component, element, subsystem, or system.
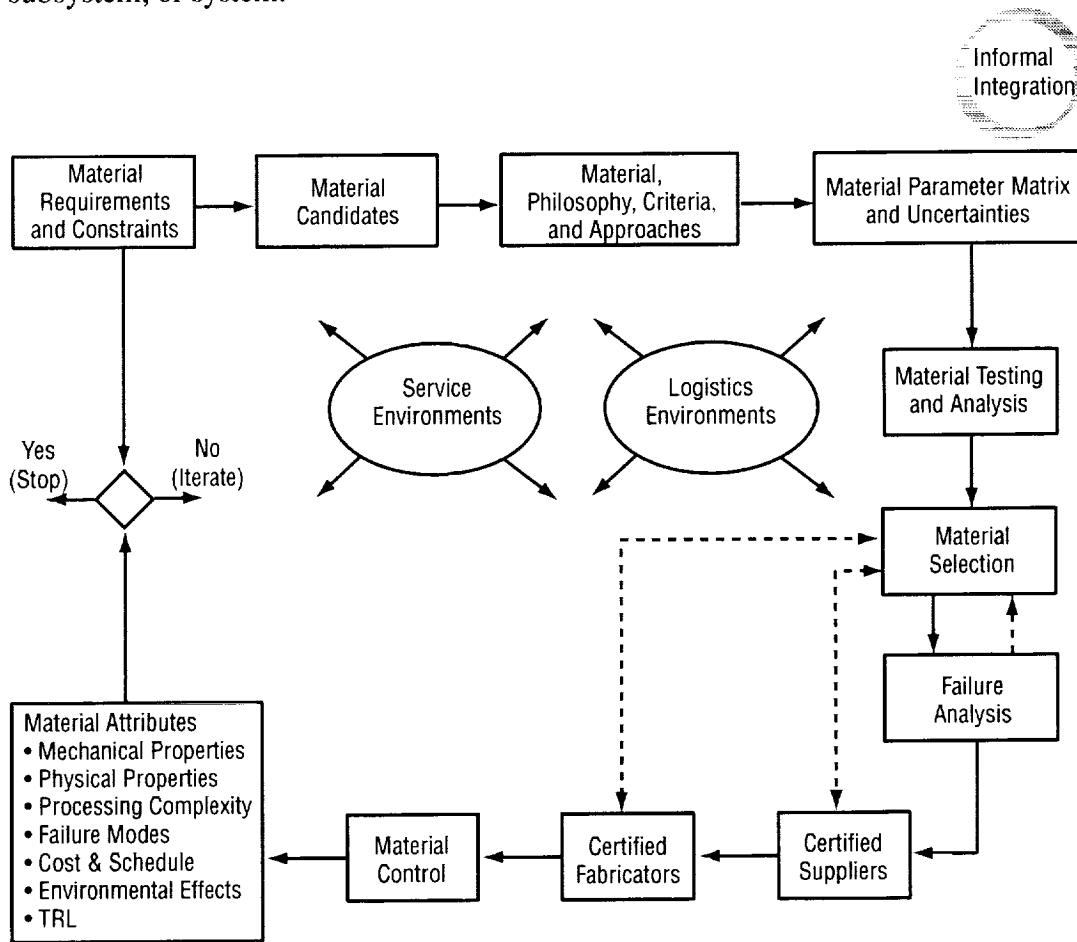
Figure 67. Materials design function plane.

The materials design function can be viewed simplistically as having overall responsibility for material selection, material control, and material performance. This responsibility extends to the full compliment of environments to which the materials are exposed, starting with their receipt and ending with their retirement from service.

Unlike the more conventional visualization of a design function, the materials design function does not directly define a component configuration. Rather it provides design data and specifications regarding materials and commercial piece parts that becomes a part of the release documentation.

The materials design function is associated with all other design functions in which a physical product (hardware) is being developed. Data bases, incorporating the mechanical and physical properties of virtually all conventional aerospace materials along with acceptance criteria for their use, are maintained and can be computer accessed by the design and analytical specialists. Additionally, it is the responsibility of the materials design function to review the evolving structural, thermal, propulsion, and avionics designs, develop further data where required, and approve the material selections and specifications contained in the release drawings.

Material specialists interact directly with process and manufacturing engineers to collectively assess the producibility of the design. They also identify long lead procurements and enabling technologies, along with their projected costs and development schedules. This becomes input to the other design planes where design features can be reconciled with resource and schedule allocations at the systems level.

Material specialists also participate in acceptance and verification testing of component hardware and systems, assessing material performance, and providing structural failure analysis when required.

The WBS elements 2.9, and tasks of reference 2 provide listings of inputs and outputs for the materials design function. The NxN diagram of reference 2 (app. A) is representative of further delineation of the associated inputs and outputs. The materials WBS elements are reproduced herein as figure 68 and table 19.
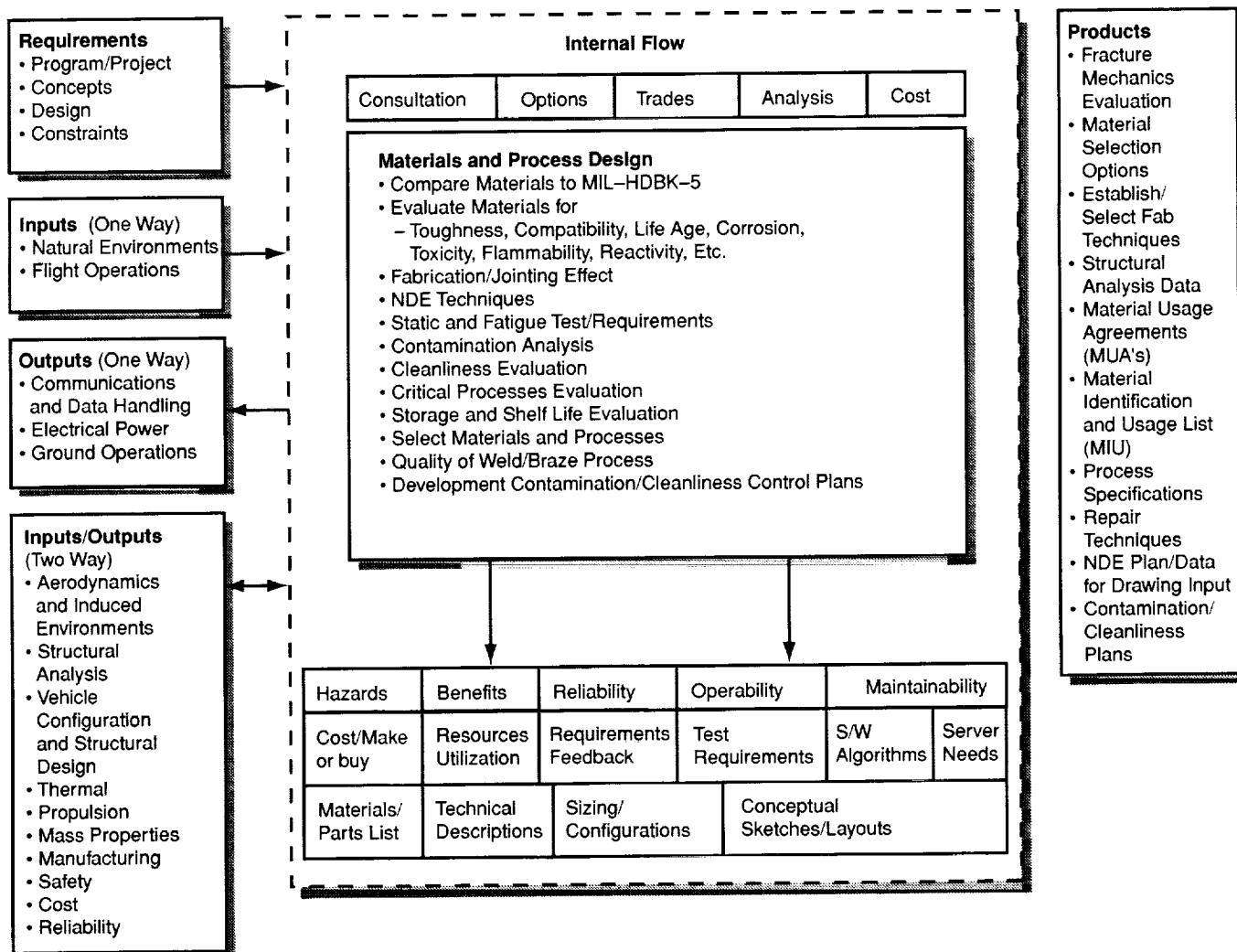
Figure 68. WBS 2.9—materials and processes design process flow diagram.[2]

Table 19. WBS 2.9—Materials design task description.[2]

Inputs	Tasks		Outputs

• Drawings
• Component function
• Load/life requirements
• Environment
  – Temperature
  – Humidity
  – Pressure
• Accessibility
• Design engineering
  and strength
  requirements
• Special material
  requirements
• MIUL
• Assembly operations
• Environment restrictions
	3.8.1
	3.8.2
	
	3.8.3
	3.8.4
	3.8.5
	
	3.8.6
	3.8.7
	3.8.8
	3.8.9
	3.8.10
	3.8.11
	
	3.8.12
	3.8.13
		Compare candidate materials to
		MIL–HDBK–5 data
		Evaluate materials per MSFC–
		STD–506 and NHB 8060
		requirements:
		Including but not limited to:
		– Toughness
		– Compatibility with intended use
		  environments
		– Life and aging
		– Corrosion, stress corrosion
		– Toxicity
		– Flammability
		– Reactivity
		– Flaw environmental and cyclic
		  growth rates
		Evaluate fabrication and joining effects
		Develop NDE techniques
		Conduct static and fatigue tests to
		obtain missing and needed data
		Contamination analysis
		Cleanliness evaluation
		Critical processes evaluation
		Storage and shelf life evaluation
		Select materials and processes
		Qualification of weld and braze
		specimens
		Develop NDE techniques
		Develop contamination and cleanliness
		control plans
			• Fracture mechanics
			  evaluation
			• Material selection options
			• Establishment and selection
			  of fabrication techniques
			• Data for structural
			  analysis
			• MUA
			• Materials selection and
			  control plan
			• MIUL– final
			• Process specifications
			• NDE inspection and
			  implementation
			• Procedures
			• Repair techniques
			• Hazardous operations
			  evaluation
			• Process schedules
			• Personnel certification
			  requirements
			• NDE plan and data for
			  drawing input
			• Contamination and
			  cleanliness plans

	Tools: • NASA and MIL data bases		

Key: •   ELV, RLV, and RBCC
        ••   RLV and RBCC
        •••   RBCC only

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4.3.11.2 Materials Design Function Gates. Decision gates for the materials design function are shown in figure 69. They are (1) performance, (2) environmental compliance, (3) producibility/availability, and (4) cost/schedule.
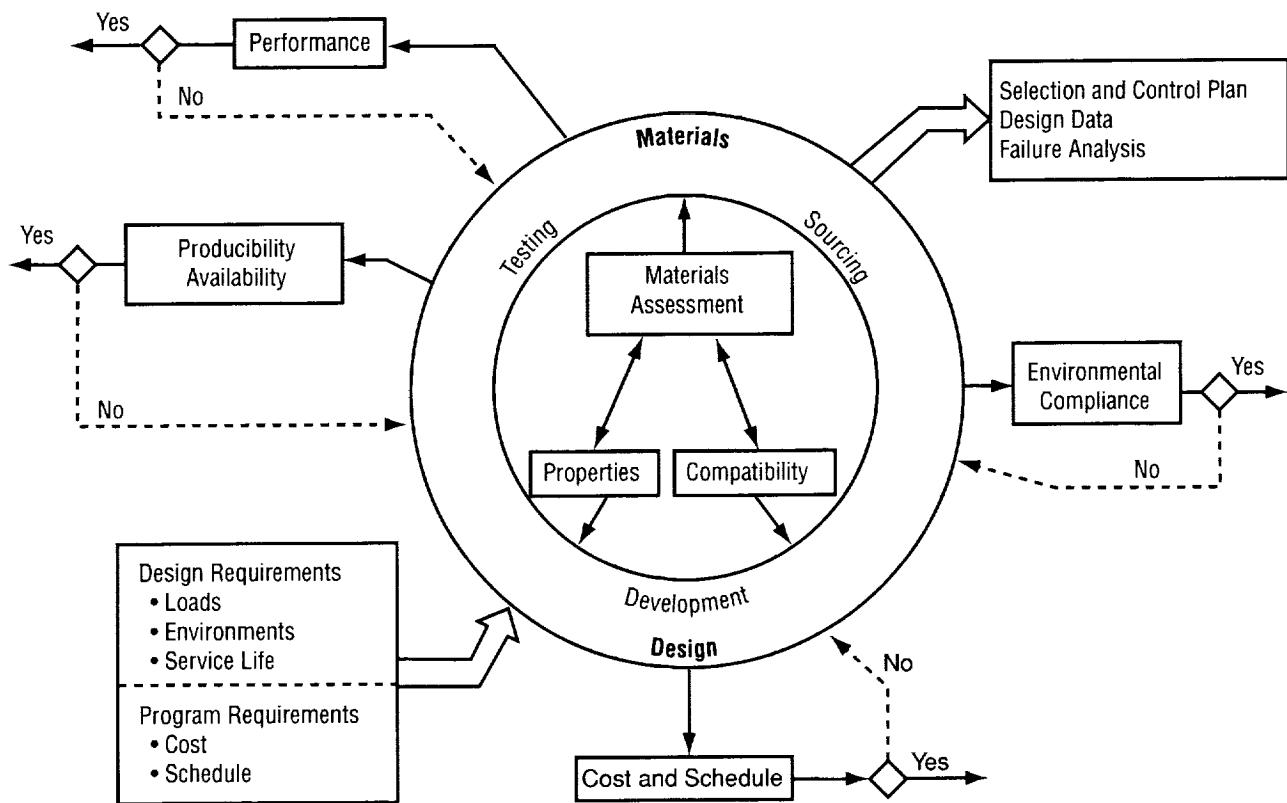
Figure 69. Materials design function gates.

Functional performance is determined by test, considering applied loads, service environments, and service/cycle life. Environmental compliance requires a thorough researching of applicable Occupational Safety and Health Administration (OSHA)/Environmental Protection Agency (EPA) regulations regarding the control of hazardous materials. This extends to the production and use of a material or component and the operation of a device that produces hazardous waste products. Producibility involves interaction with potential suppliers to determine that all materials or elements of component design are available or can be provided. Special purpose materials not readily available on the commercial market may require vendor certification. This assures that the production processes are adequately controlled to provide a product with consistent properties. Certification is also required for critical secondary processes, welding and bonding for example, that can effect the properties of the assembled structure. Cost and schedule are self-explanatory. However, in most aerospace applications, the basic material costs are relatively minor contributors to the overall cost of the system and, generally, do not influence the design.

4.3.11.3 Material Tasks. The top-level tasks of the materials plane are shown in table 20. They consist of (1) requirements determination and allocation, (2) material selection and control, (3) material development, (4) materials testing and analysis, and (5) failure analysis.

Table 20. Primary tasks for materials design function.

Activities	Interactions	Tasks
1. Requirements determination and allocation	System Structures Thermal Propulsion Manufacturing	1. Meet with system and design functions to identify initial requirements for material selection or development. 2. Consult with system and design functions to establish safety factors and acceptable levels of risk to be reflected in the materials philosophy and criteria. 3. Consult with manufacturing to confirm the adequacy of existing methods of fabrication or to determine the need for additional process development. 4. Work with system and design functions to establish cost and schedule resource allocations. 5. Work with system and design functions to reconcile nonconforming material issues, conduct trade studies, and, where necessary, revise requirement and/or resource allocations.
2. Material selection and control	Structures Thermal Propulsion Manufacturing Procurement Quality	1. Consult with designers regarding acceptable material usage. 2. Review and approve material specifications contained in design documentation. 3. Develop and maintain material data bases. 4. Consult with manufacturing to resolve primary and secondary material processing issues. 5. Coordinate material supply issues with procurement and quality. 6. Maintain material control records for critical hardware.
3. Materials development	System Structures Thermal Propulsion Manufacturing Quality	1. Consult with design to obtain requirements for new materials. 2. Consult with manufacturing regarding applicable processes. 3. Work with quality to certify new materials and processes.
4. Materials testing and analysis	Structures Thermal Propulsion Manufacturing	1. Consult with designers regarding adequacy of available materials data. 2. Perform testing to develop supplemental or "design specific" data. 3. Coordinate specimen fabrication with manufacturing.
5. Failure analysis	Structures Thermal Propulsion Manufacturing Quality	1. Consult with design and quality to develop failure analysis plan. 2. Coordinate specimen requirements for simulating service failures with design and manufacturing. 3. Work across disciplines to implement failure analysis plan, develop fault trees, and coordinate supporting tests and documentation reviews.

4.3.11.3.1 Task 1—Requirements Determination and Allocation. The allocation of materials requirements is determined jointly by the materials design function, the system design function, and other design functions that are users of the materials. Materials consults with the system design function and the user design functions to identify and flowdown the initial requirements for material selection or development. Typical requirements include mechanical and physical properties, compatibility with other materials and service environments, failure-mode constraints, environmental-compliance constraints, and cost and schedule constraints. While formal requirements allocations are made by the system design function, the materials design function has a central role in defining requirements and identifying an appropriate allocation. Likewise, the materials design function defines the materials selection and control philosophy and criteria that are then imposed formally from the system level. Metrics for the requirements are determined and included in the decision gates. If the material attributes do not meet the requirements and informal iteration among the design functions and disciplines cannot resolve the problem, the attributes and sensitivities are fed back to the systems function for trades and possible revision of the requirements allocation. As the design progresses, it is common for the requirements to be updated iteratively until convergence is achieved.

4.3.11.3.2 Task 2—Materials Selection and Control. Materials are selected based on their ability to function in the overall range of loads and environments to which they will be exposed. Selection further involves an assessment of the manufacturing processes to be employed, commercial availability, life cycle of the component, and, in some instances, cost. Initial material selections are generally made by the other appropriate design functions using information contained in a variety of databases. Material specialists assist in the selection when available data is insufficient, or where indepth assessment of viable material options is warranted. Material specialists also review the final material selections for all critical flight and test hardware and concur in the released documentation.

The materials design function is the principal repository for materials data. It maintains a current data base on virtually all-conventional aerospace materials. This data base is continually updated as new information becomes available and can be readily accessed from any appropriately computer-equipped location.

Material control, an element of configuration control, is also a primary responsibility of the materials design function with support from quality assurance. Material control is imposed on all critical flight hardware and associated test facilities. It requires that the location of all materials used in these applications be traceable and their pedigree verifiable. Issues such as cycle-life limits, out of specification service environments, quality escapes, and fraudulent parts drive the requirement for material control.

4.3.11.3.3 Task 3—Materials Development. Materials development is undertaken by the materials design function in concert with the manufacturing and hardware design functions. Materials development is normally associated with research activities to extend the present state of the art for aerospace hardware. However, it can also be the result of unique aerospace requirements for which a broader commercial market is not apparent. Traditional suppliers often cannot justify investing their resources to produce these materials without government subsidy and/or indemnification. Interestingly, in many cases, broader markets evolve once these materials are developed and their properties characterized.

4.3.11.3.4 Task 4—Materials Testing and Analysis. Materials testing and materials analysis are performed to upgrade and supplement the design data base. Testing and analysis are also done to support unique design applications or assist in analyzing service or other hardware failures. Testing and analysis ranges over the full complement of standard assessment techniques for determining the physical and

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mechanical properties of materials. It also includes simulated service testing in the environments unique to space flight, such as various forms of oxygen and hydrogen combined with high pressures and temperatures, testing corrosive media, and space radiation testing.

Certain materials are batch sensitive; i.e., vagaries in the production process result in materials that differ in service performance from batch to batch. Some nonmetallic materials used in oxygen-rich environments, for example, must be tested for impact sensitivity and individual batches accepted for use based on the test result.

Data from all tests are ultimately reviewed by material specialists for significance and accuracy. If it passes these screens, it is then submitted for inclusion in the materials data base.

4.3.11.3.5 Task 5—Failure Analysis. Assessment of material failures is performed by the materials design function. It is often conducted in concert with other design, analytical, and quality disciplines that interact to define the root cause of a component, system, or test-facility failure. The actual analysis of the failed hardware is preceded by a plan that assures evidence is not lost in the handling of the part or the sequence of dissection. Failure analysis employs a wide range of sophisticated diagnostic techniques. In many instances it requires simulating the failure in specifically designed test specimens under precisely controlled conditions. A fault tree is also a common tool used in exploring significant failure events. The fault tree starts with the resultant and explores all possible contributors, weighing and rejecting those that are less probable to arrive at the most probable cause. Fault trees are characteristically supported by analysis, testing, and detailed documentation reviews.
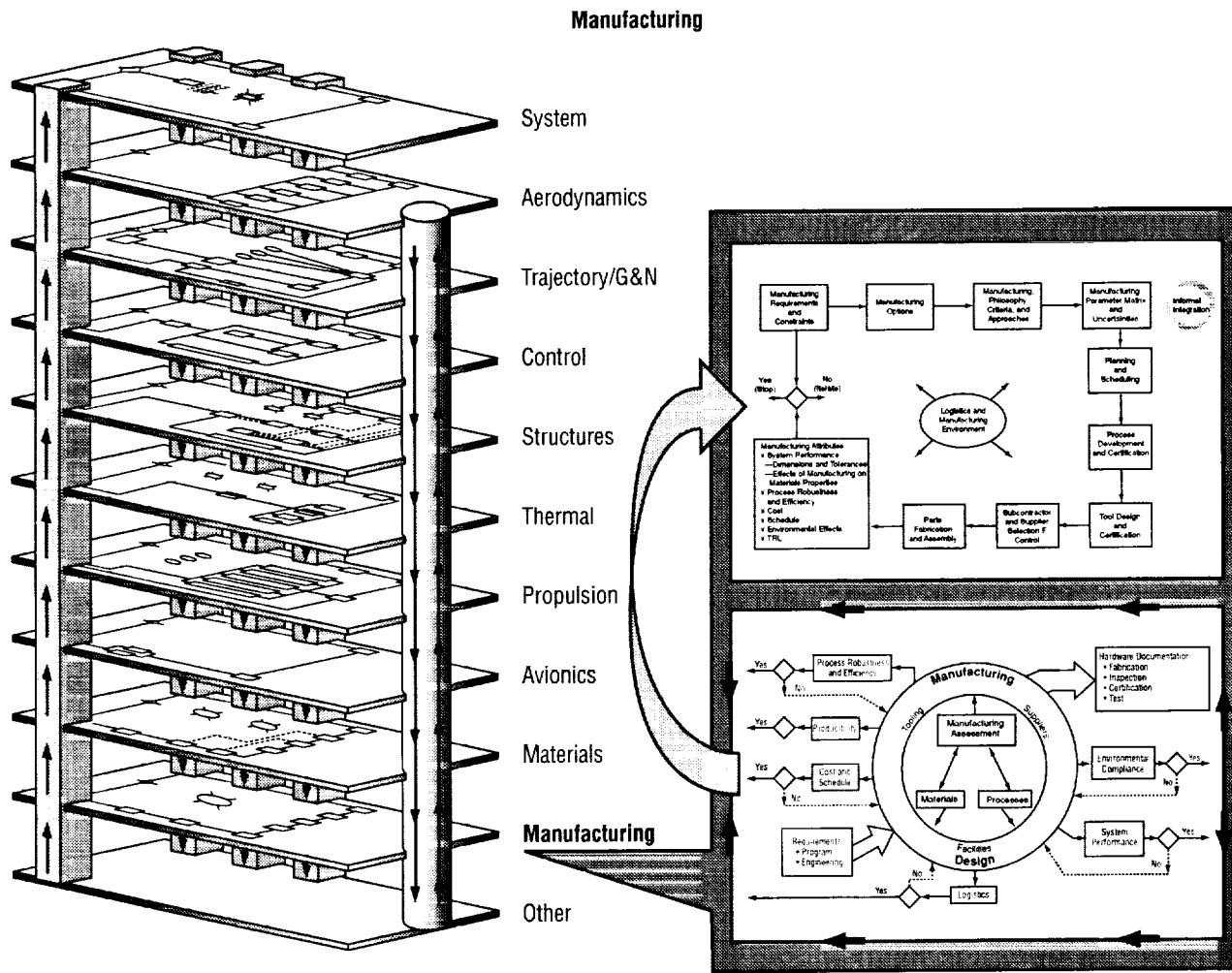
Figure 70. Design process technical integration—manufacturing design function.

4.3.12 Manufacturing Design Function

The manufacturing design function includes all activities associated with the definition and implementation of the manufacturing process. The relationship between the manufacturing design function and other design functions is shown in figure 70.

4.3.12.1 Manufacturing Design Function Plane. The manufacturing design function plane is depicted in figure 71. The main output of this plane is planning and documentation to specify fabrication, inspection, certification, and test. Residing on the manufacturing plane are the subelements involved in the manufacturing activity. The significant subelements are described in limited detail in section 4.3.12.3. They are requirements determination and allocation; planning, scheduling, and cost; process development and certification; tool design and development; subcontractor/vendor selection and control; and parts fabrication and assembly.

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┌──────────────┐      ┌──────────────┐      ┌──────────────┐      ┌──────────────┐
│ Manufacturing│      │              │      │ Manufacturing,│     │ Manufacturing│
│ Requirements │─────▶│ Manufacturing│─────▶│ Philosophy,  │─────▶│ Parameter Matrix│
│ and          │      │ Options      │      │ Criteria, and│      │ and          │
│ Constraints  │      │              │      │ Approaches   │      │ Uncertainties│
└──────────────┘      └──────────────┘      └──────────────┘      └──────────────┘
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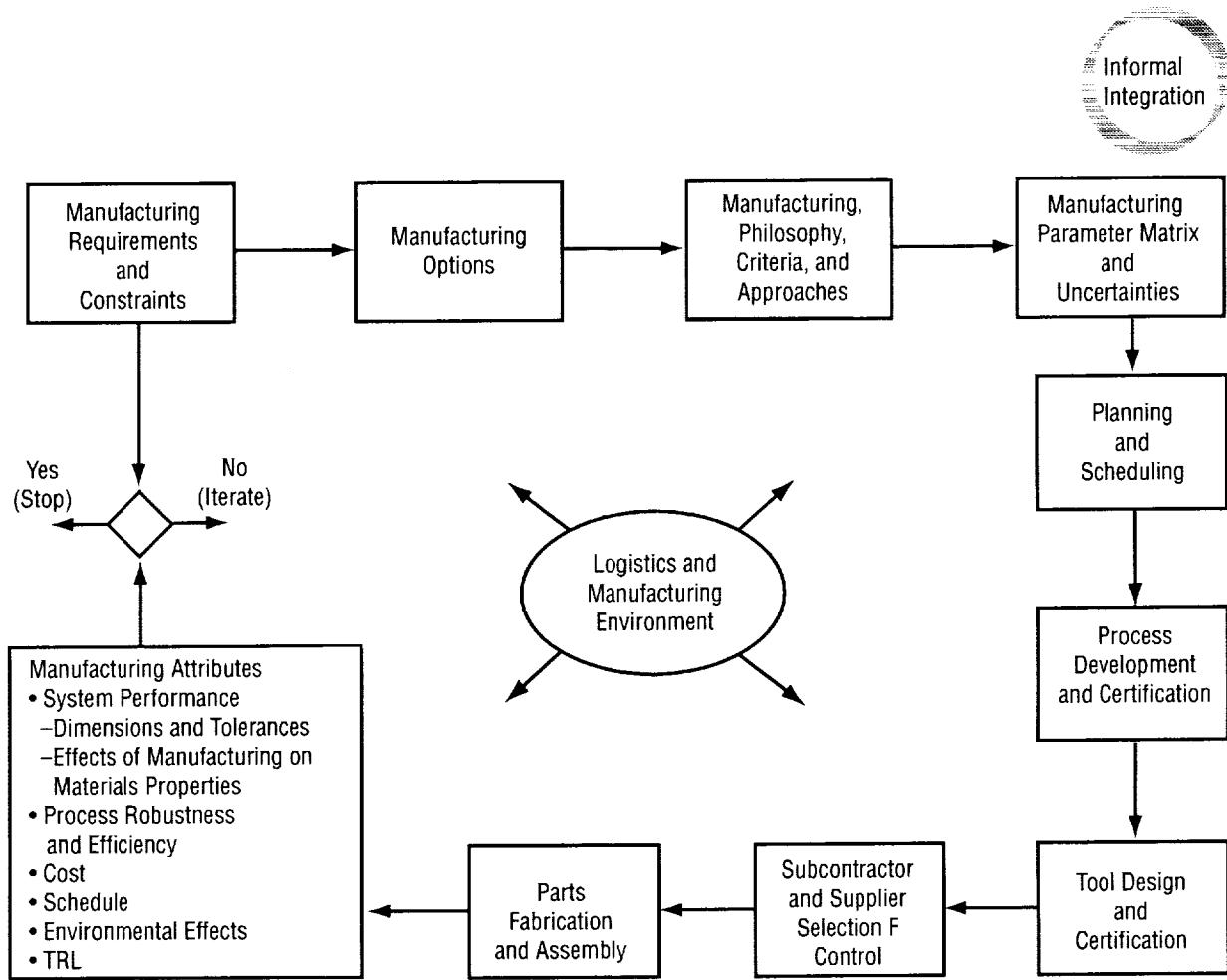
Figure 71. Manufacturing design function plane.

Manufacturing has overall responsibility for producing hardware in compliance with program demands and the requirements of the released design documentation. Manufacturing engineers and planners interact with process engineers, hardware designers, analysts, quality and safety personnel, contracting personnel, material specialists, project engineers, vendors, and contractors throughout the manufacturing cycle. These interactions are necessary to coordinate changes, adjust schedules, determine the disposition of discrepant hardware, and react to program redirection or unforeseen problems that may impact cost or schedule.

The WBS elements 2.14 and tasks of reference 2 provide listings of inputs and outputs for the manufacturing design function. The NxN diagram of reference 2 (app. A) is representative of further delineation of the associated inputs and outputs. The manufacturing WBS elements are reproduced herein as figure 72 and table 21.
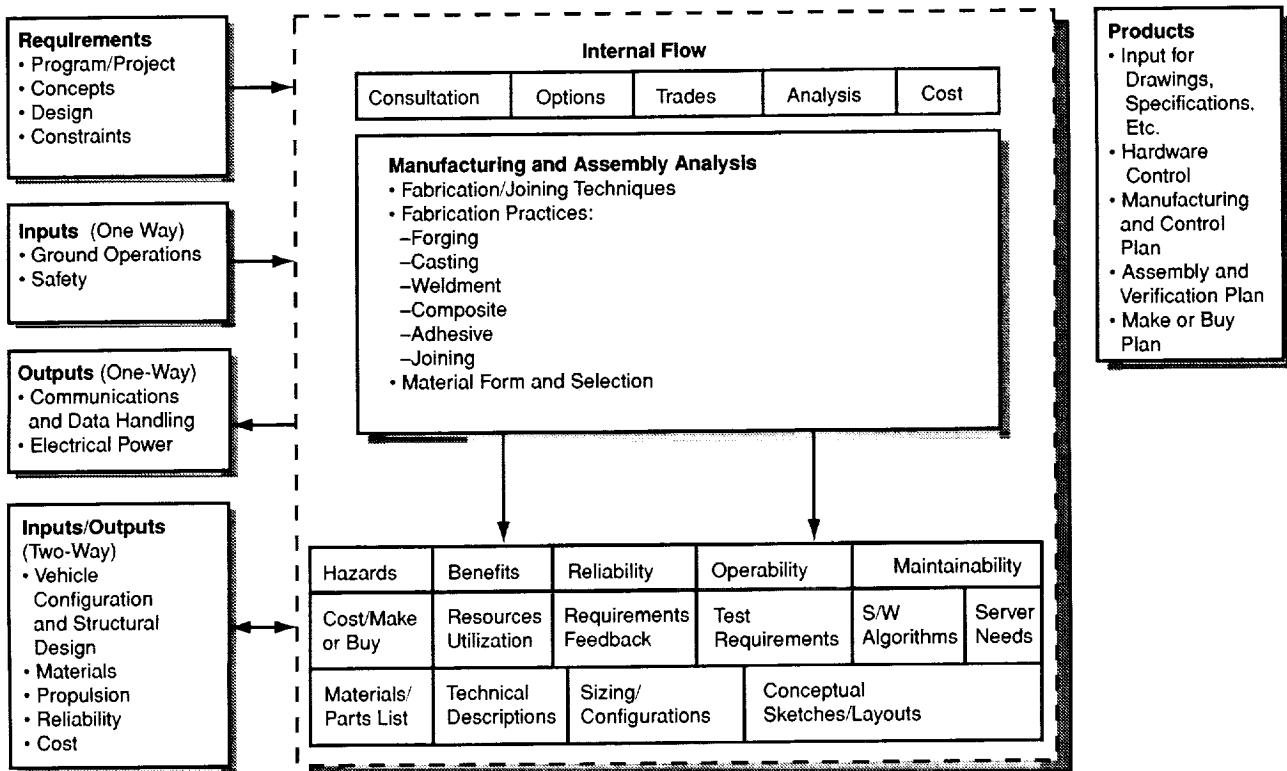
Figure 72. WBS 2.14—manufacturing design process flow diagram.[2]

Table 21. WBS 2.14—manufacturing process task description.[2]

Inputs	Tasks	Outputs

• Drawings
• Component function
• Assembly operations
• Schedules
• Inspection and assurance requirements
• Cost restrictions
• NDE plan
• Cleanliness plan
• Contamination plan
• Quality plan
	3.14.1 Develop fabrication and joining techniques
	3.14.2 Evaluate fabrication practice:
	  – Forging
	  – Casting
	  – Weldment
	  – Composite
	  – Adhesive
	  – Joining
	  – Etc.
	3.14.3 Evaluate material form and selection for best manufacturing practice
		• Input for drawings, notes, specifications, etc.
		• Hardware control
		• Manufacturing control plan
		• Assembly and verification plan
		• Make or buy plan input

	Tools: • NASA and MIL databases	

Key: •   ELV, RLV, and RBCC
     ••   RLV and RBCC
    ••• RBCC only

4.3.12.2 Manufacturing Design Function Gates. Decision gates for the manufacturing design function are shown in figure 73. They are (1) producibility, (2) robustness, (3) system performance, (4) logistics, (5) environmental compliance, and (6) cost and schedule.
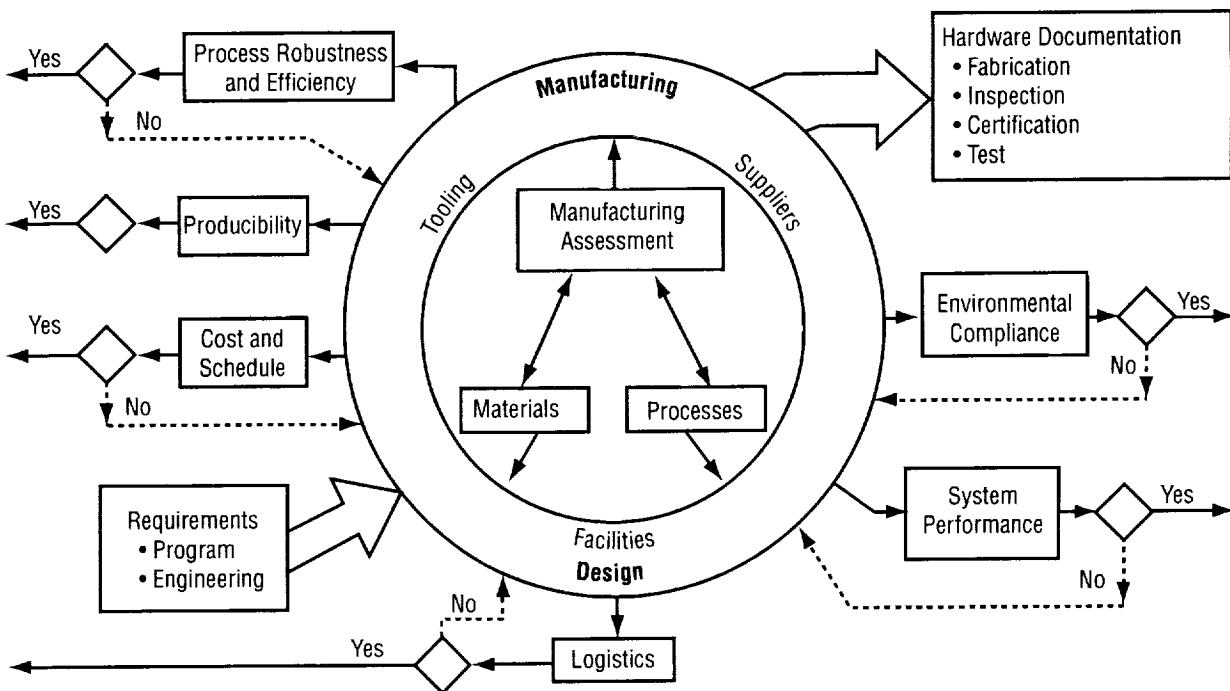
Figure 73. Manufacturing design function gates.

Producibility is addressed early in the design of a component or assembly and continues throughout the design process. Manufacturing engineers participate directly with designers, analysts, and material specialists to assure that the component or assembly can be produced and that appropriate manufacturing requirements are incorporated within the design. Often these take the form of modifications to reduce cost or simplify the manufacturing process. Producibility reviews also address the availability and adequacy of proposed facilities, material suppliers, and parts vendors to support the project. Items that require long lead times for procurement or new processes for their production are identified in the producibility reviews, along with projected costs and development schedules. The output of the producibility reviews becomes input to the other design planes where design features can then be conformed to resource and schedule allocations at the systems level.

Robustness is generally inherent in well established manufacturing processes but is often lacking in newly developed processes. These frequently rely heavily on operator skill to produce a satisfactory product. Before a new process is placed into production, formal operating procedures are developed and rigid tooling and/or modern control systems added. These promote consistency in the process and add to its robustness. They also reduce the need for highly skilled operators by limiting and controlling the degree of operator interaction allowed in the process.

System performance reflects the ability of the full complement of manufacturing activities to achieve the requirements established by the design functions. Typical requirements include dimensions and tolerances, material properties, inspection criteria, and maintenance criteria. System performance is a key attribute of the manufacturing function.

The logistics gate involves interaction with designers, analysts, and transportation specialists to assure safe packaging and transportation of large and/or delicate assemblies. Environmental compliance requires thorough research of applicable OSHA/EPA regulations regarding the control of hazardous materials. This research extends to the use and disposal of toxic materials employed in the manufacturing process and the protection of workers involved in these processes. The cost and schedule gate is self explanatory.

It is important to note that the manufacturing phase of launch vehicle development places heavy demands on program assets. It is advisable to allocate adequate time and resources to optimize the design prior to its release. Changes made to the design after its release typically have a much greater negative impact on both cost and schedule than changes made earlier in the project.

4.3.12.3 Manufacturing Tasks. The primary tasks of the manufacturing plane are shown in table 22. They consist of (1) requirements determination and allocation; (2) planning, scheduling, and cost; (3) process development and certification; (4) tool design and development; (5) subcontractor/supplier selection and control; and (6) parts fabrication and assembly.

4.3.12.3.1 Task 1—Requirements Determination and Allocation. The determination of manufacturing requirements and constraints is achieved by the manufacturing design function in conjunction with the system design function and other design functions that interact with manufacturing. These requirements and constraints are then allocated to manufacturing via the system plane and this flowdown initiates the manufacturing activities. The system design plane controls formal allocation of requirements and constraints. The manufacturing design function, however, has a central role in defining them and identifying appropriate allocations. Typical requirements and constraints include critical process identification, process verification, operator training, environmental compliance constraints, facility and process constraints, and cost and schedule constraints. The manufacturing design function also identifies the manufacturing philosophy and criteria which are then formally imposed by the design function. Metrics for the requirements are determined for the decision gates. When the manufacturing attributes cannot support the imposed requirements, informal discussions between the design functions are initiated. If the problem cannot be resolved in this manner, the attributes and sensitivities are fed back to the system design function for trades and possible revision of the requirements allocation.

4.3.12.3.2 Task 2—Planning, Scheduling, and Cost. Planning and scheduling begin in the early stages of the producibility reviews and mature into the detailed production control documents that govern the manufacturing effort. Written process instructions which also contain the inspection requirements of the quality control organization are generally adequate to manage small projects. However, large, complex projects often require that the manufacturing philosophy be defined in a comprehensive manufacturing plan. Development of this plan parallels development of the design and is normally a data requirement of any procurement effort having a major manufacturing component. The manufacturing plan outlines the tooling concepts and manufacturing processes to be employed and identifies any new processes that must be developed and certified. It describes vendor and supplier requirements, inspection requirements, and

Table 22. Primary tasks for manufacturing design function.

Activities	Interactions	Tasks
1. Requirements determination and allocation	System Structures Thermal Propulsion Manufacturing	1. Meet with system and design functions to identify initial requirements and constraints. 2. Consult with materials regarding unique material processing requirements. 3. Work with system and design functions to conduct trade studies and establish cost and schedule resource allocations.
2. Planning, scheduling and cost	Project System Structures Thermal Propulsion Materials Procurement Quality	1. Work with design, materials, quality, and procurement to define the manufacturing approach or develop the manufacturing plan. 2. Work with project, system and design to identify new facility requirements. 3. Consult with project, system and design to reconcile priority, cost, and schedule issues.
3. Process development and certification	Structures Thermal Propulsion Materials Procurement Quality	1. Meet with design and materials to establish requirements for new manufacturing processes. 2. Work with process and material engineers to develop new manufacturing methods. 3. Work with procurement and/or quality to certify new manufacturing methods.
4. Tool design and development	Project System Structures Thermal Propulsion Procurement Materials Quality	1. Coordinate tooling requirements and approach with design and materials. 2. Reconcile cost and schedule issues with project and system. 3. Work with procurement and/or design to acquire tool documentation and hardware. 4. Coordinate tool certification with design, materials, and quality.
5. Subcontractor/ supplier selection and control	Project System Design Materials Procurement Quality	1. Meet with project, system, design, and materials to reconcile unique or sole source supplier issues. 2. Work with procurement and quality to identify and certify viable suppliers and contractors.
6. Parts fabrication and assembly	Project System Structures Thermal Propulsion Materials Quality Procurement	1. Create detailed process specifications and work planning documents in concert with design, materials, and quality. 2. Work with quality to train and certify technicians to perform critical process operations. 3. Fabricate and assemble parts and coordinate changes with design. 4. Meet with interacting disciplines to disposition discrepant hardware, resolve problems, or react to program redirection.

any new facilities needed. The major tools and processes unique to the project are displayed in illustrations. The flow of parts through the subassembly and inspection stations to final assembly is diagrammed in factory floor layouts. The manufacturing plan and its implementation cost are major discriminators in selecting a prime contractor for launch vehicle production.

Scheduling a new manufacturing effort cannot be done independent of other manufacturing facility commitments. Priorities must be established, milestone accomplishments determined, and a start and completion date negotiated. Critical path scheduling within and across projects optimizes the application of resources and aids in meeting major project milestones. However, changing priorities, late delivery of vendor supplied items, manufacturing mistakes, and design changes all contribute to schedule delays. Controlling these factors requires a systems approach that cuts across functions and disciplines. Successful results are achieved by appropriately scheduling reviews and establishing clear lines of communication.

4.3.12.3.3 Task 3—Process Development and Certification. Traditional processes will be employed when manufacturing the majority of components for a launch vehicle. These processes have thoroughly established standards and controls. However, achieving higher performance in a new launch vehicle may not be possible using only traditional processes. Invariably, the introduction of new materials or shapes occurs in select areas of the design. These often require that established processes be modified or that entirely new processes be developed and certified. Projecting the time and resources required to perfect a new material or process is an inexact science and is best accomplished by a team of discipline specialists.

Occasionally program demands force the development of secondary manufacturing processes to proceed concurrent with development of the new material itself, with changes in one area affecting the other. An excellent example of this is in the space shuttle external tank. A new aluminum lithium alloy was introduced to improve performance. Attempts to weld this new alloy identified an extreme sensitivity to constituent levels and other parameters employed in its production. Major modifications to both the alloy and the welding processes were necessary. These changes extended over many months and successful resolution required a coordinated effort between discipline specialists from the material supplier, the external tank contractor, MSFC, and contributing consultants.

Many manufacturing processes contain within them a number of parameters considered critical to achieving a consistent result. Modern process development employs statistical methods to limit the number of tests that are required on combinations of these critical parameters for process optimization. Once the process is optimized, it must be certified. This certification is supported by process sensitivity studies. These studies establish the limits to be placed on each critical process parameter to assure material design properties are not compromised.

4.3.12.3.4 Task 4—Tool Design and Development. Tooling is generally understood to include such items as jigs, work platforms, handling slings, transportation dollies, assembly fixtures, and other similar devices to hold, manipulate, or move parts throughout the various stages of manufacturing. While some tooling may support several projects, the major tools for a new program are configuration unique. These tools must be considered during the early stages of the program since long lead times are required for their design and construction.

Tooling represents a major program cost element and can be a significant factor affecting both production schedules and product quality. A careful balance must be struck between the use of "hard" and

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"soft" tooling in the more demanding phases of production. Hard tooling strives to maximize rigidity and maintain the desired spatial relationship between part and process equipment throughout each operation. Hard tooling is more expensive to employ and takes longer to design and fabricate. However, its more precise features reduce the risk of failure and work arounds during startup. Also, the use of hard tooling generally results in fewer process defects and faster turn around times. Soft tooling strives to achieve the same result as hard tooling but is generally less rigid, with fewer automated features or assembly aids.

Advancements in multipurpose process systems employing robots, sensors, and part positioners linked by a computer are reducing the performance gap between hard and soft tooling. However, most large manufacturing efforts still employ a mix of hard and soft tooling, with the selection for each process driven by control requirements, schedules, and other budgeted resources. Design engineers, analysts, process engineers, and manufacturing specialists must work collectively to define the appropriate tooling approach best suited to the program constraints of cost and schedule.

4.3.12.3.5 Task 5—Subcontractor/Supplier Selection and Control. Small projects often are accomplished at one location without subcontract support and with supplier participation limited to the provisioning of raw materials or commercial piece parts. As projects grow in scope and complexity, reliance on subcontractors and outside suppliers increases. Four common factors influence the decision to use outside contractors. These are (1) the capacity of the principal fabricator to absorb the work involved in the new project, (2) the relative cost of doing the work in-house versus by contract, (3) the capability of the principal fabricator to perform a required function, and (4) government regulations requiring that portions of the work be contracted out.

Subcontractor and supplier selections are critical to program success. Their performance affects the cost, schedule, and quality of the delivered items. Specialists in manufacturing, materials, quality control, and procurement must work together to certify that each new subcontractor or material supplier has the capability and controls to produce an acceptable product. The process of certification has been greatly enhanced in recent years by the wide spread acceptance of criteria emanating from the ISO. Contractors with ISO certification have demonstrated that they have in-place a documented set of procedures that are adequate to control all facets of the work they perform, as well as satisfactory training of the personnel employing these procedures. Maintaining certification requires regular audit and approval by trained representatives of ISO.

Special attention must be given to sole source suppliers. Every effort should be made in the design and material selection phase of the project to circumvent their use. Sole source suppliers produce a product that is unique or of such limited marketability that competitive interest in the field is suppressed. Occasionally, the commercial outlet for a sole source supplier's product is reduced to the point that continued production is no longer economically viable. When this occurs, programs that rely on such materials may be required to subsidize the supplier to maintain production, fund the acquisition of alternate sources, or develop and qualify a replacement material. Any of these options can have serious cost and schedule impacts.

4.3.12.3.6 Task 6—Parts Fabrication and Assembly. The design of a component or assembly assures its final form in the manufacturing process. Manufacturing engineers and production control specialists define the processes to be used and the sequence in which they are to be performed. Skilled tradesmen are then required to implement each activity. Critical processes require that operators are trained and certified

in their use. Certifications are time limited and operators must be recertified at prescribed intervals. All critical processes and many noncritical processes are supported by detailed process instructions resident at each workstation or contained in the "shop travelers." These are the planning documents that direct the flow of parts through each step of manufacturing. These documents also contain the specified inspection points and requisite approval stamps certifying that the right parts and materials were used and that the operations were performed correctly. Although described as documents, the planning paper is frequently computer generated and displayed on interactive monitors at each process station.

4.3.12.4 Manufacturing Implementation Function. While the manufacturing design function results in planning and documenting the manufacturing process, the manufacturing implementation function produces the hardware. Manufacturing resides midway in the life-cycle flow for a new vehicle. Requirements definition and hardware design precede it. Implementation of the manufacturing function begins with the flowdown of requirements from the system plane. Hardware production, however, is generally not initiated until the final design documentation is released. Verification follows manufacturing. Should the verification activities fail to confirm all hardware design requirements, further iteration of the design with manufacturing is conducted. The process is repeated until convergence is achieved between design requirements and hardware performance. Operations is considered the last step in the life-cycle flow for a new vehicle. However, it is customary in programs having very long periods of operation for the life-cycle flow process to be repeated, albeit in abbreviated form. Program exigencies and/or evolving technologies which offer opportunities to improve vehicle performance or reduce operational cost are the catalysts for reinitiating the life-cycle flow process.

4.3.13 Other Design Functions

The design functions delineated in the previous sections are primary to the design and development of the launch vehicle. Through the activity of subsystem compartmentalization, all hardware and software products are defined. Subsequently, the major subsystem design functions are determined.

There are hardware and software items that do not belong to any of the major vehicle subsystems. They are denoted as auxiliary subsystems. However, the function of these auxiliary subsystems is critical to the successful flight of the vehicle. Their design activities may require fewer design functions and disciplines then that of the major subsystems. In addition, the number of interactions may be less, there may be fewer design iterations, there could be less technical integration, or they are specialty/unique items. As a consequence, the design functions of those subsystems are not allocated a specific plane but are grouped as "Other Design Functions" in figure 26. Typical examples of these auxiliary subsystems include recovery systems, landing gear, environmental control and life support system (ECLSS), crew interface, payload conditioning, pyrotechnics, GSE, etc. Whenever a subsystem design is influenced by one of these auxiliary subsystems, the design function of the auxiliary subsystem is represented by the "Other Design Functions" plane.

4.3.14 Reintegration Into the Complete System

Figure 9 in section 2.1 illustrated three types of compartmentalization: the system into subsytems, the subsystems into design functions, and the design functions into disciplines. Each of these compartmentalizations requires reintegration to reconstitute the total system. Figure 27 provides another view of this process. On the upper left is an example subsystem tree which illustrates compartmentalization of the

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vehicle hardware and software into smaller and smaller entities. Each of these hardware/software entities has an associated design function stack, as shown on the upper right of the figure. Each design function plane contains discipline activities. So, the tree represents subsystem compartmentalization, and the stacks represent design function and discipline compartmentalization.

On the lower left, there is an IxI diagram, which represents information flow associated with the subsystem tree interfaces. On the lower right is shown the NxN diagram which represents information flow among the design functions and disciplines, as discussed previously. An important feature that aids in the reintegration process is modeling provided by the disciplines on the design function planes. The modeling provides a means for accounting for interactions, nonlinearities, incompatibility, and uncertainties that are inherent throughout the reintegration process. The models enable the analysts to perform trade studies and sensitivity analyses that can be applied to desensitize any of the aforementioned undesirable effects and to assess their effects in order to provide adequate margins. Models applied in this manner provide the necessary understanding of the reintegrated hardware/software systems along with a high level of confidence regarding flight safety.

As stated, each of the three compartmentalizations requires reintegration. Reintegration begins with integrating the disciplines into the design functions, then integrating the design functions into subsystem designs, then integrating the subsystems into the complete system.

This finally completes the process of reintegrating the subsystems into a total system design.

4.4 Design Sequence

The elements and connections of the design process have been described in the previous section, along with specific tasks that are accomplished on and between the various design function planes. This section will address the time sequence of activities that comprise the stages of the design process. There are two parts: Section 4.4.1 describes the conceptual design stage and section 4.4.2 describes the preliminary design and detail design stages.

4.4.1 Conceptual Design Stage

The conceptual design stage is the early part of the vehicle design process which begins with hypothesizing candidate concepts to fulfill the given mission statement and typically extends to the beginning of the preliminary design stage. Concept selection is the downselection to one concept. Concept selection ordinarily occurs before starting preliminary design; however, in some cases, multiple concepts are carried through preliminary design, and in the case of a "fly-off," multiple concepts are carried through detail design, manufacturing, and verification.

4.4.1.1 Importance of Conceptual Design Stage. The conceptual design stage is crucial to the success of the total design process and the resulting vehicle system. It has been estimated that at least 80 percent of a vehicle's life-cycle cost is locked in by the concept that is chosen (see fig. 74). Another way of saying this is that choices made during preliminary design, detail design, manufacturing, and operations (although essential) can have no more than a minority effect on determining life-cycle cost. While poor detail design engineering can mess up a good concept, the best detailed design engineering will not correct a flawed concept design and selection. The right concept selection is critical.

1. Conceptual Design
2. Preliminary Design
3. Detailed Design
4. Manufacturing and System Integration/Verification
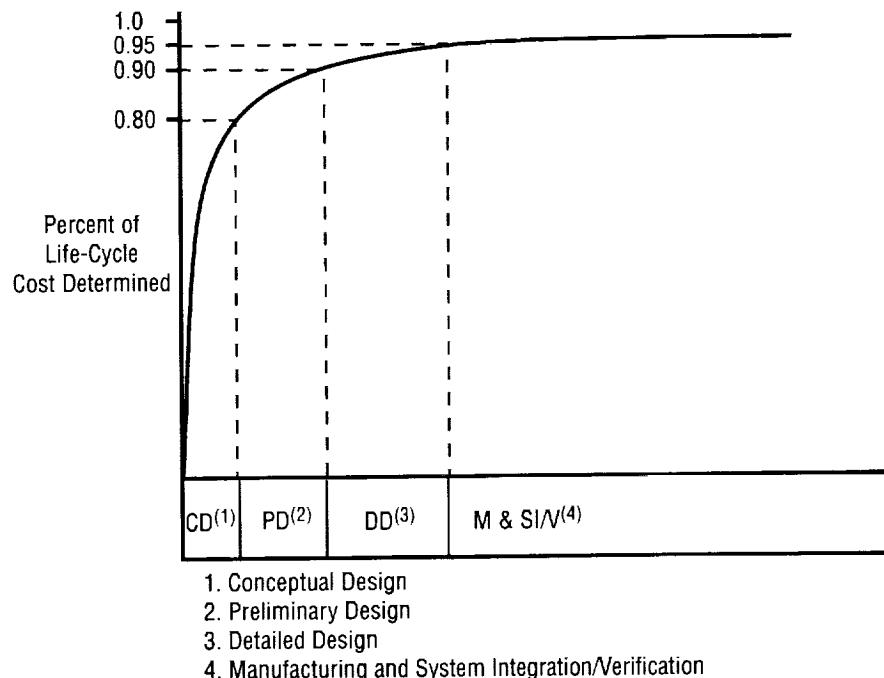
Figure 74. Representative percentage of system life-cycle cost determined as a function of design stage.

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A significant element of the life cycle cost occurs during vehicle development. Inadequate phase A & B activity is known to result in program developmental cost overruns. Empirical evidence of the influence of conceptual and preliminary design efforts on final program costs is shown in figure 75 from reference 4. Illustrated in this figure is the final cost as excess over the initial phase C commitment as a function of cost in phases A and B as percent of development cost for a number of NASA programs. It can be seen that when programs are initially underfunded (i.e., not enough up-front design effort), cost overruns can be expected. Thus, insufficient efforts in the early design process will impact program life cycle costs resulting in developmental cost overruns. Another aspect of the life cycle cost is flight and ground operations. There is anecdotal evidence that inadequate up-front design efforts will also result in increased operations costs.
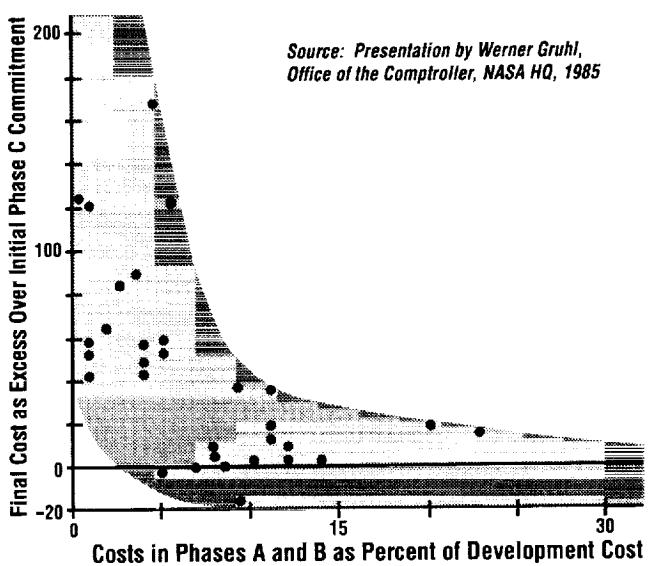
Figure 75. Cost overruns in NASA programs.

The aforementioned implies that we must put sufficient effort into front-end engineering during conceptual design. Here the familiar quality lever is at work (see fig. 76). The quality lever idea is that conceptual design decisions have a 100:1 leverage on end-product quality and cost; preliminary design has a 10:1 leverage; detail design drops to 1:1; and, during the operations stage, the leverage may reverse to 1:10. Make use of the leverage, and put the necessary effort at the front end.

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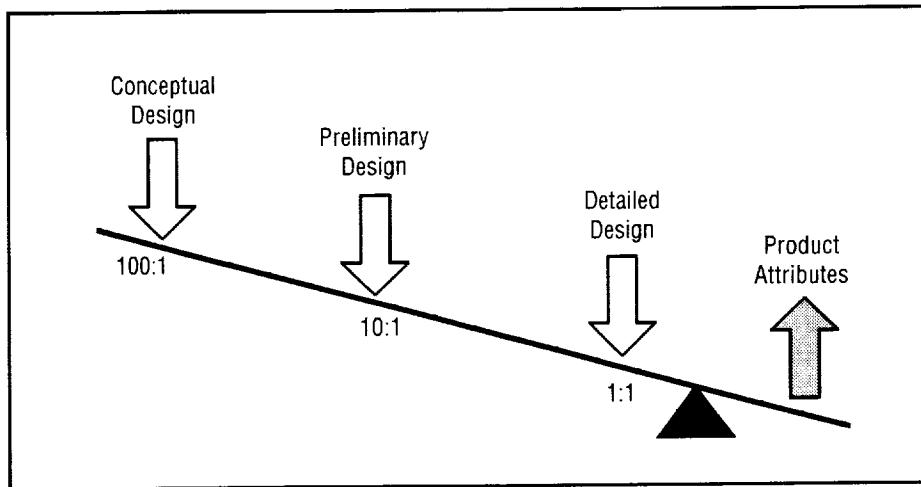
Figure 76. Quality lever.

4.4.1.2 Convergence of Process. Conceptual design and selection are a converging process, initiated by a mission statement, and concluding with a selected concept to proceed into preliminary design. It follows a series of iterations that include generating hypothesized concepts, evaluating the concepts, and discarding unfavorable concepts. This was illustrated in a previous section in figure 13. Each successive iteration entails describing and evaluating the remaining concepts in greater detail than for the previous iteration. Thus, an iterative downselection is accomplished to fewer concepts, with increased penetration on each iteration. New concepts may be introduced and requirements may be refined at each iteration. A change in requirements necessitates a look at new and previously discarded concepts in light of the revision. The process is completed upon selection of a single concept to carry forward into preliminary design, or in some cases, multiple concepts to carry forward. A program might choose to carry multiple concepts forward if no clear-cut winner is apparent without going to the level of detail entailed in preliminary design or if a fly-off philosophy is used (for which the program must have sufficient development resources).

4.4.1.3 Conceptual Design Activity Sequence. An overview of the conceptual design process is illustrated in figure 77. The activity sequence begins with the program providing a mission statement and initial requirements that specify objectives and constraints for performance, cost, reliability, safety, operability, and schedule, and indicate any TRL constraints, etc. In addition, program-level strategy and philosophy are identified. Typically, the initial program requirements are expanded and refined as the concept iterations proceed. This is even more true of the program strategy and philosophy which initially are rudimentary and high level and are modified and expanded as the concepts mature.

Given these requirements and strategies, creative designers and idea generators conceive of candidate vehicle system options that may meet the requirements. Functional decomposition is used to guide the idea generation process. Sketches of architectural options put form to these ideas, and concept evaluation criteria are selected. Concept evaluation criteria will include the attributes of performance, cost, reliability, etc., corresponding to top-level program requirements. Other measures such as dry weight margin sensitivity as a function of dry weight may be included as appropriate.

At this point, an informal screening may eliminate concepts that are clearly not competitive (but if in any doubt, leave the concept in!). The remaining concepts are then subjected to quantitative evaluation.

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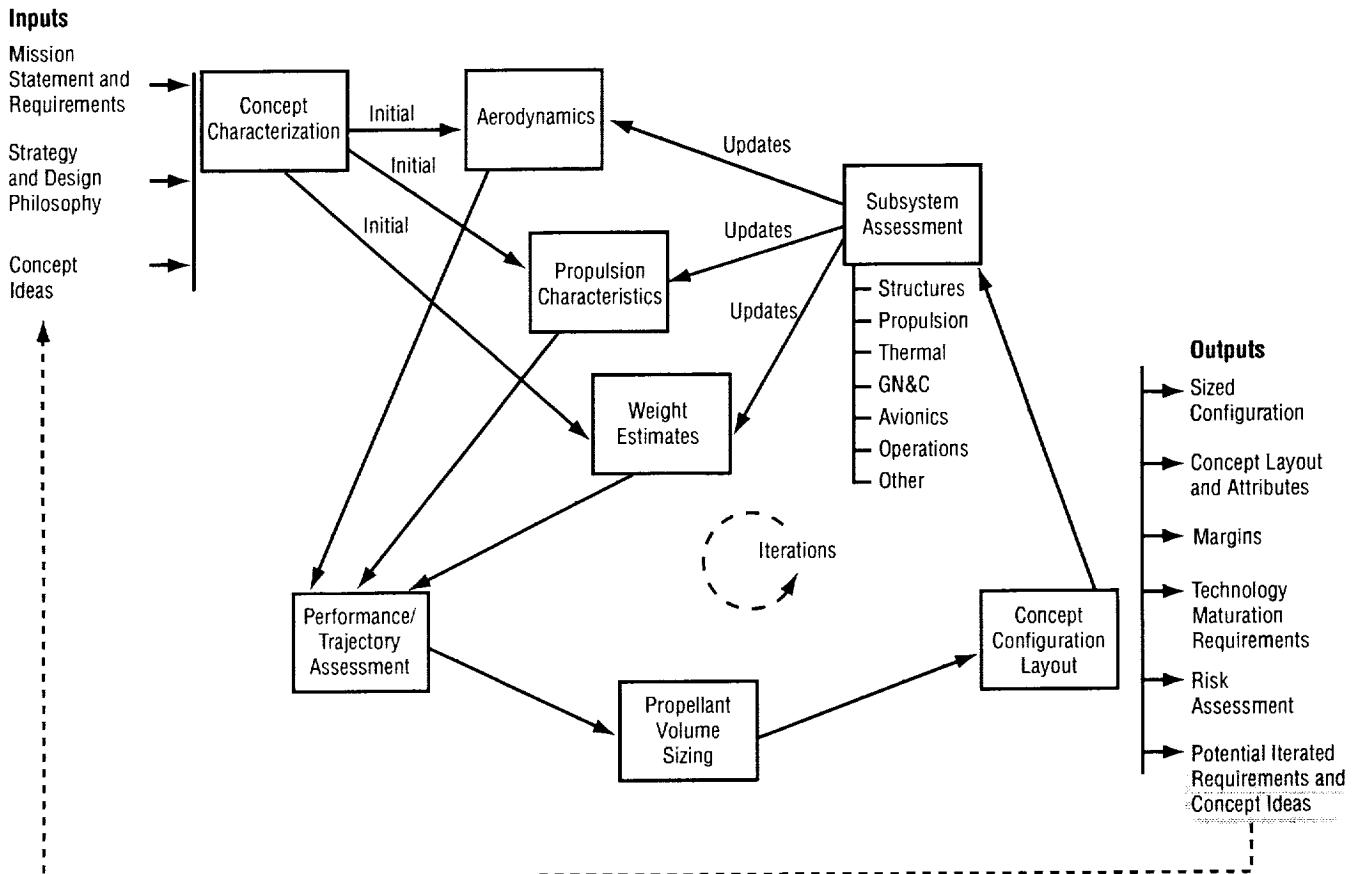
Figure 77. Conceptual design stage—sizing and functional flow sequence.

Each competing concept is characterized at the idea-sketch level and is set up in a sizing program. In this report, the term "sizing program" applies to the set of interconnected programs that manipulate top-level system variables and "rubberized" subsystem descriptors to converge to a consistent set of vehicle/subsystem weights and performance. Variables in the sizing program may be free to change, or may be fixed at the concept designer's discretion. The iterative sizing process is started with initial estimates of basic aerodynamics (drag, lift), propulsion characteristics (thrust, I_{sp}), and weights. These initial estimates are used in an initial performance/trajectory assessment, which then feeds a propellant volume sizing adjustment. The adjusted volume is represented in a concept configuration layout that includes subsystems reflecting the adjusted volume. An assessment of the adjusted subsystems leads to updates in the aerodynamics, propulsion characteristics, and weight estimates. This iterative process continues until the sizing and performance have converged.

Since current sizing programs are approximate tools with significant simplifying assumptions, an assessment of each concept is required by design and discipline specialists. Initially, this assessment typically consists of an overview of sizing program assumptions, inputs, and outputs by a small group of experienced specialists. These specialists provide the subsystem assessment shown in figure 77, carried beyond the level of detail included in the sizing program. The fidelity then may be augmented with more detailed analyses and assessments by additional discipline specialists. By the time the design reaches the preliminary design stage, the need for fidelity has exceeded the capability of current sizing programs, and

the design functions are performed by design specialists in each area. The transition from the design functions being performed by the sizing program to being performed by specialists ordinarily occurs in the latter part of the conceptual design stage.

The outputs of the conceptual design process include (1) the sized configuration, (2) an updated concept layout, (3) estimates of the concept attributes (these include cost and -ility attributes in addition to the performance attributes represented in the flow cycle of figure 78), (4) identification of margins appropriate to the uncertainties and sensitivities of the concept, (5) identification of technologies needed and their maturation requirements, and (6) a risk assessment. The process frequently results in a need to iterate the requirements or in generation of new concept ideas.

Technologies required for each concept are identified, technology readiness levels are determined, and the effort to bring the technologies to maturity is scoped. The primary attributes of cost, operability, etc., are estimated. Top-level system failure modes are identified, and a risk assessment for each concept is performed. This includes assessing performance risk, cost risk, and schedule risk, and a potential risk mitigation plan.

All competing concepts are assessed in a matrix of attributes that reflect evaluation criteria including refined top-level requirements. The concept evaluation criteria are used to evaluate and downselect among the concepts. Downselection reduces the number of competing concepts and allows for the introduction of additional concepts at this point, if additional ideas have been generated by the process. Concepts may be modified in a direction indicated by the analysis and evaluation process. In addition, it is typical for concept evaluation to reveal the need to modify or refine the system requirements or philosophy.

Those concepts that remain after downselection are defined in greater detail, and more detailed analysis is performed, repeating the cycle until a final concept is selected. In some programs, competing concepts are carried through manufacturing and testing before final selection is made. Throughout the concept design and selection process, it is crucial to consider uncertainty and sensitivity and to carry margins appropriate to the fidelity of the system definition. There is not a single set of margins which are correct for all projects, because the appropriate margins depend on the characteristics of the project. Highly interconnected vehicles and those using more advanced technology should use higher margins than their simpler or more conventional counterparts. A well characterized vehicle should have at least 20 percent performance margin at the end of the conceptual design stage. More complex vehicles or those requiring significant technology development should have greater margin—up to 30 or even 50 percent, depending on the specific situation.

4.4.1.4 Process for More Indepth Assessment. The process indicated in figure 77 represents the internal interactions of the sizing program as augmented by a small number of discipline and design function specialists. For concepts that are relatively close to the experience base and have relatively low sensitivity and uncertainty, the process represented on the figure is adequate for conceptual design. If there are very high sensitivities and uncertainties, or if the concept is highly unconventional, a more indepth assessment is required to achieve the correct conceptual design. In this case, a larger group of design and discipline function specialists are needed to provide the increased penetration.

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Figure 78 illustrates the more indepth assessment from a structures/thermal/flight mechanics perspective. There would be similar processes for more indepth assessments of the propulsion and avionics systems. The process starts with the concept definition and outputs from figure 77, and proceeds as indicated to put more realism into the concept design. That is, iterations are made through the indicated disciplines to bring the concept to a more refined definition that is consistent with the physical realities represented by the disciplines.
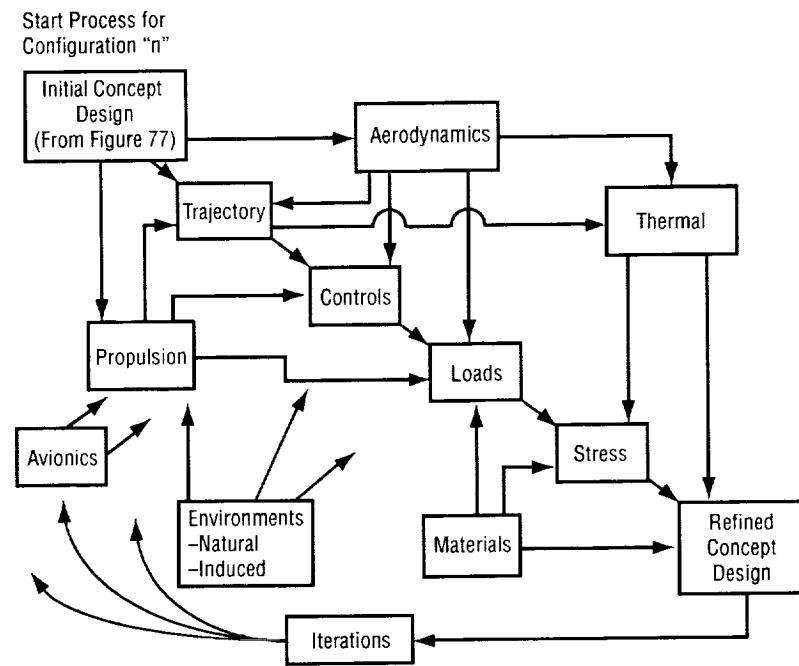
Figure 78. Conceptual design stage—process for more indepth assessment.
(Structures/thermal/flight mechanics perspective.)

The process shown in figure 78 is detailed and complex, involving many concurrent activities and interactions. The individual design functions and disciplines execute their respective tasks as best determined by the persons comprising those design functions and disciplines. Detailing these design and discipline-specific activities is beyond the scope of this report; however, there is an overall pattern and sequence that will be addressed below.

Major steps in the process for each competing concept include the following:

a. Put form to the concept.
   • Make initial sketches
   • Estimate initial configuration parameters (elements, size, mass, etc.)

b. Estimate primary propulsion system characteristics.

c. Estimate primary aerodynamics.
   • Total forces and moments for trajectories
   • Distribute forces and moments for loads and control

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d. Perform basic trajectory/performance analysis, iterating among structures (weight), propulsion, and aerodynamics to size the vehicle for the required payload.

e. Generate baseline trajectory and design reference trajectories. Include trajectory shaping constraints based on abort or recovery requirements.

f. Determine the control system philosophy, logic, and architecture, based on experience.

g. Determine control authority, and analyze rigid body control response to variations in key parameters.
   - Variations in aerodynamics, propulsion, mass properties, etc.
   - Use load indicators

h. Assess key stability issues if they appear to be significant design drivers.
   - Aeroelasticity, propellant sloshing, Pogo

i. Determine bounding vehicle loads for each flight event.
   - Lift-off
   - Ascent
   - Reentry
   - Landing and recovery

j. Conduct an overall stress analysis to assess top-level design.
   - Use fundamental versus finite element analysis

k. Iterate with structural designers to converge structures configuration.

l. Select TPS and thermal control system concepts (concurrent).
   - Determine thermal environments from thermal reference trajectory and natural environments
   - Obtain surface weight/density allowance
   - Develop options
   - Select TPS and thermal control system concepts

m. Develop conceptual propulsion system definition (concurrent).
   - Propellants
   - Components
   - Weight and performance

n. Develop conceptual avionics system definition (concurrent).
   - Components
   - Redundancy
   - Power, weight, cost

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o. Develop conceptual definition of auxiliary systems, sufficient for estimating weights, size, cost, and effects on major subsystems.
   • Separation systems
   • Landing, recovery systems
   • Pyrotechnics, etc.

p. Identify initial production and operations plan.

q. Refine design content of concept.
   • Material, mass distribution, type and size of element, etc.
   • Induced environments
   • Sensitivities
   • Margins

r. Iterate at each level to arrive at a converged configuration.

s. Assess attributes, technologies, and risks in view of system requirements.

4.4.1.5 Overall Integration. During the conceptual design stage, the project leader and the systems discipline are heavily involved in all major activities and associated decisions. These activities consist of developing concepts and project requirements, constraints, philosophies, procedures, criteria, and guidelines that are required to be mutually compatible. During this process, inputs are received from all technical areas including operations. Consideration is focused on the concept(s) attributes of performance, cost, reliability, safety, schedule, operability, failure modes, and the TRL constraints. The necessary mutual compatibility is achieved with the aid of formal and informal integration. Formal integration is accomplished by the leader on the system plane, supported by system engineers, discipline engineers, functional managers, and working groups. Their focus, as stated above, is developing concepts with balanced attributes that satisfy the requirements, constraints, philosophies, procedures, criteria, and guidelines.

As shown in figure 79, the formal integration is horizontal and, in the conceptual design stage, predominates informal integration. The functional flow sequence associated with formal integration is shown in figure 77. This activity is orchestrated by the leader and represents the initial system design function. The informal integration is accomplished by design and discipline engineers. Their initial activities consist of subsystem assessments for structures, propulsion, thermal, GN&C, avionics, operations, and others that could have a significant impact. It is noted that these subsystems or a variation eventually become the vehicle-level design functions as the design progresses. After the subsystem assessments are completed they are formally integrated into the conceptual design process. Then the entire conceptual design is reevaluated as an integrated system. If there is conflict and balance cannot be achieved, then the system plane is required to resolve the conflict. This can result in changing the requirements, constraints, philosophies, procedures, criteria, and guidelines in an overall sense or rebalancing them among the subsystems. At this stage of the design process, the informal activities are at a lower level than the formal activities, as shown in the figure. However, the informal input from the design and discipline engineers is very important since they represent the core technical assessment. These inputs at this stage of the design process can significantly impact the downstream preliminary and detailed design processes. Every effort should be made to achieve balance and convergence at this stage and avoid delaying the balance to a later

design phase. In some programs the balance has been delayed when new technologies were required to be developed to achieve program success. In other cases, balance was delayed because mass fraction could not be achieved early in the conceptual design stage. These shortcomings during the conceptual design process resulted in subsequent program delays and rework and in operational complexity which increased operational cost.
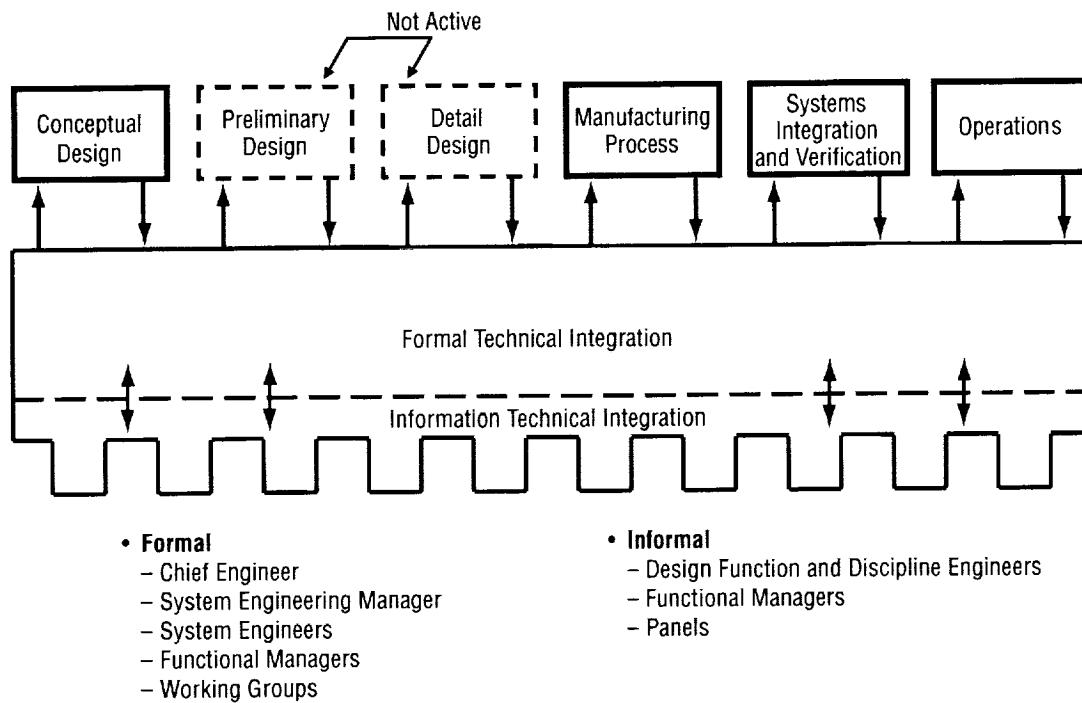
Figure 79. Conceptual design stage—overall integration.

4.4.1.6 Ideas and Options. During the idea-generation stage of conceptual design, the full range of possible options to satisfy the mission statement should be explored. An option that is not brought forth as a concept to be evaluated misses the cut by default. Figure 80 indicates example subsystem options to be considered in developing candidate concepts. The options on this list are not nearly exhaustive but are included as reminders of major options that may be chosen.

4.4.1.7 Conceptual Design Stage Products. The primary product of the conceptual design stage is the concept or concepts that have been downselected to proceed to the next stage, preliminary design. The downselected concept will have been screened for feasibility at a relatively low level of detail and should have appropriate performance margins. The preliminary design stage will entail indepth trade studies and assessments with higher-fidelity system/subsystem definition.

In addition to the primary product (the concept), activities of the conceptual design stage produce other outputs that are carried forward with the concept or are retained as a record of the downselection process. A listing of these products is given in table 23.

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Top-Level Subsystem Categories for Trade Options

- Propulsion System
- Control System
- Materials System
- Aerodynamics System
- Avionics System
- Flight Mechanics/Trajectory Constraints
- Structural System
- Thermal System

Propulsion System
- Liquid
  - RP–LO$_2$
  - LH$_2$ –LO$_2$
  - RP–Air Breathing
- Solid
- Hybrid

- Pressure Augmented
- Engine Cycle

Aerodynamic System
- Lifting Body
- Control Augmentation

Structural System
- Main Frame
  - Composite
  - Metallics
  - Hybrid

- Casting
- Welding
- Fastener

- Tankage
  - Integral/Conformal
  - Nonintegral
  - Lines
    - Internal
    - External

- Shape, Size, L/D
- Bulkhead Configuration

Avionics System
- Distributed/Centralized
- Redundancy Level
- Degree of Autonomy/Self Check

Thermal System
- Active
- Passive
  - Metallic
  - Ablative
  - Reflective
  - Heat Sink
  - Insulation

- Integral with Airframes
- Nonload Path

Material Systems
- Metallic
  - Steels
  - AL's
  - Ti's
- Composites

- Manufacturing Options
  - Casting
  - Extrusions
  - Welding
  - Fasteners
  - Milled
    - Chemical
    - Machined

Flight Mechanics/Trajectory Constraints
- Flight Mechanics
  - Staging
    - Single
    - Multistaged
    - Parallel Burn
    - Air Assist
    - Air Launch

- Guidance loop Closure
  - Early
  - Deferred
  - Open

- Disturbance Accommodation Approach
  - Wind Biasing
    - Generic
    - Short Term
  - Propulsion Performance
    Anomaly Accommodation

- Trajectory Constraints
  - G Maximum Acceleration
  - Q Maximum Dynamic Pressure
  - α, β Pitch and Yaw Angle-of-Attack
  - Separation Attitude and Orientation
  - Thermal
  - Atmospheric Winds
  - Azimuths
  - Orbit
  - Mixture Ratio
  - Launching Sites
  - Special
    - Dynamic Pressure/Mach number
    - Thermal

Figure 80. Conceptual design stage—options and ideas.

Table 23. Conceptual design stage products.

Establish Program Strategy/Philosophy • List of constraints (mandatory requirements) • List of preferences, criteria, and weightings • Uncertainty levels; e.g., 3σ, for system and combination   approach for survivable failure modes • Failure tolerance requirements; e.g., FS/FS/FO; engine(s) out • Verification philosophy; e.g., prototype/protoflight

Generate Systems Concepts (Ideas)
• System sketches; includes vehicle configuration,
  manufacturing process, and operations
• Top-level discriminators
  – Performance criteria/constraints and margins
  – Derived criteria and margins
  – Weighting factors

Evaluation of Alternative Concepts
• For each concept
  – Point design
  – Sensitivities
  – Uncertainties
  – Margins
• Concept validation provided by functional disciplines
• Performance parameters for each concept
• List of nonmatured technologies
  – Define TRL's, cost, and time to maturity
• Risk definition and mitigation
  – Estimate of risk levels and their consequences,
    includes failure modes definition
• Attribute matrix for each concept

4.4.1.8 Managing To Ensure Proper Concept Selection. Proper concept selection depends on having the right skills, the right tools, excellent communication, and process leadership which enables the desired synthesis while avoiding pitfalls that can delay the process. Experience has led to the following guidance which is reiterated in the lessons learned section:

- The right concept selection is critical. The large majority of life-cycle cost is locked in by the concept that is selected.
- The best detailed design will not correct a flawed concept selection.
- Put sufficient effort into front-end engineering (quality lever).
- Ensure that options are fully explored, converging with successive refinement (greater detail) of concepts and requirements.
- Pick a concept only after appropriate convergence, considering all the concepts; i.e., do not eureka the concept.
- In early phases, discipline specialists must assess validity of sizing program results. Do not depend on sizing program alone.
- Avoid concepts having too many technologies at low TRL's.

4.4.2 Preliminary and Detail Design Stages

Preliminary design takes the concept(s) that was downselected by the conceptual design stage and defines it in significantly more detail. Major trade studies are conducted to balance and specify the subsystems. System attributes of performance, weight, and cost are determined with good fidelity. The detail design stage continues the refinement process, detailing the system, subsystem, and component design, and producing the drawings and specifications necessary to go into manufacturing.

Preliminary design and detail design follow much the same process in refining the design definition as better data are obtained from tests and analyses. Both stages proceed toward convergence in a series of design cycles having a typical basic pattern discussed in the following paragraphs.

4.4.2.1 Design Cycles. A design cycle is a sequence of activities among the design functions and disciplines that produces a consistent set of subsystem definitions; i.e., where the designs of the structures, propulsion, trajectory, etc. work together and are not contradictory. The Space Shuttle had five design cycles (sometimes called loads cycles) and three or four abbreviated cycles to study special problems. The special cycles (sometimes called minicycles) arise when a phenomenon is not initially revealed by analysis or test and must be dealt with by design changes. Changes in operations are another means of dealing with design shortfalls; however, these usually entail increased operational complexity or constraints on launch availability.

An example of a special minicycle is the Space Shuttle lift-off dynamics coupled with lift-off ignition overpressure. Not only did the complex multipoint dynamic constraint problem have to be dealt with (loads too high if not considered), but also the high overpressure energy at SRM ignition had to be accommodated by design changes to the vehicle hardware and the launch facilities (water suppression system). Many external tank protuberances, etc., had to be redesigned and qualified.

Many design cycles must deal with a critical issue in a short period of time. The question arises: How do we know when a cycle or cycles are complete? Generally, there are two types of criteria:

1. The first criterion is task completion. Complete all the tasks in the process, and make appropriate design changes. It will take a given amount of time to accomplish each task sequentially, making use of parallel efforts where possible. The cycle is not over until all the tasks are accomplished.

2. The cycle is not complete until all gates and criteria are met; in other words, the problem has been solved. Where it is clear that further refinement of the design remains to be done, or if other problems requiring a design cycle have surfaced, a new baseline is developed for the next design cycle, including sensitivity data and special discipline study results.

It is not possible to quantify how many design cycles will be required. The complexity of the system and the evolving top-level requirements have an effect on the cycles required. The minimum number is around three: one each for PDR, CDR, and DCR. At DCR, the design cycle must include all the verified models, a gate for this cycle only. The Space Shuttle had five design cycles during Phase C which were called Integrated Baseline Vehicle Configuration (IBVC) I, II, III, etc. In addition, minicycles were performed for—

- Overpressure (STS–1)
- Aerodynamic problems (STS–1)
- ET protuberances
- Minicycles in engine design
  - Two-duct manifold
  - Wide throat combustion chamber
  - Advanced turbomachinery development
- Space Station had three major cycles and several minicycles, such as:
  - Node gusset
  - Common berthing mechanism
  - Meteoroid/debris shields.

Some think that with modern techniques the design can be accomplished in one cycle. Certainly that is desirable, but even with the most efficient approach, two cycles appear a minimum. Experience has shown that if you cut too much from the mainstream design effort on high performance systems, problems will occur, creating minicycles which end up extending the schedule and raising cost. The design cannot violate nature. Ensuring a realizable and consistent design with the current compartmentalization/ allocation approach requires iteration.

4.4.2.2 Activity Sequence. The previous sections have dealt with various aspects and tasks of the design process, indicating activities sequencing. This section summarizes key elements of this sequence. In this document, the design sequence will be addressed primarily from the perspective of the aerodynamics, trajectory, G&N, control, structures, thermal design functions, and system design function. It will include propulsion and avionics at a summary level only. Also, interfaces with materials and manufacturing are shown without developing the specifics of those design functions. Propulsion, avionics, materials, and manufacturing can be expanded in detail similar to the above design functions, but this is beyond the scope of this document.

A design cycle in either preliminary design or detail design follows the same basic sequence but with differing levels of detail and fidelity of input data. The activity sequence of the interacting design functions and disciplines is similar to that of the conceptual design stage which was illustrated in figure 77. The starting point, however, is the baseline design of the previous cycle, along with its sensitivities and supporting data. The first cycle of the preliminary design stage has as its starting point the output of the conceptual design stage.

A number of activities can proceed in parallel and should do so where possible. However, some activities require as input the results from other activities and so must be accomplished sequentially.

The following are the major steps in the activity sequence for a design cycle. The steps are illustrated on figure 81, which will be discussed at the end of this section.

a. From the previous cycle, collect and review the requirements and constraints; the philosophy, procedures, and criteria; the baseline design, including sensitivities and supporting data; and any identified problems or design shortfalls. Determine the direction of modification for the upcoming design cycle. The systems plane, in consultation with the other design functions, allocates requirements and constraints to the design functions, reflecting the desired modifications.

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b. Propulsion provides propulsion system characteristics, based on its design cycle and on the above allocations.

c. Structures design modifies the vehicle configuration, directed toward resolving problems of the previous cycle's baseline or expanding the level of detail of its definition.

d. Aerodynamics provides updated aerodynamic forces, moments, and pressure distributions based on updated configuration, wind tunnel tests, and analyses. Aeroelastic stability is assessed to specify stiffness requirements or trajectory constraints on dynamic pressure.

e. Ascent trajectory/performance analysis is conducted to determine the payload performance of the vehicle, including margins, reserves, and fuel bias, and to determine the flight path of the vehicle under constraints developed at both the systems level and the discipline level. Typical constraints levied in order to have a tractable and reasonable design include at least the following:

- Targeting points for staging and insertion
- Abort/failure targets for engine out
- Dynamic pressure for aeroelasticity and loads
- Axial acceleration for human passenger and payload limits
- Angles of attack for loads
- Thermal constraints.

The trajectories can be modified for operations, within limits.

f. Reentry and recovery trajectories are determined, considering dispersions in initial conditions and variations in environmental and vehicle parameters.

g. Design reference trajectories are generated for control, loads, and thermal analyses. These trajectories are chosen to represent potential operational missions, attempting to envelop the design parameters to maximize a variable such as a load indicator, while maintaining a physically realizable trajectory. The parameter combination for a reasonable maximization of the desired variable is determined by a judgment choice, guided by numerous dispersed trajectory runs.

h. Basic control response analysis is performed for the design reference trajectories plus parameter variations to determine the vehicle's response to winds and other forces during high-q ascent flight and the transition response during reentry. This basic simulation is also used to determine the control logic for stabilizing and controlling the vehicle. The control logic is adjusted to meet additional constraints of load indicators like q-alpha and q-beta, control authority limits, etc.

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

j. Thermal indicator models use trajectory, control response, and configuration information to produce estimates of heating at critical locations on the vehicle.

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k. Approximations of design capability corresponding to the loads and thermal indicators are determined from the existing design description.

l. The loads and thermal indicators are used to provide estimates of the structural and thermal system demand that are compared with the approximate design capabilities to determine adequacy or impact. This information guides decisions on potential further design changes.

m. In addition to these activities that are focused on system performance, the cost, reliability, operability, safety, and other attributes of the design are assessed and compared with requirements and allocations.

Also fed by the design reference trajectory outputs are detailed analysis and design activities that constitute the indepth determination of the design, and are the basis of the approximations used in items i, j, and k above. These include the following:

n. G&N systems for each flight phase are synthesized and analyzed, balancing the magnitude of off-nominal dispersions and performance loss with the accuracy (cost, complexity) of the sensors and software requirements. Abort and contingency targeting are a major consideration.

o. The structural dynamics discipline generates dynamic models of the elastic structure for use in control and loads analysis.

p. Control systems are synthesized and analyzed in detail, including all pertinent nonlinearities and effects. Sensor and actuator requirements are identified and updated in coordination with avionics.

q. Making use of the dispersed response data and the chosen method of combining uncertainties, consistent vehicle loads are determined for each major loading event:

- Transportation
- Lift-off
- Ascent max q
- Ascent max g
- Docking
- Reentry
- Landing and recovery.

Iterations with other disciplines may be necessary to bring the loads to within an acceptable range, through changing the aerodynamics, trajectory, control, parameter variation approach, criteria, etc.

r. Acoustics/overpressure environments are determined and applied as loads to the structural elements where this high-frequency loading is significant. The vibroacoustic environment is determined for components and is converted to component design and test criteria.

s. Aerothermodynamic and plume heating environments are determined consistent with the updated design reference trajectories and configuration.

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t. Thermal analysis and design can be done in parallel with loads analysis. Induced environments are determined from aerothermodynamics, plume heating, propulsion system inputs, avionics, and other on-board system inputs. Based on these induced environments and the natural environments, designs are accomplished for TPS's, cryogenic and propellant insulation, and TCS for components and compartments. These design activities interact strongly with other design functions and disciplines. Material selection for TPS and insulation systems is crucial and, in conjunction with temperature requirements of the vehicle systems, provides the basis for sizing the TPS and insulation. Designing active and passive TCS likewise requires selection and sizing of materials and components.

u. Based on the thermal systems designed above, structural temperatures and gradients are calculated, and thermal environments of components and compartments are determined. As in other systems, the analysis is part of the iterative design process. Outputs to other design functions and disciplines are made after convergence of the thermal design.

v. Stress and life analyses are performed for the baseline configuration, using the loads and thermal data provided. Stress fields and deflections are determined and compared with specified criteria. Deflection and buckling stability are analyzed. Fracture and fatigue analysis are performed to obtain cycles and time to failure and to develop fracture control plans for fracture critical parts. The level of modeling detail is set to be appropriate for the maturity of the design cycle being analyzed. If criteria are not met, either the environments must be reduced or the structural design must be changed.

w. Structural design works closely with the stress and durability disciplines to identify design modifications to correct structural strength or life shortfalls. Meanwhile, structural design receives inputs from and interacts with the other design functions, including thermal, propulsion, avionics, and auxiliary subsystems. The structural design is modified as required to accommodate these other subsystems as their designs evolve. In this role, structural design has a primary packaging and integrating function. The structural design as modified becomes the baseline for the next cycle. If modifications are complete or are essentially complete (as indicated by successfully meeting criteria and interfaces), drawings and specifications are finalized.

In parallel with the summary-level and detailed discipline analyses and design activities described above, there are special analyses of specific phenomena that must be assessed and designed for, but which are handled separately from the primary design loop. These typically are stability or transient phenomena such as flexible mode control stability, pogo stability, aeroelastic stability, separation transients, docking transients, etc. Provision or "headroom" is made for these effects in the primary design loop, including appropriate margins. Examples are shown in the next four items.

x. Control stability analyses are conducted using elastic body dynamics and slosh dynamics models. These produce slosh baffle requirements and algorithm requirements for stabilizing elastic and slosh modes. Confirming analyses are run with the baffle models and stabilizing algorithms simulated to confirm satisfactory margins.

y. Aeroelastic stability is assessed by structures, aerodynamics, and (if pertinent) control. The design is moved away from any aeroelastic stability limits, allowing adequate margins.

z. Pogo stability analyses are run to determine the requirement for a pogo suppression system.

aa. Special transient events are assessed, including liftoff and separation clearance, docking response, landing or recovery response, etc. Results of these assessments produce requirements on the vehicle design and its interfacing ground systems.

Completing the design cycle involves the following activities:

bb. Concurrent with the above activities are related design and analysis activities that are influenced by the primary design cycle but are less coupled to it. These include landing and recovery systems, pyrotechnic systems, compartment venting design, life support systems (if applicable), and breakup/disposal analysis.

cc. Also concurrent with the above are the major propulsion, avionics, materials, and manufacturing design activities which can be described in similar detail to the items above (beyond the scope of this document). They interact with the other parts of the system design to ensure compatibility.

dd. All subsystems develop verification plans, production plans, and operations plans. Verification of analysis models and development testing of the designs constitute an important part of the design maturation.

ee. The end of the cycle produces the baseline design and sensitivities to begin the next cycle or, if complete, produces the drawings and specifications for entering the production stage.

ff. The hardware and software are produced and verified, involving many components and process steps.

gg. Operational procedures and constraints are developed from the above activities, drawing heavily on the analysis and verification program to ensure that the vehicle maximizes its operational capability while not violating safety constraints.

The activity sequence discussed above has a multiplicity of facets. A clear visualization of the design sequence can be illustrated with the application of the various categories of activities and/or models delineated in section 3.5. Recall, these models consist of a generalized model, specialized models, and discipline specific models. Shown in figure 81 are the design process activities (i.e., activities *a* through *gg*) and their association with the three models. This illustration indicates where the various activities fit relative to the models, as well as how the models are applied after the initiation of a design or a design change.

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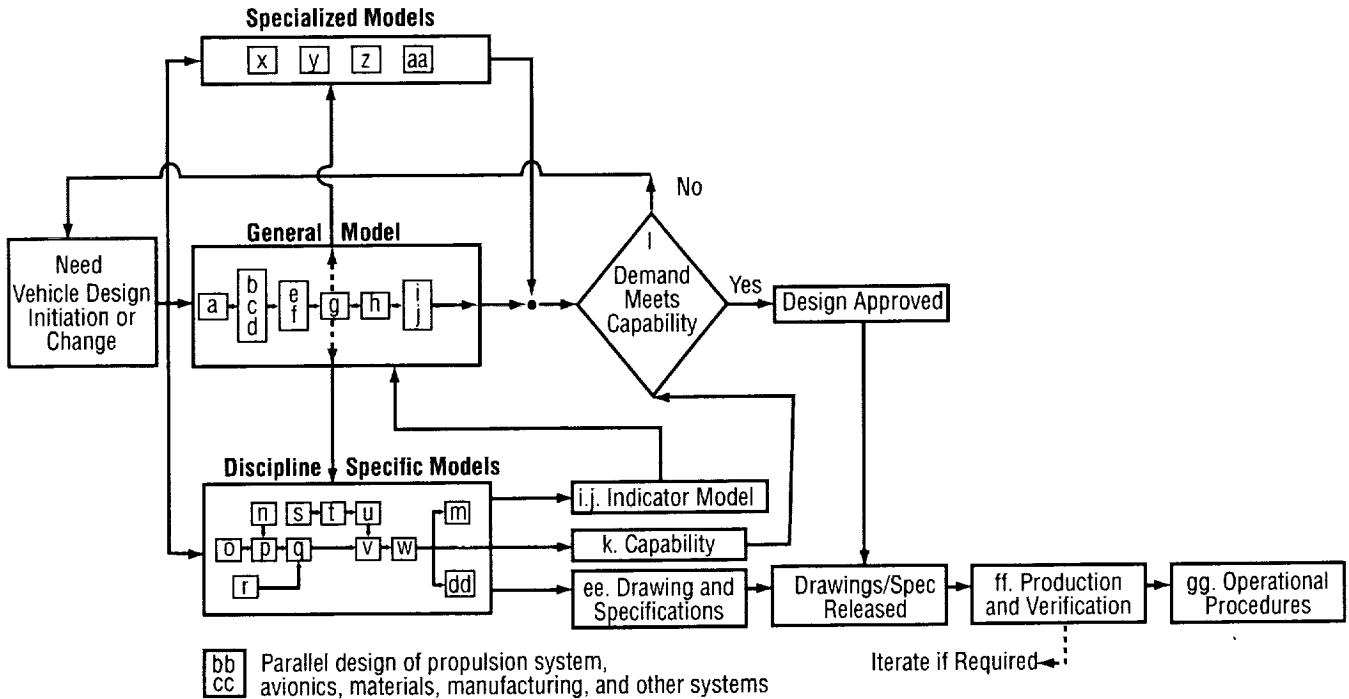
Figure 81. Design process activities interactions.

Subsequent to initiation, the characteristics of the trajectory are determined using the generalized model. It can be seen that properties of the trajectory (i.e., *g*) drive the specialized models and the discipline specific models. The major outputs from the discipline activities are drawings/specifications, the design capability, and indicator models. The indicator models are included in the generalized model to assess the loads and thermal demand versus the capability of the design. In a parallel fashion, results (e.g., stability determination) from the specialized models are also compared to the capability. When the total demand is within the capability and has acceptable margins, the design is approved and the hardware goes into the production, verification, and operational stages.

For every iteration of the design, all primary subsystems are assessed (see *bb* and *cc*). Since many subsystems are coupled to the vehicle system (e.g., propulsion, avionics, etc.), the impact of their interactions is required to be evaluated. This evaluation is accomplished through an activity sequence similar to that of the vehicle activity sequence. For those subsystems, a figure parallel or similar to figure 81 could be developed to illustrate their specific design cycle activity sequence. It would include a generalized model that describes the subsystem attributes, and the associated specialized models and discipline models.

While figure 81 has been developed to illustrate launch vehicle design, a similar illustration could be developed for operations. For instance, after a payload is selected, similar vehicle generalized model is applied to assess the impact of the payload on the vehicle and vice versa. Assuming that the demand meets the capability, the generalized model is applied to assess the operational constraints for flight; e.g., day-of-launch wind limits.

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5. PROCESS IMPROVEMENT

The major focus of this document is to characterize the launch vehicle design process. This characterization can then serve as a baseline to identify and evaluate improvements on the current process. As discussed in section 1.1, there is a clear need for low cost, high performance, reliable launch systems. NASA and the aerospace community must attain significant advances in launch system technologies in order to meet this need.

There are two categories of technologies applicable toward this objective: (1) hardware/software technologies, and (2) design process technologies. The first category includes the obvious technologies of new materials, new propulsion concepts, etc., that address the physical aspects of launch systems. It is essential that these technologies be advanced, and major efforts are underway toward this objective. The second category recognizes that the conduct of the design process is itself a technology that must be advanced in order to achieve more capable and cheaper systems.

5.1 Vehicle Hardware/Software Technologies

This category deals with the different ways of optimizing the effects of the physics of the problem as was so well expressed by Rick Fleeter[12] when he said that the energy available in splitting the molecules (propellant) was just sufficient to overcome gravity to get to orbit. Technologies in this category range from advanced energy transfer and propulsion concepts to new structural materials and alternative avionics systems. These areas must be pursued to achieve the needed major advances in cost, reliability, and performance. Several such technologies are being explored and matured; new technologies need to be identified.

5.2 Design Process Technologies

In addition to essential advances in vehicle hardware/software technologies, the design process itself must be improved. The efficiency and effectiveness of the process can be improved by application of the experience-based principles and lessons learned identified in section 7. In addition, the technology of the design process itself must be improved. This is the subject of the remainder of the section.

It should be noted that the ideas and suggestions presented here are by no means all inclusive. They are just ideas and suggestions that are intended to stimulate thought and action toward improving the design process.

5.2.1 Design Process Shortcomings and Potential Approaches for Improvement

An examination of the current design process and its history indicates areas of shortcomings, including at least the following:

- The process is fragmented and not well organized, producing inferior designs.

- There are deficiencies in the ability to predict (model) design performance, especially cost, reliability, and operability.

- Synthesis is an idea-driven process that may miss promising concepts if the designer stays within his experience "box."

- There is low confidence in the conceptual design stage where a high percentage of the cost is locked in.

- The design process has difficulty in handling the vast quantity of required data and information and in providing necessary visibility to all involved.

New design process technologies should be sought to address the above deficiencies. Approaches for high leverage improvement include—

- Reduction of process fragmentation; more seamless design in
  - Subsystem, design function, and discipline function compartmentalization
  - Design for all mission events and design stages

- Improved modeling and knowledge base, especially for cost, reliability, and operability

- More direct synthesis approaches
  - Conversion of requirements to concepts and designs
  - Ideation and visualization of design space

- Improved conceptual design process
  - Better synthesis and higher fidelity models
  - Scaleable representations that mature into subsequent design stages

- Means for efficiently conveying and displaying necessary design information to all participants.

5.2.2 Evolutionary Improvements

There are many options for fine tuning the present design process. Several are discussed in the following paragraphs.

5.2.2.1 Requirements and Criteria. The tendency in aerospace has been to place all our lessons into the form of requirements and criteria. This takes many forms. Analysis of failure modes is replaced by various detailed criteria instead of understanding and preventing failures. The requirements/criteria are so stated that many times they dictate the design and leave very little room for innovation and creativity. Required documentation, procedures, etc., are often very excessive. Currently in the Space Station program, NASA is insisting on excessive documentation and traceability of not only hardware but also all analysis, test, etc. No use or very limited use is being made of electronic databases, etc., to meet the documentation requirements. A key task for fine tuning the system is to strongly work the requirements and criteria, making the system efficient and allowing for the interjection of creativity and innovation.

5.2.2.2 Design for Simplicity. The "Experienced Practitioner" survey (section 7.1) has many references to designing for simplicity. There are many measures of simplicity that can be used as guidelines:

- Simple load paths
- Number of functions
- Number of parts
- Complexity of functions
- Number of turnings
- Number of steps/offsets
- Etc.

This is only a partial list. Pugh in *Total Design*[3] and other publications emphasize designing structures by load lines/paths. Others illustrate the approach in different ways. Present launch systems are very complex. Future systems require simplicity. The key task is to study simplicity and implement ways of incorporating it into design.

5.2.2.3 Improved Modeling Tools. Initiatives are in progress to improve modeling and simulations related to essential aspects of the design process. These include:

- High fidelity simulations for virtual flight
- More granular operability and maintainability modeling
- Embedding more probabilistic methods into the design process
- Bottoms-up cost modeling for smoother interface with current top-down cost models
- Multidisciplinary modeling using CAD geometry as basis
- Rapid modeling techniques to enable a greater number of sensitivity analyses.

5.2.2.4 Integrating Various Discipline Analyses Into Single or System Tasks. The process today for structural design is for the dynamic specialists to first run a load analysis and then pass the loads to stress analysts for strength and durability analyses. These results are then passed to the designer for design changes, etc. Instead of sequential analysis, a better method would be multidisciplinary analysis. At various stages of the design, the multidisciplinary analyses take different form. This process is more efficient, and confidence in the results increases, without putting any discipline out of business. Activities directed toward this end are—

- Load transformation matrices
- Stress transformation matrices (allow time consistent stresses)
- Integrated trajectory, control, and loads
- Thermal transformation matrices
- Improved sizing programs
- Combining multidisciplinary equations into a single set and developing codes for the integrated system
- Applying design of experiments for analysis and test.

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5.2.3 Revolutionary Advances

As noted in the previous section, evolutionary improvements in the design process should be pursued as an immediate means of increasing process efficiency and effectiveness. However, as discussed in section 1.1, revolutionary changes are required to achieve major advances in launch vehicle cost and capability.

The following discussion is intended to stimulate thinking and ideas toward needed revolutionary advances. Revolutionary changes in design process technology can address the two general problems with current design process: (1) The current process does not arrive at the best design because of its many compartmentalization/reintegrations, its ad hoc experienced-based synthesis, and its fragmented analysis of limited fidelity; and (2) the process is too long and costly.

The ideal design process would be an automated process that converts requirements into an optimal design in a single step. Achieving such an approach lies in the distant future but should be the guiding star target for our efforts in the interim. Until the ideal one-step approach is achieved, we will need to seek revolutionary advances in the multistep process that is characterized by compartmentalization, synthesis, analysis, and reintegration. We can consider advances in each of these areas.

5.2.3.1. Compartmentalization/Reintegration Technology. Generically compartmentalization/ reintegration technology currently is applied, not only to vehicle system/subsystem compartmentalization, but also to design functions, disciplines, requirements accommodation (i.e., performance, cost, etc.), operational events (lift-off, atmospheric flight, reentry, etc.), and stages of the program. Technology advances are needed to unify as many of these compartmentalized areas as possible into a seamless whole.

5.2.3.2 Synthesis and Design Update Technology. Currently, any design synthesis or design update depends on the designer's ideas and experience base on an ad hoc basis. Possible approaches to technology leaps in this area include idea stimulus approaches; use of artificial intelligence and knowledge-based systems to convert designer's judgments and rules of thumb into algorithms; techniques for visualization of the design space; multidisciplinary optimization; and automated synthesis or inverse engineering, using, for example, approaches like structural shape and topology optimization.

5.2.3.3 Analysis Technology. Potential advances in analysis technology might be pursued along several fronts, including combining discipline analyses, major advances in fidelity, inclusion of life cycle metrics, and full probabilistic design enablement.

5.2.4 Interactive Information and Communication System

As a design proceeds through the various stages from the concept stage to the operational stage, there is a need for an interactive information and communication system (I^2CS). The system would consist of various computerized and electronic tools to facilitate all aspects of the design process. These hardware and software tools could improve the information flow, interactive team communications including those from remote locations, multidisciplinary model implementation, etc. Specific examples of various computerized tools would consist of the following:

- A residence and/or placeholder for the design description and specifications, associated attributes, ICD's, and supporting data (this tool could be based upon the design process characterization model along with the NxN and IxI diagrams)
- A real time interactive communications system
- A management related information system (this tool would include the WBS, cost spending profiles, allocations, reserves, schedule, etc.)
- An electronic mock-up with fidelity consistent with the design stage
- A flight performance simulation with fidelity consistent with the design stage that displays key performance indicators versus flight time
- An advanced interactive multidisciplinary optimization systhesis system that can search for architectures per given requirements and constraints but driven by optimization algorithm
- A virtual reality design system that can focus on the vehicle system, element, subsystem, or part where the design participants can assess the realization of their design decisions in real time
- An interactive synthesis tool with "design-to" models that include performance, cost, reliability, safety, operations, etc.

In addition to the above examples there are certain features that are required to enable these tools. Typical examples of these features are as follows: tools must be secure, configuration controlled, accessible by all participants and compatible with industry counterparts; system permits simultaneous viewing and communications by multiple users interactively; framework implements compartmentalization and reintegration with residence and/or placeholders for all design related data and includes prompts, impact assessment, traceability, etc.; hypertext characteristics for data, graphics, etc.; action items and tracking; trade study tracking; scalable for growth; seamless file transfer; searchable and interrogatable; and platform insensitive. Other features would also include e-mail, telephone, video conferencing, and manufacturing and testing real time video acquisition.

The I^2CS design tools are needed to improve the design process efficiency and effectiveness. This system will provide the designer the unique capability to achieve the best real-time design within the performance, cost, reliability, etc., requirements and constraints. It is imperative that the requirements for the I^2CS design tools be developed by the STS designers in collaboration with the tool developers. While much of the technology needed for I^2CS exists currently, implementation of the system would provide a potential revolutionary improvement in the design process.

The potential improvements listed above can apply to any design stage. Noting the high leverage effect of the conceptual design stage, particular attention should be given to technologies that enable selection of the correct concept. Discovering and developing revolutionary design process technologies are essential ingredients in meeting the mandate for major improvements in launch cost, capability, and schedule.

6. ILLUSTRATIONS OF PROCESS

This chapter illustrates aspects of the design process using historical examples. An overview of the Space Shuttle conceptual design process and subsequent Phase C configuration cycles is given in section 6.1. Section 6.2 illustrates technical integration by describing the design process for flight mechanics with a loads modeling example drawn primarily from Space Shuttle history with some comparisons to Saturn/Apollo and X–33.

6.1 Overview of Space Shuttle Design History From Phase A Through Phase C

When examining the design process for launch vehicles, it is instructive to consider the history of past launch vehicle design. This section provides an overview of the Shuttle concept selection and major configuration design modifications (Phase A through Phase C) which illustrates the magnitude of its conceptual design process and the extent to which the design selection was determined by external considerations, such as political, budgetary, etc. Much of the material comes from the excellent book *Space Shuttle, The History of Developing the National Space Transportation System.*[13]

6.1.1 Political Activities

Political considerations shaped not only the existence of the Shuttle program but also the form of the vehicle design itself. These directions and constraints resulted from national needs and priorities, the economic environment, and multiple government agency roles and interests during the 1969–1971 time frame (see table 24).

In 1969 President Nixon formed a Space Task Group composed of senior NASA and Air Force personnel and headed by Vice President Agnew. This group was charged with identifying the Nation's next directions in space exploration. They recommended three ambitious options including a lunar station and Mars exploration, the least ambitious option being a $5B per year program for both an Earth Space Station and a Space Shuttle. Nixon rejected all three options as being unaffordable in the economic environment of the time.

Meanwhile, NASA formed a Space Shuttle Task Group (SSTG) led by Leroy Day which defined classes of Shuttle missions and recommended trade studies among broad vehicle characteristics such as reusable versus expendable stages, categories of engines, cross-range capability, payload size, launch orientation, and series versus parallel burn. The SSTG defined three classes of vehicles: Class I—reusable orbiter/expendable boosters; Class II—stage-and-a-half expendable tanks; Class III—reusable two-stage-to-orbit (TSTO). Class III was the SSTG's first choice.

In 1970, NASA Administrator Paine and Secretary of the Air Force Seamans established a NASA/Department of Defense (DOD) STS Committee. The White House rejected the resulting proposal for a Shuttle program (without a Space Station).

Table 24. Space Shuttle history—political activities.

CONCEPTUAL DESIGN STAGE PRODUCTS		
February 1969	**February 1969**	**January 1970**

• Space task group formed by Nixon
• Team:
  – Spiro Agnew
  – Senior NASA and Air Force personnel
• Recommendations:
  – $8–10 B/yr Lunar Space Station,
    50 person Earth Space Station,
    Mars Exploration
  – $8 B/yr 50 person Earth Space Station,
    Mars Exploration
  – $5 B/yr Earth Space Station
    and Space Shuttle
• Result:
  – Nixon rejected all three proposals
  – NASA had to propose
    • Space Shuttle first step
      to Space Station
	• SSTG
	• Team results:
	  – Leroy Day (Leader)
	  – Six missions defined
	    • Logistical support for
	      for Space Station
	    • Service low Earth orbit (LEO) satellites
	    • Propellant delivery to LEO
	    • Satellite service
	      and maintenance (LEO)
	    • Delivery of LEO payloads
	    • Short manned missions
	  – Trade studies recommended
	    • Reusable vehicle
	    • Pilot fly back versus expendable
	      booster
	    • Off shelf versus new engine
	    • 230 miles versus 1265 cross-
	      range capability
	    • 15 K versus 50 K payload
	    • Vertical versus horizontal launch
	    • Sequential staging versus parallel burn
	  – Defined classes of vehicles
	    I Reusable orbiter/expendable
	      boosters
	    II Stage-and-half expendable
	      tanks
	    III Reusable TSTO
	      (SSTG choice)
		• MSC started in-house
		  STS Design
		  – Concerned over ϕB RFP
		    requirements
		  – 8 × 30 ft payload bay
		  – Payload 10 K to 15 K
		  – Class III
		  – Cross range 200 mi
		  – Orbit 310 mi, 55°
		  – 30 flights/yr
		  – Cost $5.8 B

September 1970	**February 1971**	**September 1971**

• NASA administrator (Paine)/
  Secretary of Air Force (Seamans)
  Established NASA/DOD STS committee
• Shuttle project rejected by White House
	• NASA Administrator (Fletcher)
	  – Significantly reduced cost
	  – DOD committed to use it
	    for all launches
	    • Must meet all DOD requirements
	  – STS was first program subject to
	    formal economic analysis
	    and requirements by OMB
	  – STS must be the only launch vehicle
	    during the 1980's and later
	  – Space Task Group (STG), DOD,
	    Presidential Scientific Advisory
	    Committee, NASA, American
	    Institute of Aeronautics and
	    Astronautics (AIAA)—all support
	    STS development
	  – DOD requirements
	    • Payload bay 15 × 60 ft
	    • Payload 40,000 polar orbit
	      60,000 due east
	    • Cross range 1,100–1,500 miles
	      (issue: reentry heating)
	  – DOD, CIA, NASA, etc. supported
	    Shuttle as the only launch vehicle
		• DOD did not provide dollars
		  but—
		  – Contributed facilities for
		    orbiter construction at
		    Palmdale
		  – Presented united front with
		    NASA to Congress

New NASA Administrator Fletcher in 1971 determined that keys to acceptance of a Shuttle program were to significantly reduce cost and obtain broad support for the program from all involved Government agencies and organizations. DOD committed to use the Shuttle for all of its launches provided that it meet all DOD requirements. The necessary support was obtained from the numerous agencies, and a commitment was made that the Shuttle would be the only launch vehicle developed in the 1980's. The Shuttle program was the first of its kind to be subjected to formal economic requirements by the Office of Management and Budget (OMB). The DOD did not provide funds but contributed Palmdale facilities for orbiter construction. With these agreements, the agencies presented a united front with NASA to the Administration and Congress, enabling the acceptance of the program.

6.1.2 STS Phase A

Phase A of the Shuttle program began before the previously discussed political activities, and had its foundation in reusable vehicle studies undertaken during the history of spaceflight (see figure 82 and table 25). In 1968, MSFC and the Manned Space Center (MSC) (JSC predecessor) issued a joint request for proposal (RFP) for integral launch and reentry vehicle concept studies. Five awards were made: General Dynamics (GD), McDonnell Douglas (MAC-DAC), Lockheed, Martin Marietta (MM), and North American Rockwell (NAR). A 4-month study led to NASA continuing funding for all of the four except Martin Marietta, who continued work with internal funding. The Air Force provided oversight by the Aerospace Corporation, plus in-house work on stage-and-a-half concepts by Flight Dynamics Laboratory (FDL). The five NASA contractors focused on Class III vehicles (fully reusable) and spent 200 man-years of effort, along with extensive aerodynamic, materials, and structural testing. Categories of orbiter configurations were lifting body (rejected), variable wing (rejected), straight wing (proceeded to Phase B), and delta wing (proceeded to Phase B). In addition to these concept studies by industry and government, a series of technology working groups were chartered to develop the key technologies required (see fig. 83). Each of these working groups had extensive activities and significant expenditures.
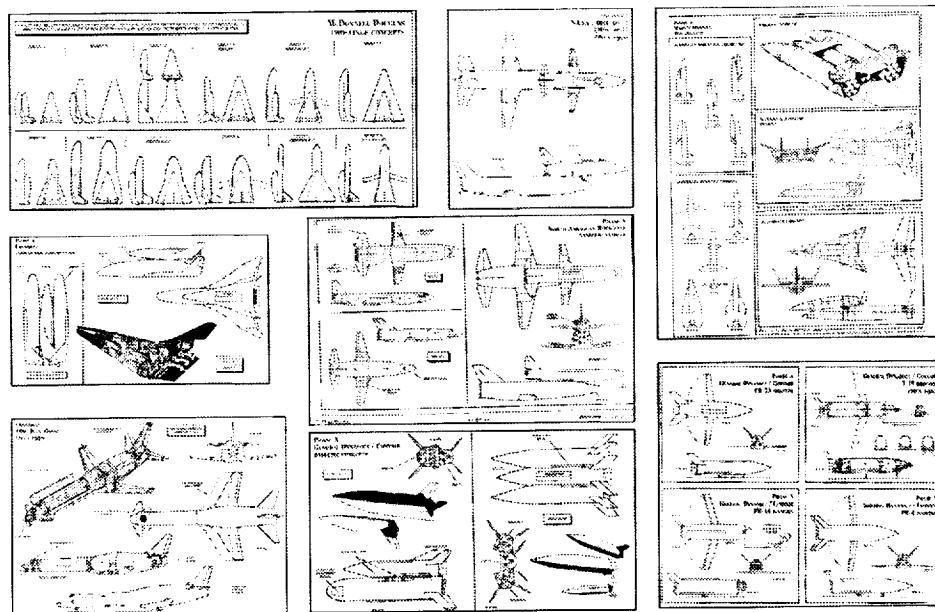
Figure 82. Space Shuttle history—example Phase A configurations.

Table 25. Space Shuttle history—Phase A.

Year	October 1968 Integral launch and reentry vehicle Joint RFP (MSFC and MSC)	February 1969 NASA concept study	October–December 1969 φA results:
Requirements • Focus • Pld (K#) • Orbit (miles) – Baseline • Cross range (miles) • Engine	Cost and safety 5–50 115–345 300 450 MSFC		**Effort** • 200 man years • Extensive aerodynamic, materials, and structural testing **Four baselines** • Straight wing (Phase B) • Delta wing (Phase B) • Variable wing (rejected: complexity, etc.) • Lifting body (rejected: packaging, etc.)
Contractors	GD MAC-DAC Lockheed MM NAR	GD (MSFC) MAC-DAC (LARC) Lockheed (MSFC) MM In-house ($) NAR (MSC) Air Force Space Division • Aerospace oversight of NASA • FDL (stage + 1/2)	**Configurations** • III (2) • III (12); $5.9B; 21 months $67/# • III + II (4); $5.5 B; $25/# • III (25) • III (1 + Opt); 52 months

Balancing Act Between Requirements and Design Leads to Class III

• Parallel Concept Studies
  – Government and Contractors

• Identified Key Technologies

• Uncertainties
  – Winds
  – Thrust Vector Misalignment
  – Rigid Body Aerodynamic Coefficients
  – Thrust
  – I_{sp}
  – Weight
  – Fuel Residuals

• Develop Key Technologies
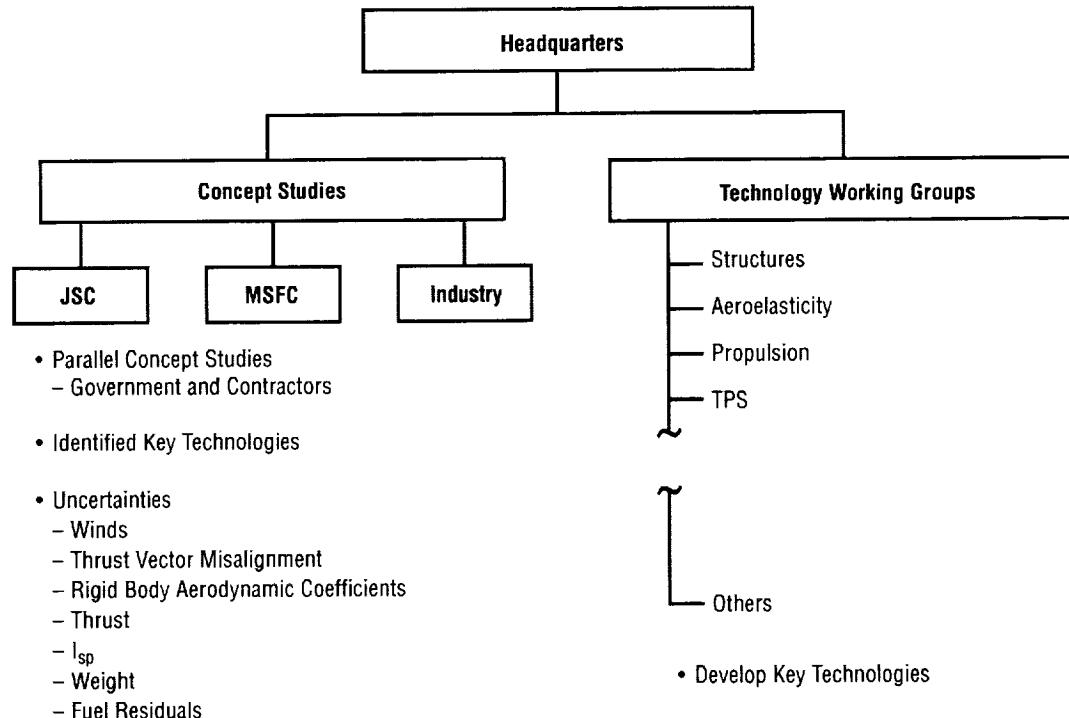
Figure 83. Space Shuttle history—Phase A concept studies and groups.

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6.1.3 STS Phase B

The convergence of concepts during Phase A led to the issuance of a Phase B RFP in 1970 for a fully reusable two-stage vehicle (see fig. 84). Major requirements of the RFP are listed in table 26. Two orbiters were to be developed: one capable of 230 miles cross range and the other capable of 1,726 miles cross range. Go-around capability was required for both orbiter and booster, which implied the use of air-breathing engines on both vehicles. Two teams were awarded contracts: MAC-DAC/MM and NAR/GD. Two months later, requirements were revised to increase payload from 15,000 to 25,000 pounds and to specify JP–4 fuel for the air-breathing engines (safety issue). During the Phase B activities, both teams matured their designs through trade studies, arriving at low and high cross-range orbiter configurations with a common booster. The orbiters had hot-structure TPS's and two main engines each. Two engines provided best performance and lowest cost but later gave way to the three-engine configuration to better provide abort capability with engine out. The baseline Phase B configurations are shown in figure 85.

Year	July 1970 RFP	September 1970		December 1970	May 1971
Requirements	See Table 26	• Revised Requirements – Payload 15–25 K – Fuel (JP–4) – Pressurized Payload Bay • Technology Assessment General Area of Concern: Aerothermodynamics Dynamics and Aeroelasticity Propulsion Structures/TPS and Materials Biotechnology Integrated Electronics Operations and Maintenance	Cost in ($): 3,715,000 5,740,000 18,130,000 51,745,000 1,960,000 8,355,000 2,215,000	Results	Results
Contractors	A. *MSC–Responsible ————————→ 1.MAC-DAC and MM 2.NAR and GD			A-1 15 × 30 Payload Bay 15 K 2 Engines + Turbofans 2 Configurations MAC-DAC—Orbiter MM—Booster	A-2 15 × 60 payload bay LCR–46 K HCR–20 K 2 Engines and Turbofans 2 Configurations NAR—Orbiter GD—Booster
	B. MSFC—Alternate Space Shuttle Concepts (ASSC) 1.Chrysler ————————————————————→ 2.Lockheed 3.Grumman/Boeing (MSC)			1. SSTO 2. Stage and a Half 3. Stage and a Half – External LH₂ Tank – 3 SSME's – $6.7 Billion	

* Lead Center Concept Developed
  • MSC Integration of Shuttle Activities
  • MSFC Responsible for Propulsion

Figure 84. Space Shuttle history—Phase B.

Table 26. Space Shuttle history—Phase B.

Phase B Program Requirements	Requirements Levied by Various NASA Centers
The shuttle shall be a fully reusable two-stage vehicle	Each element (orbiter and booster) shall have a two-man flight crew and be flyable under emergency conditions by a single crewman
The integrated vehicle shall be launched vertically and landed horizontally	
The initial operational capacity shall be in late 1977	The stages shall be capable of positive separation without the use of special separation rocket systems of the type employed on Saturn
The reference mission shall be a 310-mile 55° inclination circular orbit from a launch site located at 28.5 ° north latitude (Kennedy Space Center)	In-flight refueling (subsonic or supersonic) shall not be used to meet design mission requirements
The payload bay shall have clear volume 15 ft in diameter by 60 ft in length, with a reference mission capacity of 15,000 lb	The booster and orbiter shall be capable of pilot-controlled landings under FAA category-2 conditions
Two orbiters shall be developed: one capable of 230 miles and the other of 1,726 miles crossrange	The vehicle shall incorporate on-board provisions to quickly and easily place the vehicle in a safe condition following landing to permit crew and passenger egress
The mission duration (from lift-off to landing) shall be 7 days	There shall be no propellant cross-feed between elements (booster and orbiter)
The booster and orbiter shall have a go-around capability during landing operations (basically implying the use of air-breathing engines)	The vehicle elements (booster and orbiter) shall be capable of landing on runways no longer than 10,000 ft.
Launch rates will vary from 25 to 75 per yr	
Total turn around time from landing to launch shall be less than 2 weeks	
Both elements shall provide a shirt sleeve environment with trajectory load factors of less that 3G	
A 43-hr turn-around capability shall be provided for rescue missions	
All subsystems, except primary structure and pressure vessels, shall be designed to fail-operational after failure of the most critical component, and to fail-safe for crew survival after failure of the two most critical components.	

While a fully reusable two-stage concept was the clear choice for lowest operational cost per flight, it became apparent that concurrent development of both an orbiter and a booster vehicle would be expensive. Peak-year development funding was becoming a concern. Addressing this issue, alternate Space Shuttle concept (ASSC) studies were initiated to look at alternatives to fully reusable two-stage concepts. Chrysler, Lockheed, and Grumman/Boeing studied single-stage-to-orbit (SSTO), stage-and-a-half, and external fuel-tank concepts. These studies provided the groundwork for future program decisions.

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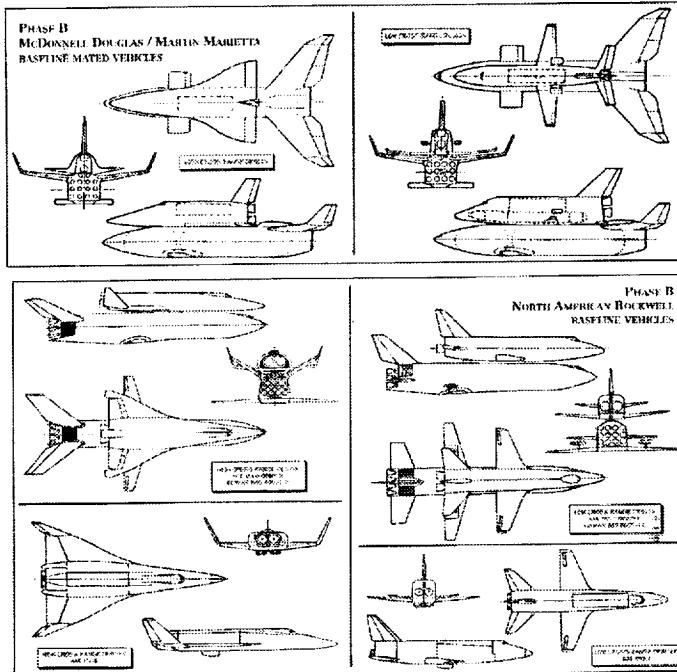
Figure 85. Space Shuttle history—Phase B baseline configurations.

6.1.4 STS Phase B′

In 1971, OMB informed NASA to expect no budget increase in the next 5 years. At that time, the total NASA budget was $3.2B, with no more than $1B per year being allocated to Shuttle development. The Phase B fully reusable two-stage configurations required a development cost of $10B, peaking at an annual cost of $2B in some years. The budget constraints forced an extension of Phase B, designated Phase B′, to search for ways to deal with the budget limitations (see table 27).

Sacrificing lowest operational cost in order to obtain lower development cost, NASA endorsed a variation of stage-and-a-half which moved the fuel tanks outside the orbiter and also used expendable boosters. The contractor groups were expanded from the two Phase B teams by the addition of Lockheed and Grumman/Boeing from the ASSC studies, and the teams were told to reevaluate their proposals with requirements for using the MSC "040" orbiter, external tanks, and three main engines. Examples of Phase B′ configurations are shown in figure 86.

6.1.5 STS Phase B″

At the end of Phase B′, development cost projections had been reduced significantly but were still too high (see table 28). An extension was provided to further study booster configurations, including recoverable liquid boosters and solid boosters. A major issue was whether the orbiter main engines would burn in parallel or in series with the booster. In December 1971, parallel burn was adopted, and abort SRM's were added. Total development costs were now estimated at $5.8B. NASA further estimated that use of solid boosters would save $700M in development although carrying more operational costs and unknowns. In March 1972, NASA adopted solid boosters to go with the external tank and three-engine orbiter, entering Phase C with a configuration basically similar to today's Shuttle, as shown in figure 87.

Table 27. Space Shuttle history—Phase B′.

| May/June 1971	September 1971	October 1971

• OMB informs NASA no budget increase for 5 years
 	
TSTO (ϕB) Shuttle development cost $10B with peak of $2B some years
 	
Proposed total NASA budget was $3.2B for 1972
 	
Only $1 B/yr for STS
 	
MSC considered external tanks first time in their in-house studies
  – 15 × 30 payload bay
  – 20 K payload
  – 4 engines
  – Internal lox tank
 	
NASA endorses variation of stage and a half (called semi-reusable)
– Some configurations developed in 1965–1968 by Air Force
– Decrease in DDT&E cost
– Increase in OPS cost
 	
MSC studied 53 Orbiter configurations during 1971–1973
	Contractor teams expanded to four:
	  – MAC-DAC and MM
	  – NAR and GD
	  – Lockheed
	  – Grumman and Boeing
	
	Requirement:
	  Reevaluate proposals
	  – MSC—040 Orbiter
	  – External tank
	  – Three high-pressure chamber main engines
		B′ ended

Rebalance for New Budget Constraints
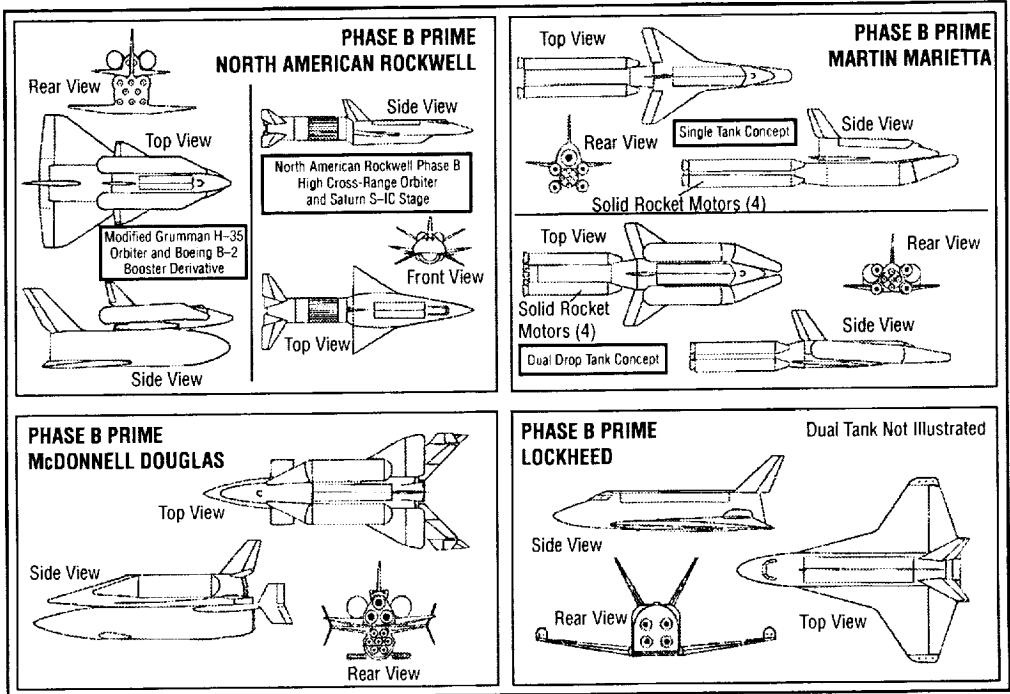
Figure 86. Space Shuttle history—example Phase B′ configurations.

Table 28. Space Shuttle history—Phase B″.

November 1971	December 1971	March 1972	May–October 1973

Phase B′ costs still too high
• $2.8M contracts to continue
  – Grumman/Boeing
  – Lockheed
  – MAC-DAC/MM
  – NAR
 	
• New Ground Rule:
  Stage below 4,100 mph
 	
• Technical issues
  – Booster configuration
    • Fully recoverable, new liquid
      engine, pressure fed
    • Fully recoverable, based on
      SIC stage
    • Solid boosters
  – Series burn/parallel burn
    • Separation dynamics
      (favored series)
    • Ground handling
      (favored parallel)
    • Main engine start on pad
      (parallel)
    • Cost analysis (favored parallel)
	Adopted parallel burn
	
	Added abort SRM's
		Adopted solids
		– Cheaper development
		– Faster
		– But higher OPS cost
		– More unknowns
			MM and others TPS study
			– Ablative versus reusable
			– Tile technology

Design Significantly Impacted by Budget
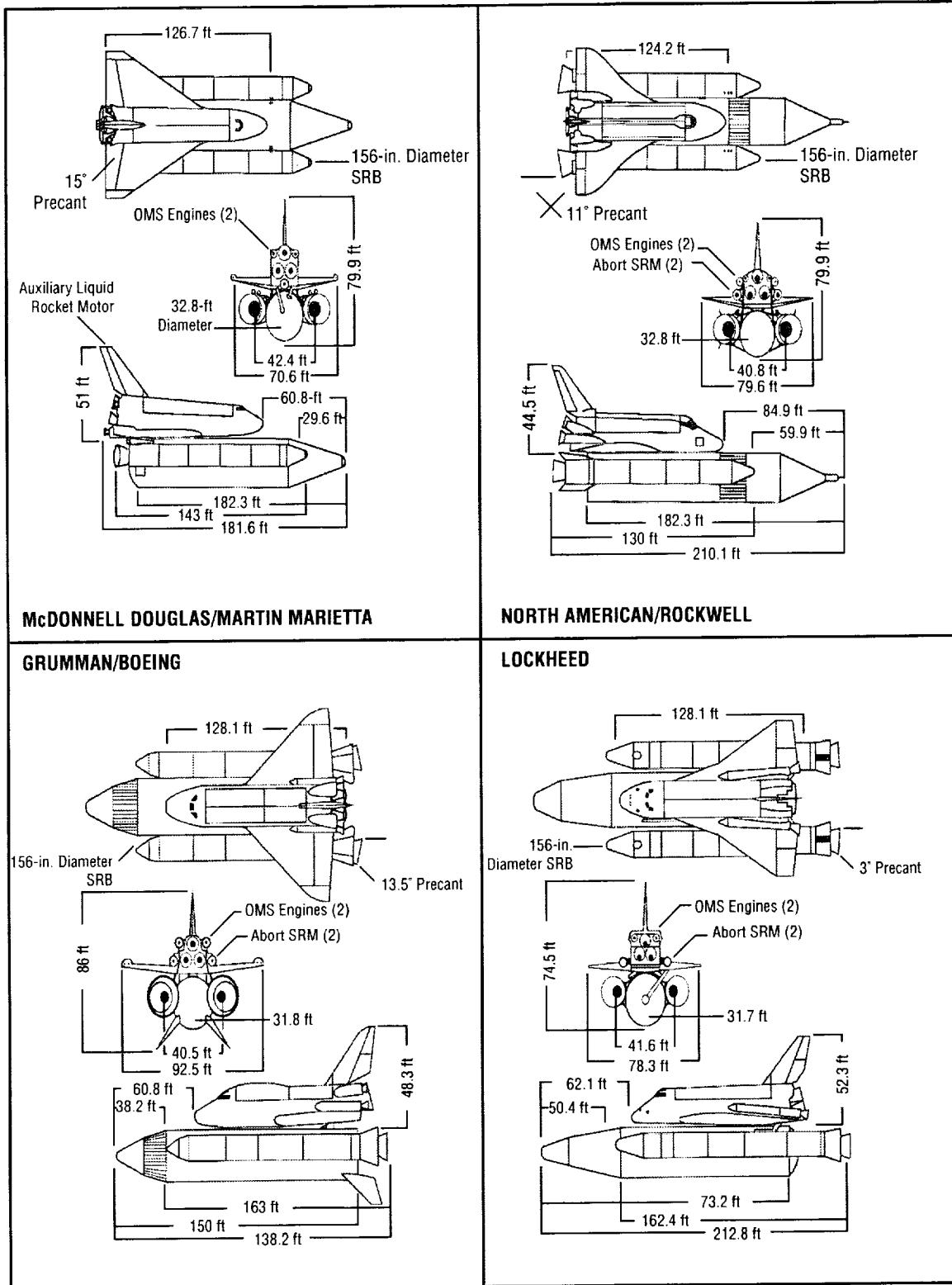
Figure 87. Space Shuttle history—example Phase B″ configurations.

6.1.6 STS Phase C

Phase C, detail design, began with a baseline configuration established at the end of Phase B″. Table 29 shows the main contractors and major configuration changes. In 1972 and 1973, contracts were signed for the development of the Shuttle elements and for systems integration. During the 2-year detail design phase, the Shuttle configuration underwent a number of design modifications in order to achieve a workable system and attain the desired balance of system performance. There were six major overall configurations involving geometrical and structural changes, adding and deleting air-breathing engines and abort SRM's, and subsystem evolution (see fig. 88). The balancing act between subsystems/design functions and requirements/attributes continued until the final production vehicle configuration was released. Even after the point where the design was frozen, tradeoffs and balancing were done between requirements, performance, and operational constraints.

The following observations are among the many which can be made concerning the development history:

- Political decisions heavily influenced the development process. Budgetary constraints drove the design itself. This is common for programs of this magnitude.
- Requirements underwent major changes during the process, significantly driven by the above considerations.
  - The concept started as fully reusable, but cost drove to the stage-and-a-half configuration of Phase C.
  - DOD requirements also drove the configuration.
  - The continuous requirements flux demanded a continuous design balancing act
- The development effort was extensive, spanned several years, involved most of the space community, and had large expenditures.
  - Hundreds of variations of vehicles were studied.
  - Seventeen contractors participated in 29 major study contracts worth $127M issued from 1969 to 1973.
  - There also was significant funding for technology groups and large in-house activities by NASA and the Air Force.
- The complexity of the configuration and its resulting sensitivity and interactivity provided design challenges which carried over into operational complexities and flight constraints.

Table 29. Space Shuttle history—Phase C.

Contract awards	Major Configuration Changes	

August 1971
• SSME to Rocketdyne
  (Contract signed
  August 1972 after protest)
 	
July 1972
• Orbiter to Rockwell, system
  integration to Rockwell
 	
August 1973
• External tank (ET) to Martin
• Solid rocket boosters
  (SRB's) to USBI
• SRM's to Thiokol
 	
Requirements
• 65,000 lbs due east
• 15' × 60' payload
• 1,265 mi cross range
	Orbiter structural weight trades
	(~1,000 lbs)
	
	• Thrust structure, wing spar, drag
	  attachments, separate crew module,
	  composite bay doors, composite
	  OMS pods
	
	See 1994 AIAA Propulsion Conference
	Short Course on How Phase
	B"/C Requirements Impacted SSME
	Design[16]
	<hr>Scenario of vehicle modifications
	(see fig. 88)
	
	"Vehicle I" (authority to proceed (ATP))
	"Vehicle 2" (program readiness review
	  (PRR))
	• Moved OMS Pods
	• Forebody shape
	• Orbiter/ET incidence
	• Abort SRM's deleted
	• Air-breathing engines deleted
	• ET Ogive nose
	• SRB's shortened, moved aft
	• SRB TVC added
		"Vehicle 2A" (150K orbiter)
		• Orbiter resized smaller
		• Wing planform change
		• Body reshape
		• Air-breathing engines returned (ferry)
		• Abort SRM provisions returned
		• SRB's further shortened and moved aft
		• ET shortened
		
		"Vehicles 3 and 4" (mid-1973)
		• Minor geometry adjustments for
		  aerodynamics and aerothermo
		• ET shortened
		• ET retrorocket (spike) removed
		• SRM thrust termination dropped
		
		"Vehicle 5" (early 1974)
		• Modified OMS pods
		• Abort SRM provisions dropped
		• Added orbiter braking chute
		
		"Vehicle 6" (production, mid-1974)
		• Exposed RCS
		• ET and SRB lengths changed slightly
		• Umbilical door modifications
		• Thermal glass on windows

Balancing Act Continues: Requirements/Design and System
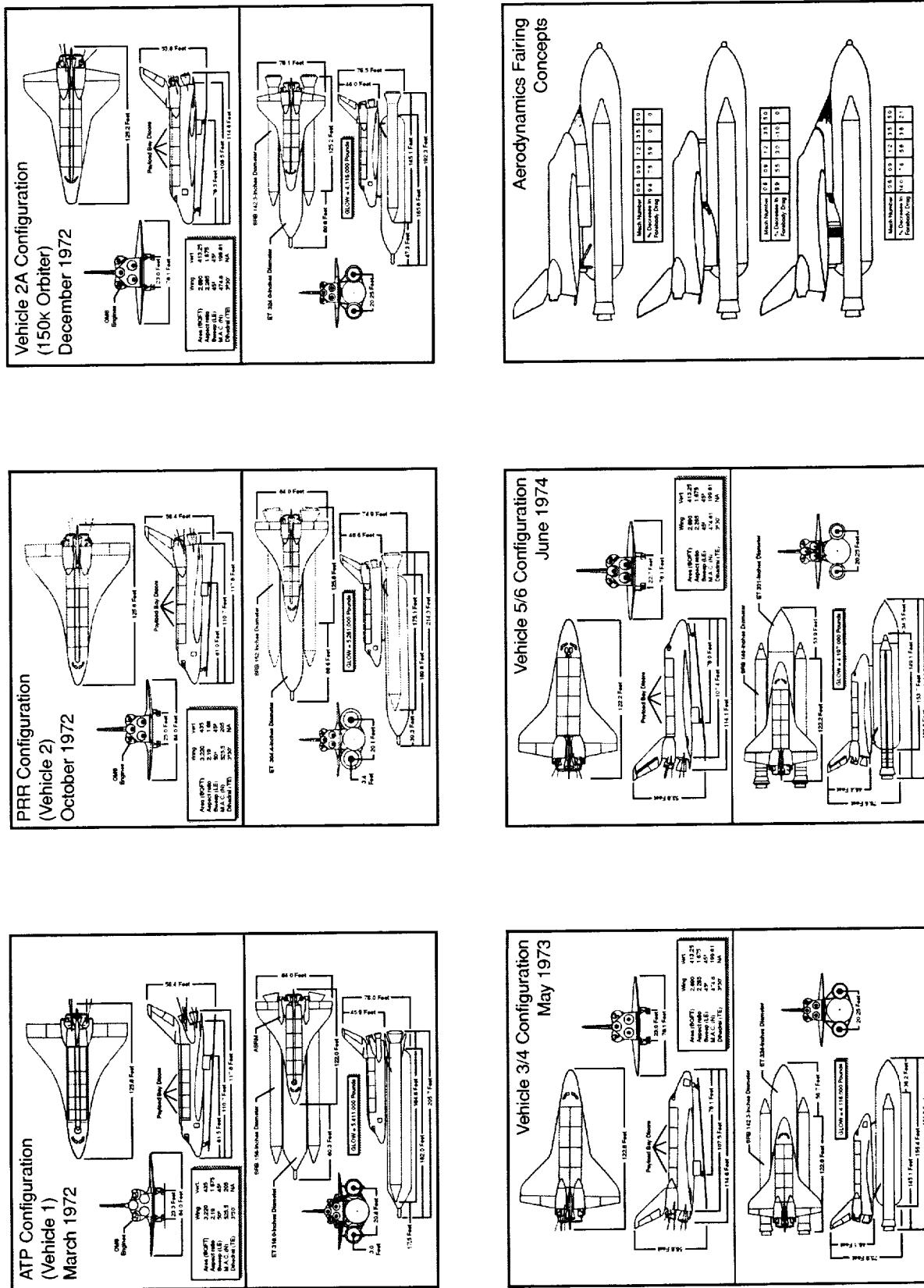
Figure 88. Space Shuttle history—Phase C configurations.

6.2 Design Process for Flight Mechanics With Loads Modeling Example

In this section, the complex technical integration process for flight mechanics and loads modeling is illustrated by describing how this process has been accomplished for past programs.

6.2.1 Space Shuttle Flight Mechanics Technical Integration

The Space Shuttle is used as the primary example for technical integration of flight mechanics. Table 30 shows a set of initial assumptions developed during the preliminary design phase in order to simplify the design process. These assumptions cover topics such as assuming that the ascent loads are bounded by reentry loads. Some of these assumptions proved to be wrong, such as the assumption that ascent crosswinds would not impact design. In order to achieve proper integration, discipline panels were formed initially to handle such topics as aerodynamics, loads, etc.

Table 30. Space Shuttle preliminary design.

Preliminary Design
Allocations and assumptions implemented to simplify the design process:

• Ascent loads required to be within re-entry thermal and aero loads
• SRB not designed by water impact but assessed by attrition
• Weight allocation:
  – Element dry weight and geometry
  – Vehicle "glow"
• SRB/TVC
  – Full TVC
  – Trim TVC with active ailerons
• Ascent crosswinds would not impact design
  – Consequences: 1. High wing loads; wing failed
                           2. Element interface loads sensitive to
                               combined aero loads ascent accelerations

Panels formed to enable technical penetrations and communications:
• Panels: Aero, Flight Mechanics, Loads, etc.

Going into the detail design phase, problems in integration started to occur, and two major working groups were formed to aid the integration process (table 31). The Ascent Flight System Integration Working Group (AFSIG) and Propulsion System Integration Working Group (PSIG) were formed as integrating and sounding groups for the panels, with recommending authority to the System Integration Manager and Shuttle Program Manager. The first major tasks were to set up procedures and methodologies as well as defining appropriate parameter uncertainties to use in design. These uncertainties were identified by the various disciplines for each flight event (fig. 89). AFSIG's role was to assure completeness and consistency of the parameter uncertainty matrix, assuring that the uncertainty levels chosen were sufficient for design but not overly conservative. Figure 90 is an excerpt from the parameter uncertainty matrix. More detail of the parameter uncertainty matrix is given in the appendix.

Table 31. Space Shuttle detail design.

Detail Design

• Formed working groups
  – AFSIG and PSIG
  – Expanded number of panels; integrated by AFSIG and PSIG
 	
• First major task
  – Set up procedures and methodologies
  – Set up parameter uncertainty matrix by flight events
 	
• Outputs of technical integration activities
  – Impacts on vehicle design and sequence
    • Parameter combinations for engine out; detuned wind gust and engine-out by 6 seconds and all other uncertainties were 1σ.
    • Baselined lift-off dynamic analysis using 2σ worst-on-worst approach.
    • "A" factor and squatcheloid approach baselined for max Q.
    • 95% wind speed and 1/2 magnitude of shear and gust applied deterministically; other half of the shear and gust used as uncertainty with other parameters for max Q.
    • Monthly mean wind biasing for design reference trajectory.
 	
  – Impacts on procedures and models
    • Delayed SRB ignition
    • SRB separation motor orientation, location, fuel combination, timing, and number of motors.
    • Necessary load relief control increased thermal environments, increased TPS, and reduced payload.
    • Three axis load relief baselined for max Q.

ED6171

ORGANIZATION SYSTEMS DYNAMICS LABORATORY	MARSHALL SPACE FLIGHT CENTER	NAME R. RYAN
CHART NO.: 15	**AFSIG REVIEW**	DATE APRIL 1986

Parameter Matrix

Discipline

Trajectory Performance
Pogo
Flutter
Control
Thermal
Liftoff Clearance (Drift)
Separation
Loads
Environments
  Overpressure
  Acoustic
  Shock
  Winds
Propulsion
Dynamics
Criteria
Failure Modes

Event

Prelaunch
Launch
Max Q
Max G
Pre-SRB Separation
Post-SRB Separation
SRB Separation
Second Stage Ascent
ET Pre-Separation
ET Separation
Total Ascent

Figure 89. Space Shuttle AFSIG—example parameter matrix event.

ORGANIZATION SYSTEMS DYNAMICS LABORATORY	MARSHALL SPACE FLIGHT CENTER **BASIC PARAMETERS**	NAME R. RYAN
CHART NO.: 16		DATE APRIL 1986

SRM Propulsion   **Analysis Tolerance**

- TC227A–75 Thrust Versus Time Curve Per SE–019–083–2H $\left\{\begin{array}{l}\text{ETR} - 81\ °F\ (\text{Mean})/\ 83.4\ °F\ (\text{Max})\\ \text{WTR} - 52\ °F\ (\text{Mean})/\ 44.5\ °F\ (\text{Max})\end{array}\right.$
  (SRB System Data Book) for Bulk Grain Temperatures
  (TC227H Is Proposed as Update)

- Flight-to-Flight Propellant Burning Rate $\left\{\begin{array}{l}\pm\,5.3\%\ (\text{One SRM})\\ \pm\,4.7\%\ (\text{Two SRM's})\end{array}\right.$

- Thrust Level Development Uncertainty $\pm\,3\%$

- Thrust Oscillation (Dynamic Factor Assumed for $\pm\,5\%$
  Loads Analysis)

- Steady-State Thrust Mismatch Between Motors   85,000 lb (Ref. vol. X,
                                                   fig. 3.3.2.2e)

- Thrust Misalignment $\pm\,0.75°$ Per SRB

- Flight-to-Flight Thrust Level Dispersion $\left\{\begin{array}{l}\pm\,5\%\ \text{Single Motor}\\ \pm\,4.9\%\ \text{Both Motors}\end{array}\right.$

Aerodynamics

- Pressure Distribution Test Data Match with Aerodynamic $\pm\,3\%$
  Coefficient Test Data

- Elevon Deflection Schedule #6 (Hinge Moment Limiting $\Delta\delta_e 0 = f\ (\Delta C_{HM} = 0.02)$ Aero
  Feedback) Per Rockwell Internal Letters ACDA/FSA/76–527   Data Adjusted to New
  and 531 $(\delta_e 0 + \Delta\delta_e 0)$

- SD72–SH–0060–2 (Mated Vehicle Aero Design Data Book)   None

- Include Aerodynamic Tolerance Effects on Coefficients: Wind   Values Per PRCB Briefing on
  Tunnel Deviations Plus Power-on Deviations Plus Reynolds   8/18/76 MCR 3378 "5.3 Ascent Load
  Number Effects   Adjustments"

Figure 90. Space Shuttle AFSIG—example parameter variations.

Many impacts to the design occurred due to how the parameters/uncertainties were implemented. Impacts that were too severe were resolved by changing how the uncertainties and their application were used in the design process. The prior approach of worst on worst was too severe for the high performance characteristics of a vehicle like Space Shuttle. Table 31 lists a number of these procedural and criteria changes made by AFSIG to minimize the effect of uncertainties and maintain a highly reliable system. Vehicle operational changes were made to reduce impacts of uncertainties on loads, etc. For example, the SRM ignition was delayed 5 sec after SSME ignition in order to capture a minimum stored energy condition, thus reducing lift-off dynamic loads. Three-axis load relief was another addition. These changes reduced loads but resulted in a loss of performance.

Table 32 delineates other changes that were made to reduce weight/increase performance (i.e., reducing the safety factor on the external tank from 1.4 to 1.25, increasing the SSME thrust level from 100 to 109 percent, introducing the high performance SRM, etc.). Special teams were formed to solve particular design problems such as the Orbiter Tile Team, SSME Design Team, and SRB Recovery Team. Certain risk mitigation activities were performed such as the mated vehicle ground-vibration test and SSME improvements.

Table 32. Space Shuttle change examples.

Even with all these special activities, problems occurred such as loss of load margins on the orbiter wing and on the interface members between the orbiter and external tank and between the external tank and the SRB's. The program was now in the flight test phase, so operational work-arounds were sought (see table 33). In order to launch safely with these lower margins, the Launch System Evaluation Advisory Team (LSEAT) was formed to perform day-of-launch wind monitoring with specific constraints. As the system evolved, day-of-launch I-load updates were employed which utilize the measured wind profile 2 hr prior to launch. Many design changes were implemented to reduce problems uncovered early in the flight test program such as water troughs for overpressure reduction, super light weight tank (SLWT) for added performance, etc.

Table 33. Space Shuttle change examples—test and operations.

Flight Test and Operations	

• Changes required*
   – Organized LSEAT
   – Day of launch monitoring/launch constraints
     — Balloon flight day of launch/realtime flight assessment
   – Day of launch I-loads update
   – Special instrumentation for SRB AFT skirt
   – ET TPS (Ice team)
   – Engine operations procedures; engine redesigns
   – Redesigned AFT skirt due to water impact
   – Two changes in SRB parachutes
   – Changed how orbiter tiles were attached
   – Debris/tile team
   – SSME 104% versus 109%
   – SRM overpressure accommodations
   – Changes to meet EPA regulations
     — ET TPS
   – RSRM
   – SLWT
	Two Duct HGM
	Damping seals
	Single crystal turbine blades
	Large throat nozzle
	Silicon nitride bearings
	P and W high pressure turbo pumps

* This list is representative; not all inclusive.	

6.2.2 Loads Modeling Example

    The basic process, figure 91, models the plant (the vehicle) with its uncertainties as well as the natural environments with their uncertainties. Combining these together produces a response with variations. What is needed is for the response to have an assured probabilistic level to produce adequate margins. Achieving this requires considerable work with the input variables, the uncertainty combination approach, and the design. The process starts with the generation of the trajectory, figure 92, which produces the basic ideal performance. Since the ideal cannot be reached because of the effects of variations, in order to secure analysis efficiency, specialized reference trajectories are generated. These reference trajectories become the basis for analyses using uncertainties to determine perturbated responses. These responses are used as inputs to generate loads acting on the vehicle (see fig. 93). The figure shows the outputs of the responses that become the inputs for loads. The sketch shows this wind-induced perturbation from the nominal trajectory as well as the dynamic elastic-body response.
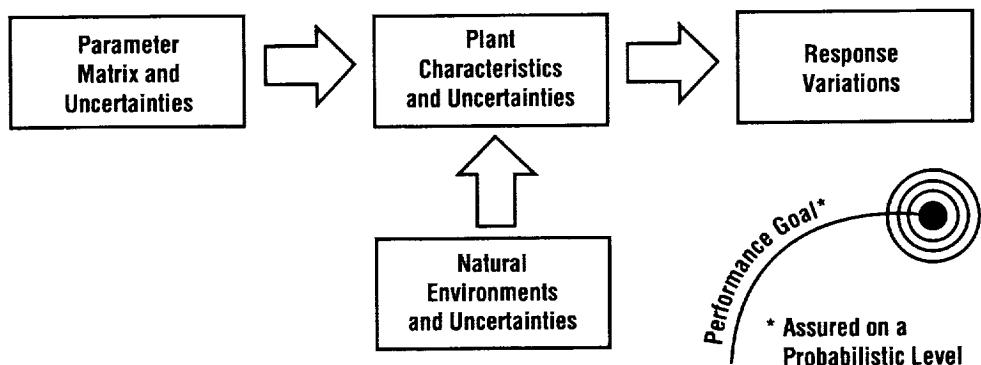
Figure 91. Overall concept for flight mechanics.

Step 1 — Ideal Optimized Trajectory (Response) ⟹ – Ideal Optimized Trajectory and Potential Payload Margins / – Input to Step 2

Step 2 — Reference Trajectory/ Trajectories ⟹ – Specialized Trajectories Generated to Achieve Analysis Efficiency / – Reference Trajectory Input to Step 3

Step 3 — Non Ideal Perturbed Response (Uncertainties) ⟹ – 3σ Response

Note: Steps 2 and 3 Performed for and Tailored to Each Mission Phase as Well as for Special Situations

Figure 92. Method to achieve performance goal.

- Rotational Acceleration
- Translational Acceleration
- Gimbal Angle and Rates
- CG offset
- Thrust
- Aero Loads, Moments, and Distribution

Reference Trajectory To Orbit

Target
- Location
- Payload and Margin

Natural Environment
– Wind Velocity and Direction
– Temperature
– Density

Data Requirements for Load Analysis
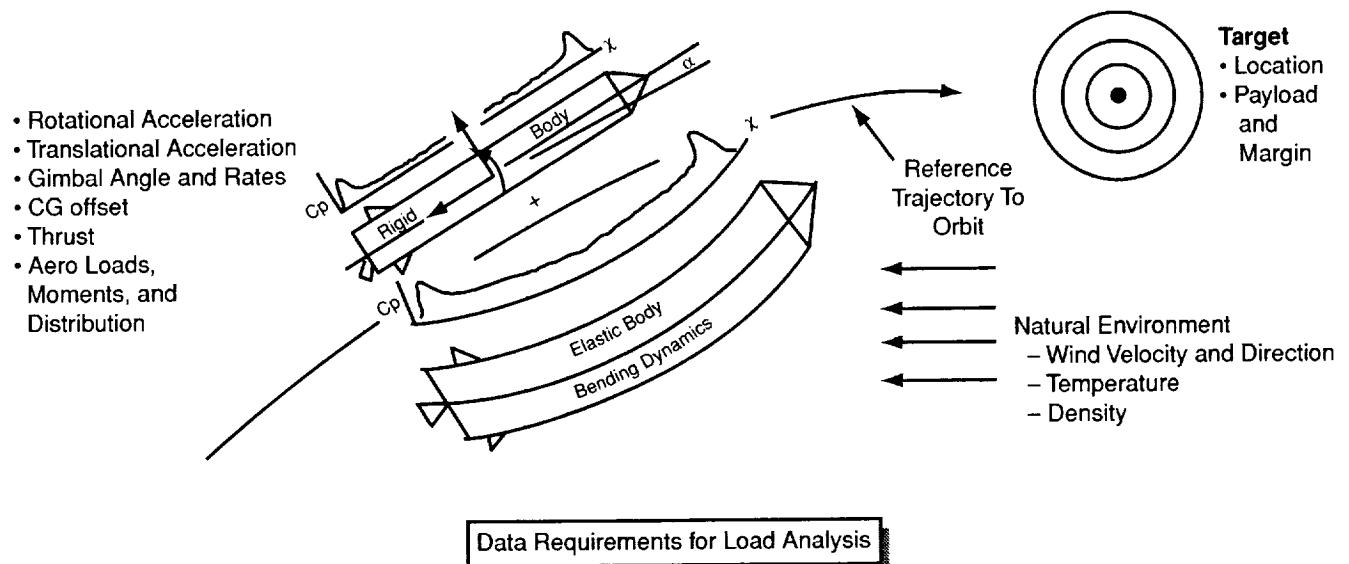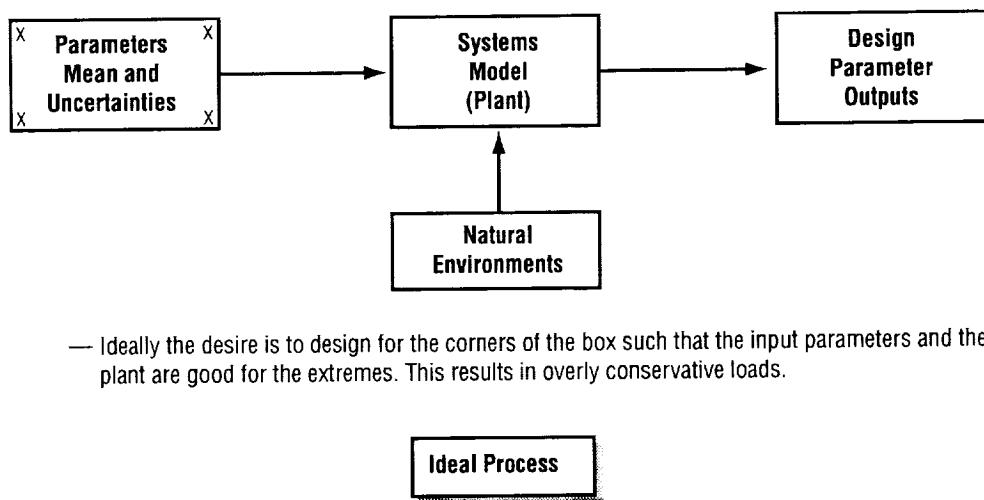
Figure 93. Illustration of design process: structural loads.

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To achieve the most conservative design, ideally one would want to design for the corners of parameter uncertainties space, as shown in figure 94; however, this is generally not practical because of performance impacts. The next most desired approach is to accomplish a pure statistical analysis such as Monte Carlo of the vehicle parameters and the natural environments. This has not been practical until recent years and is still costly. Therefore, the synthetic wind model was developed along with a root-sum-square (RSS) and A-Factor approach for uncertainties (see table 34). The approach is a conditional probability approach which says that given the 95 percent wind speed combined with 99 percent shear and gust effects RSS'd, the load must be maintained within the 3-sigma bound. This approach was very efficient for Saturn Apollo and has been validated by a Monte Carlo analysis.

— Ideally the desire is to design for the corners of the box such that the input parameters and the plant are good for the extremes. This results in overly conservative loads.

Figure 94. Structural loads illustration.
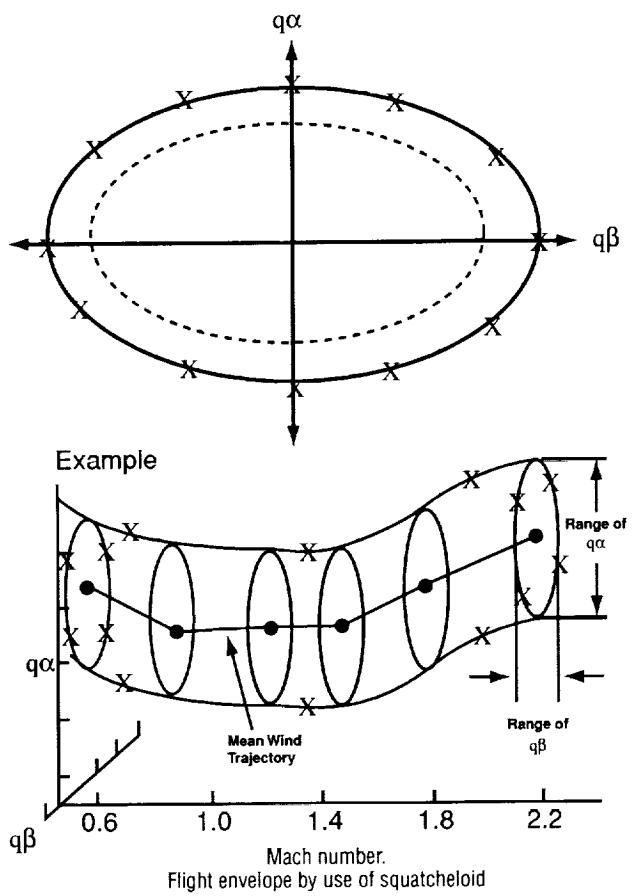
The Space Shuttle followed a similar approach during design with some significant changes in the wind model (see table 34). Other than the wind model change, the same conditional probabilistic approach was used. The wind model change was introduced to remove conservatism without impacting safety. Figure 95 shows how the approach was applied to different load parameters called squatcheloids that are q-alpha and q-beta plots as a function of Mach number. Combining the squatcheloids as a time function of Mach number produces a loads envelope tube as a function of ascent trajectory time. At each point on the squatcheloid, time consistent accelerations, velocities, and positions are used for load analysis. This approach saved significant amounts of computer time. The X–33 patterned their approach after Shuttle but used only 2-sigma variations instead of 3-sigma (table 35).

Table 34. Structural loads illustration.

• The desire is an all up Monte Carlo of the vehicle parameters and the natural environment parameters. In the past and to some extent in the present, this was not possible or, if possible, not design analysis efficient. As a result alternate procedures were developed.

• Saturn Apollo/Skylab
  Saturn used a conditional probabilistic approach, where a synthetic deterministic wind profile is the condition. The vehicle's response is determined to this profile using the mean and the 3σ parameter uncertainties (individually) producing a set of responses which can be root sum squared then multiplied by a factor of three producing: 3σ response against the condition (winds).

  – Wind model (deterministic) (the synthetic wind profile model was generated for each critical altitude/match number)
    • 95% worst month scalar wind speed
    • 99% worst month wind shear and gust (due to the conservatism, the shear and gust were RSS'd)

  – Plant models (Two)
    • Rigid body with and without propellant sloshing dynamics
    • Rigid plus elastic body with propellant sloshing dynamics

  – Parameter uncertainties
    • 3σ about mean
    • Normal distribution assumed

  – Analysis approach
    • Run response to synthetic wind profile (one altitude) using mean of parameters
    • Run response to synthetic wind profile (same altitude) using mean of all parameters but one, which is the $+1\sigma$ level
    • Repeat for -1σ level of parameter
    • Repeat process for + and – of each individual parameter
    • RSS for each response, develop a single time response run which produces a time consistent response that produces the same 3σ peak. (Time consistent set of response data required for balanced load set.)
    • Repeat process for each critical altitude/Mach Number
    • Produce conditional probability set of design data
    • Engine out phased with wind gust

  – Operations
    • Bias trajectory to monthly mean wind to obtain margins.

  – Validation of synthetic wind approach was made using individual measured wind profiles (50m wave length, 150 profiles per month) in conjunction with Monte Carlo approach. (Winds only, vehicle parameters nominal.) Good correlation with synthetic profile.

• Space Shuttle

  – Space Shuttle used the conditional probabilistic approach; however, the wind profile model was changed. (Remove conservatism)

  – Winds model (synthetic profile; looked at using directional speed change).
    • Trajectory biased to monthly mean wind (design)
    • Synthetic profile directional
      – 95% worst month wind speed
      – 50% of 99% shear and gust magnitude RSS'd.
    • 50% of 99% shear and gust treated as uncertainties along with all other vehicle parameters.

  – Winds model (Individual profiles)
    • Monthly detailed wind profile (50m wave length) 150 per month (special studies)

  – Analysis approach
    • Same conditional probability approach as was used for Saturn except using squatcheloid as output. (See fig. 95)
    • Simultaneous pitch and yaw synthetic wind profiles required
    • Engine out delayed 6 seconds past gust peak. 1σ vehicle parameter uncertainties, used with engine out
    • Bending dynamics response accounted for by multiplying rigid body loads by 10% (conservative based on special studies). Liftoff and landing analysis made using bending dynamic models.
    • Liftoff used 2σ worst-on-worst parameter uncertainty method

Figure 95. Structural loads illustration—squatcheloid approach for loads.

Table 35. Structural loads illustration—X–33.

• X–33
  – X–33 used the conditional probability approach for max "Q"; same as Shuttle for lift off
  – Monthly mean wind biasing
  – 2σ parameter variations
  – Wind model
    • Synthetic profile
  – Analysis approach
    • Squatcheloid approach as was used for shuttle

Table 36 is a summary of lessons learned this example. Although only a snapshot of the loads process was provided, the lessons are applicable to all the various design activities. Uncertainty analysis is required, and this analysis complicates the design process. Creativity and innovation of engineers are keys to establishing accurate, efficient approaches for the specific vehicle being designed.

Table 36. Structural loads illustration—summary.

Design Process for Flight Mechanics with Loads Modeling Example
• Uncertainty analysis key to a reliable design • Uncertainty significantly complicates the design process; load analysis used as example; established and verified • Similar uncertainty analyses were also used for all other design functions • Creativity and innovation of engineers key to establishing accurate, efficient design process. Uncertainty Drives Innovative Methodology

7. EXPERIENCE-BASED KNOWLEDGE

7.1 Survey of Experienced Practitioners in Aerospace

A survey was conducted of experienced practitioners in aerospace using the question, "What is the essence of engineering design based on your many years of experience?" Many have responded with very clear and succinct lessons. Their responses have been collected and are included by their individual names. The statements are unaltered and provided without comment.

7.1.1 James Blair (Retired NASA, presently at University of Alabama in Huntsville)

"In a vehicle system, all parts are connected; a change in one affects the others. The more fully the design organization acknowledges this system connectivity, by means of communications, organization, and especially the individual engineers' perspective, the more successful will be the design."

7.1.2 Bob Brotherton (Former McDonnell Douglas, presently with Boeing)

"Engineering is logical."

7.1.3 Jack Bunting (Lockheed Martin, Denver)

"Test what you fly, and fly what you test."

7.1.4 W. E. Campbell (Retired Aerojet)

"Success lies in attention to detail, with a methodical top-down approach to identify the areas of concentration."

"One-fourth to one-half of historical rocket engine failures seen to be attributable to out-of-print hardware, process escapes, and the like. One probable contributor is insufficient priority on producibility in favor of performance, weight, and envelope. It must be the mandate of project and technical management to balance these priorities."

"Stacking worst-on-worst tolerance (or schedules, costs, contingencies, margins, etc.) results is an untenable, noncompetitive design, product, or program. Some form of probabilistic approach will point toward a competitive but successful solution."

"Project scheduling should include small enough task increments that an event "miss" can be recovered with reasonable downstream workarounds. Last minute surprises on long-span tasks are project disasters."

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"Nearly everything in the world has a distribution. A simplified probabilistic approach (which does not become frustrated by imprecise algorithms or incomplete data bases) is an excellent tool to identify drivers, screen options, and evaluate sensitivities."

"A part fracture failure occurs when "stress" (in some form) exceeds "strength" (in some form). This can be the starting assumption for failure analysis, which must identify and rectify the combination of higher (than expected) stress elements and/or lower (than expected) strength elements—both of these including the effects of operating conditions and environment, manufacturing processes, part history, and the like—that resulted in failure."

7.1.5 Chris Chamis (NASA Lewis Research Center)

"Simplicity in formulations wins over complexity in every respect—succinctly better-faster-cheaper."

"Simple solutions to engineering problems require insight that is gained by experience and maturity."

"Major hurdle in simplicity is resistance from inexperienced colleagues and *not* very knowledgeable supervisors."

"Simple solutions to complex problems require continuing management support: person power and other required resources."

"Successful engineering solutions are not based on the proverbs: 'The nail that sticks out gets the pounding' or 'The wheel that squeaks gets the grease,' which is the current practice."

7.1.6 David Christensen (Lockheed Martin, Huntsville)

"One good test is worth a thousand opinions."

"Too much analysis can cause Design Paralysis."

7.1.7 Peter Christie (Boeing Seattle)

"It is important to always do an analysis before testing. It is equally important to conduct at least one valid test in order to confirm the accuracy of the assumptions in the analysis."

"Engineering design knowledge must be combined with an understanding of materials and manufacturing process in order to achieve the most successful design."

"The performance of each system in an aerospace design affects the performance of other systems in the design. For example, in pressurized commercial aircraft fuselage, all joints are sealed with a polysulphide sealing system. The sealant adds weight and cost and affects the fatigue life of structural joints. It also minimizes the bleed air requirements of the engine, while increasing the corrosion resistance of the joint."

7.1.8 Werner Dahm (NASA MSFC Chief Aerodynamic Scientist)

"Mother Nature does not read our paper. If we don't follow her way, she lets us fall."

"Paper is patient. Sense or nonsense, it accepts all we write." (This is an old German proverb.)
"As your design proceeds, weights always go up."

"The chief decision maker should steer clear of the glory hounds. Their quest for personal fame and glory has cost us dearly and will always do so."

"If you aim for about 80 percent of the theoretically possible performance, your costs will stay moderate and your chance of success will be good. If you aim for more, your costs and risk will grow exponentially." (This caveat was passed to me by Hans Multhopp, the designer of the FW 190 fighter plane of late WWII.)

7.1.9 Harold Dioron (Retired NASA, presently with InDyne, Inc.)

"A complex model isn't very useful without a simple model to guide interpretation and provide sanity checks."

7.1.10 Jim French (NASA and Aerospace Consultant)

"In a system design, no change takes place in isolation. Every change has system level effects and any change no matter how good it sounds in isolation, must be reviewed in terms of its impact upon the system and every other subsystem."

7.1.11 Philip Glynn (Retired NASA, presently Boeing Space Station)

"Engineering is the process of creating, evaluating, and assuring performance of any defined human need."

"Engineering uses the laws of physics and mathematics to expand man's horizons and improve the quality of life on earth. As such it is the enabling environment to improve man's relationship with man."

"Engineering excellence is a state of satisfaction known only to the group which has endured the pain of attention to the details."

7.1.12 Micheal Griffin (Orbital Sciences Corporation)

"Look aggressively. The absence of a symptom does not imply the absence of a problem."

"Don't shoot the messenger. Messages, but not problems, will cease arriving."

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7.1.13 Ron Harris (Retired NASA, presently with Boeing North American)

"Arrive at a decision, don't rush into them."

7.1.14 John L. Junkins (George J. Eppright Chair, Texas A&M)

"Cooperate with Mother Nature to the maximum extent possible, minimum energy solutions are almost always the most reliable."

"It is hard to conduct an orchestra when every musician thinks himself a composer."

"Faster, Better, Cheaper? Maybe, but not very likely with five levels of management."

"Keep simplifying the most important questions and simultaneously try to define corresponding analytical, computational, and experimental tests that answer the question."

"World-class determination will usually trump world-class intelligence, but thank God for the miracles that can be performed when you find both attributes in the same person."

"The best advice I can give to a project manager: Know who your best engineers are, seek them out immediately when the tough questions arise, and challenge several proven individuals (not a committee) to propose solution strategies. Then convene the committee."

7.1.15 Dick Kohrs (Retired NASA, Associate Administrator, presently with Kistler)

"Systems Integration is 95 percent communication and 5 percent engineering."

"It is better to be on orbit and be criticized for not having enough capability, than to be on the ground and be criticized for not being in orbit.' This is what J.R. Thompson preached to me during Space Station."

"Consistency is the work of dull minds, but we must be consistent."

7.1.16 Wayne Littles (Retired NASA , Associate Administrator, MSFC Director, presently with Pratt and Whitney)

"Capable discipline engineering with the products accurately transmitted to well trained manufacturing technicians and software developers, along with a thorough test program, are necessary elements in producing quality flight hardware and software, but the essential ingredients to ensure program success are sound Systems Engineering and effective communications."

7.1.17 John McCarty (Retired NASA, presently a consultant)

"Proper use of dispersions, tolerances, in analysis and test is key to propulsion system design."

"A high quality propulsion system is one that has high reliability."

"Failures are when engineers learn how things really work."

"The price of any design change, because it is a change, is the introduction of new failure causes."

7.1.18 Dale Myers (Retired NASA Deputy Administrator, presently with Kistler)

"Keep it simple stupid" (The KISS Program).

"If it isn't worth doing at all, it isn't worth doing well."

"A program without reserve is like a dinner without wine."

7.1.19 Owen Morris (Retired NASA)

"When attacking a problem, remember that things usually are truly as they appear to be."

7.1.20 Joyce Neighbors (Retired NASA, presently with Lockheed Martin)

Career path in engineering: "First become a specialist in some discipline, learn how other disciplines interact with yours. Learn systems engineering but stay grounded in your specialty; this gives experience and technical qualification for becoming an engineering or program manager for high technology products."

Mission success: "Understand and prioritize requirements for the life of the product early in design cycle. Analyze during design and test to corroborate analysis before putting product into operations."

7.1.21 Larry Pinson (Retired NASA)

"All the easy problems have been solved."

"As engineering managers, we like to focus on formal management structure while people motivation usually is the real issue."

"If people are sold on a project outcome, formal organization is nearly irrelevant."

7.1.22 Robert S. Ryan (Retired NASA, presently a consultant)

"The higher the performance requirements, the greater the sensitivity (nonlinear) to variations in environments, design, manufacturing, etc. Performance requirements drive the design."

"Political viability shapes a project as much as engineering."

"The Physic (Mother Nature) of the problem reigns supreme (The God of Design). Either you bow down to her or you fall down."

"All design is a paradox, a balancing act. Understanding sensitivities, interactions, is the key to success."

7.1.23 Lucien A. Schmit, Jr. (Retired Professor, University of California)

"The engineer's main task is to anticipate possible failure modes and loading conditions. If we are not imaginative, nature will punch a hole right through our design."

"The value of simple limiting cases as test problems for assessing computer codes cannot be over estimated."

"Behavior sensitivity analysis and optimum design sensitivity analysis are powerful tools for obtaining quantitative answers to 'what if' questions traditionally asked by designers."

7.1.24 Luke Schutzenhofer (Retired NASA, presently at University of Alabama in Huntsville)

"Skillful leaders communicate the goal and objectives, reward creativity and good work ethics, consider all ideas, encourage debate, and discourage the fear of failure."

"Focus on working the right problems right."

"Better can be the enemy of good."

7.1.25 David Sisk (Lockheed Martin, Huntsville)

"In designing any structure, start with and continuously focus on the joints. If you get the joints right, the rest will fall into place."

7.1.26 Parker S. Stafford (Retired Martin Marietta, Consultant)

"The design, development, and test of a system should be done with the mission operations objectives in mind; i.e., systems tests should duplicate real mission operations and sequences. Use flight hardware, software, and ground systems wherever possible."

"Flight software should be validated in a realistic mission dynamic simulation environment which is functionally equivalent to the actual environment. This should include the initial flight load and all planned and contingency uplinks to the spacecraft."

"Analysis data used to define qualification tests, operating ranges and tolerances, etc., should be configuration managed as released engineering."

7.1.27 John Thomas (Retired NASA and Lockheed Martin)

"Any endeavor without understandable, achievable objectives and well thought out plan will not enjoy success."

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7.2 Design Suggestions From Selected References

7.2.1 J.E. Gordon (Author of *Structures, or Why Things Don't Fall Down*[5] and *The New Science of Strong Materials*[15])

"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?"

7.2.2 Helmut Horn (Deceased, NASA and V–2 German rocket engineer)
Provided by Robert Ryan

"If you can't explain it with a simple analog, you don't understand it."

"You cannot be a good system engineer unless you have penetrated one discipline in depth."

7.2.3 Henry Petroski (Professor of Civil Engineering, Duke University, and author of *To Engineer is Human: The Role of Failure in Successful Design*[16] and *Design Paradigms: Case Histories of Error and Judgment in Engineering*[17])

"Every solution of every design problem begins, no matter how tacitly, with a conception of how to obviate failure in all its potential manifestations."

"If any small change is made to a system, the whole system must adjust to that change."

"Lessons are best learned when we are familiar with a wide variety of textbook case studies of past failures, not only within our own field but also outside it, so that when we do make analogous errors we get a nagging feeling that something similar might be wrong in our reasoning and that we should double check our work."

7.2.4 Stuart Pugh (Author of *Total Design*[3])

"Concept selection improperly done can never be righted with the best engineering. Neither can the best concept selection be saved (realized) using poor engineering."

7.2.5 David Pye (Author of *The Nature of Design*[6])

"When you put energy into a system you can never choose what kind of changes shall take place and what kind of results remain . . . All you can do, and that only within limits, is to regulate the amounts of the various changes. This you do by design."

7.3 Lessons Learned

The combined experience of the authors in conjunction with this activity, the survey of experienced aerospace workers, and the referenced literature have resulted in a series of lessons learned for technical integration of launch vehicle design. Each lesson learned has a subset of attributes and/or tasks for accomplishing or applying the lesson.

7.3.1 Specific Lessons Learned

1. Although engineering skills are essential, people skills are mandatory for achieving successful products.

    - Choose a strong leader with decision-making capability who listens and encourages everybody to integrate.

    - Organization is a tool to accomplish the job; however, with proper leadership and motivation, the organization is secondary.

    - Provide a reward system to encourage the alignment of roles and responsibilities with project missions and objectives.

    - Encourage engineers to enhance their cooperative interactive skills as well as their technical skills.

    - Train engineers to be specialists with a systems focus.

    - Reward specialists who participate in integration activities in order to formulate a world view of the total system.

    - Provide an open environment which encourages innovation and stimulates communication.

2. Manage to ensure good technical integration.

    - Technical integration is crucial to the design process. Make every effort to encourage technical integration and assess that it is being done.

    - Communication is the key, predominant part of technical integration.

    - Most integration communication is informal, both within and between planes.

    - Understand the physics of interaction.

    - Continuously check requirements flow.

    - Continuously check assumptions.

    - Proper compartmentalization (subsystems/design functions/disciplines) facilitates integration.

- Working groups can enhance technical integration.

- Focus people skills toward integration.

- Integration is everyone's responsibility, but leadership must ensure technical integration.

3. Manage to ensure proper concept selection.

- The right concept selection is critical. The best detailed design will not correct a flawed concept selection.

- Put sufficient effort into front-end engineering (quality lever).

- Ensure that options are fully explored, converging with successive refinement (greater detail) of concepts and requirements.

- Pick a concept only after appropriate convergence of the various concepts; i.e., do not eureka the concept.

- In early phases, discipline specialists must assess validity of sizing program results. Do not depend on sizing program alone.

- Avoid concepts having too many low-level TRL's.

4. Requirements, constraints, and criteria greatly influence design.

- External/political considerations and constraints strongly drive design (for example, Space Shuttle).

- Technical constraints also drive the design, so apply them carefully and judiciously.

- Analyze and challenge requirements, constraints, and criteria at all levels to obtain the greatest possible engineering design flexibility.

- Do not accept unrealistic schedules and budgets.

- Poorly defined and vacillating top-level requirements cost the program dearly in terms of wasted design effort and compromised design.

- Overspecified criteria suppress the creativity of the design engineer.

- Criteria must be tailored for the specific project.

5. All design is a balancing act between conflicting requirements. You get some of what you want with some of what you do not want.

- Balancing must occur among disciplines (energy redistribution).

- Balancing must occur among program requirements, the design, and operating plans.

- Cost, risk, and performance are linked attributes. An improvement in one attribute typically produces a detriment in another.

- The balancing act requires open communication and key decision judgments.

- Assessing risks versus consequences is a key ingredient of the judgment process.

- Problems which cannot be cured in design must be compensated for in operational compromises and constraints (e.g., may lead to reduced probability of launch).

- All designs must achieve margins or probabilities acceptable for safety while maintaining performance.

6. Consideration of system sensitivities and uncertainties is crucial to design process.

- Successful design requires that sensitivities and uncertainties be properly accounted for and managed.

- Uncertainty significantly complicates the design process. Incorporate appropriate philosophy and procedures for handling uncertainty throughout the process.

- System sensitivities (both within and between design functions) are indicators of how much concern should be given to uncertainties.

- High performance systems have high sensitivities, requiring more attention to details of design.

- Design must either reduce sensitivities and uncertainty or provide additional margin.

- In the early stages of design, ensure that adequate margins are provided to cover the sensitivities and uncertainties of the specific vehicle, considering its coarse state of definition.

7. Engineers' judgment and creativity is essential to design process.

- The complexity of the system requires applying judgment and innovation to the specific launch vehicle situation. This cannot be supplanted by dogma, rules, or recipe.

- Tools enhance efficiency but cannot replace the judgment and creativity of the human mind.

- Guidelines and criteria should be tailored or adapted to the particular project to avoid a dogmatic approach which unnecessarily constrains design solutions.

- Many decision gates are not deterministic but are judgment based, requiring indepth discipline, system knowledge, and wisdom.

- The level of penetration is an engineering judgment, determined by project characteristics, design stage, sensitivity, and uncertainty.

8. The design process is complex and laborious; improve it wherever possible.

- Continually explore approaches to high-leverage improvements, both evolutionary and revolutionary.

- Reduce process fragmentation; move toward more seamless design.

- Improve design modeling, especially for cost, operations, and reliability.

- Explore more direct synthesis approaches to better convert requirements to concepts and designs.

- Improve the conceptual design process through better synthesis and higher fidelity representations.

- Develop and mature an information system for efficiently conveying and displaying necessary design information to all participants.

7.3.2 Associated Discussion

Lesson 1: The first lesson is very important. It emphasizes people skills, putting them in the same category as the engineering skills. Dick Kohrs has said that "Communications is 90 percent of integration." Whether it is 90 or 60 percent, it is key to quality products. The T-model presented earlier emphasizes this by requiring the discipline specialist to also have a system focus. The reward system of the organization must support this emphasis.

Lesson 2: Just as important as the people skills is the truism, "You manage to ensure good technical integration." As has been stated many times, "The integrity of the product is in the system; i.e., the integration." Engineering is accomplished by compartmentalizing the design tasks by subsystems and then further by design functions and disciplines. In order to ensure that each is compatible requires the process to be managed to achieve the goal of technical integration. There are many ways to achieve technical integration. Working groups (technical and systems) worked well on Saturn and Space Shuttle. Skunk works and design centers have also been successful. Management must ensure that each person understands and accepts his or her role and responsibility for technical integration.

Lesson 3: Concept selection is key to successful products. It is generally accepted that at least 80 percent of the life-cycle cost is determined during the concept selection stage. Pugh has said, "Engineering can never right a poor concept selection." The quality lever indicates the same focus. The process is iterative, and it weeds out poor concepts, then looks in more depth at the remaining concepts. The process repeats with further increased depth until a clear winner is established. More than two new technologies are generally too risky for the development phase. The results of the trade studies and sensitivity analysis should be carried forward for future reference, along with the selected concept. The concept selection is therefore critical and must be emphasized by the leadership.

Lesson 4: Requirements, constraints, and criteria dictate the product design. Pugh says. "It is the mantle of the design." As important as constraints, standards, and criteria are, if they are too restrictive, the design suffers; creativity and innovation are lost. Greenleaf in *Servant Leadership*[18] emphasized this point. Many times they can dictate the design; instead of saying what is to be accomplished, they say how it is to be accomplished. Criteria sometimes are used to replace failure mode analysis, which is a mistake. Constraints perform in the same way. The SSME weight constraint led to essentially an all-welded structure. The all-welded structure led to many fatigue and fracture problems in the welds, requiring many redesigns. Each project should carefully tailor criteria, constraints, and requirements, gleaning out all the "how's" and reducing the "what's" to only those that are essential.

Lesson 5: All design is a balancing act between conflicting requirements. You get some of what you want with some of what you do not want. Pye has said, "When you put energy into a system and transform it, you cannot totally determine how that transformation will take place. You get some of what you want and minimize what you don't want. This you do by design engineering." This process is therefore a balancing act requiring firm technical and programmatic data. The decision in the end is usually a judgment call. The balancing act is first of all among the design functions and technical disciplines (energy redistribution), then between the program requirements, the design, and operations. Problems occurring in the balancing act, if not resolved, are pushed downstream and are solved through operational procedures and flight constraints, many times at high cost and reduced performance.

Lesson 6: Consideration of system sensitivities and uncertainties is crucial to the design process. All major programs must find a way of designing for off-nominal conditions at a given probabilistic level of risk without over penalizing the performance and cost. Sensitivities of the system to the parameter variations are a measure of the level of concern one should put on an issue or an interaction. In general the higher the performance requirements, the higher the sensitivity of the response to any variation of the environments, manufacturing tolerances, etc. The sensitivity/performance curve is highly nonlinear. For example, in the case of fatigue of metals, the sensitivity curve is the inverse of the SN curve. Design for robustness is a desired method for dealing with uncertainties and sensitivities. A robust design is one where the responses to perturbations are adequately managed. Robust design falls into two categories. In the first category, a robust design could be one whose response is inherently insensitive to perturbations. In the second, a robust design could be one where the response is sensitive to perturbations; however, the system is designed such that the responses are maintained within acceptable limits. This can be achieved by designing within predetermined margins, controlling the variations in significant response parameters, actively or passively controlling the response, adding redundancy, and/or developing operational procedures and constraints. Therefore, several approaches, either individually or together, are listed below that can be used to accomplish robustness.

- Increase margins
- Reduce parameters uncertainties
- Reduce sensitivities (response to uncertainties)
- Redundancy
- Operational procedures and constraints.

All good design practices intelligently account for and deal with uncertainties and sensitivities as design parameters using appropriate philosophies, procedures, and tools.

Lesson 7: In the final analysis it is the engineer's judgment, innovation, and creativity that develop the design and the product. All else are tools and aids to the human mind and the human skills. This means that the organization must be a learning organization that constantly hones personal mastery and team learning, using to the fullest the uniqueness/diversity of the individuals and the organization. In the end it is usually the engineer's judgment, not deterministic metrics, that determines the product. Openness, acceptance, inquiry, and advocacy are essential to the engineer's development and the quality of the product.

Lesson 8: Finally, the design process is complex and laborious. Significant improvements are needed. Improve the process wherever possible. Apply lessons learned, and seek innovative ways to revolutionize the process, as discussed in section 5. High leverage areas to explore include those listed in section 7.3.1, item 8. Ideas for improvement can come from related fields of research such as multidisciplinary design optimization, or may come from apparently unrelated fields. The keys to attaining highly effective and efficient designs lie in the creativity, initiative, and judgment of the engineers who execute the design process and continually seek to improve it.

8. CONCLUDING SUMMARY

This report provides a baseline characterization for the design process for launch systems as it is currently practiced. The various areas of emphasis are shown below. The current design process was characterized by using hardware/software compartmentalization and interconnected design function planes along with their corresponding decision gates for determining task completeness. The process characterization provides a framework for a comprehensive integrated information and communication system that is recommended for any major effort. In specific areas suggestions for improvements have been made. A survey of experienced practitioners in aerospace on the essence of engineering was included, as was a detailed bibliography. Categorized lessons learned were provided, as were recommendations for future enhancements of the design process.

The launch vehicle design process has been characterized, delineating the following elements:

- Compartmentalization/reintegration associated with subsystems, design functions, and disciplines
- Technical integration illustrating both the formal and informal aspects associated with design and discipline functions
- Design function (plane) features and related significant decision gates
- Information flow model associated with subsystems and design functions; i.e., the I×I and N×N matrices
- Major activities, interactions, and tasks.

In addition to the characterization, necessary ancillary features of the design process were provided. They include:

- Thumbnail sketch of process
- Essentials considerations
- Project technical framework
- T-model of technical integration
- Requirements, architecture, philosophy, etc., definition
- Design sequence including conceptual, preliminary, and detail design stages
- Illustration of the design process, shown through historical examples.

Finally, the process characterization provided the following: (1) A means for practicing engineers to understand where they fit in the process, and their interactions, (2) a basis for understanding and improving the process, and (3) the necessary symbolism to develop a variety of electronic design tools. The characterization applies to the design of any launch vehicle regardless of the organization/project structure.

9. RECOMMENDATIONS

It is recommended that the launch vehicle design process characterization developed herein be utilized as a basis for understanding and improving the process. The current process must be constantly improved to increase effectiveness and efficiency. Lessons learned should be implemented and process improvement technologies should be incorporated as they are developed. The need to improve cost, reliability, and operability leads to the need for revolutionary advances in launch system technologies. These technologies include the categories of hardware/software technologies and process technologies. It is essential that hardware/software technologies be developed, and these activities are currently underway. Likewise, design process technologies must also be advanced to achieve effective and efficient designs.

Specific recommendations for design process technologies are as follows:

- Utilize the design process characterization as a basis for understanding and improving the process.

- Refine the present process to improve effectiveness and efficiency
  - Work requirements and criteria to avoid stifling creativity and innovation
  - Design for simplicity
  - Improve design-to models
  - Integrate discipline analyses.

- Pursue revolutionary technologies for major improvements in the design process such as
  - Advanced approaches for high-fidelity concept definition, sizing, and assessment
  - Unified compartmentalization/reintegration process into a seamless whole; i.e., seamless integration related to the subsystems, design functions and discipline functions
  - Improved process ideation toward advanced idea stimulus approaches; e.g., direct synthesis methods for concept identification
  - Advanced analyses technology; i.e., high-fidelity design-to methods for performance and for life-cycle attributes such as cost and reliability.

The challenge of providing unlimited access to space requires the best of people, technology, and processes. Those who practice design must continuously improve the process.

APPENDIX A—NxN DIAGRAM FROM REFERENCE 2

Figure 96 is the NxN information flow diagram from reference 2. It was developed by MSFC to represent typical information flow in the design process for example launch vehicles. This figure delineates inputs and outputs relative to various engineering design and discipline functions. For each entity on the diagonal, its information outputs are shown on the horizontal row, and its information inputs are shown on the vertical column. Therefore, connectivity is represented among all included entities.

Figure 96. N×N matrix from reference 2.

APPENDIX B—SPACE SHUTTLE PARAMETER MATRIX ITEMS

Appendix B is an extract of certain portions of the Space Shuttle's parameter matrix (figs. 97–99). Space Shuttle engineers developed matrices for each event and each basic design area. The matrix identifies the parameter, the parameter values or reference source, the 3-sigma parameter uncertainties, and, where applicable, the procedure for usage. The parameter matrix was developed by the specialists in each discipline area based on a combination of historical data, current analysis, and current testing. The parameter matrix document for a vehicle design must be a living document, changing both the base (mean) and uncertainty values (reducing if possible) as the design matures. Critical to the process is development of a comprehensive list of interacting parameters, both natural and induced. New systems need a comparable parameter matrix definition to assure uniformity in the design. The discipline specialists with their knowledge of the system and the data are central to its development. In the final analysis, design trades (balancing act) are made using uncertainties coupled with sensitivities and appropriate weighting metrics. The importance of parameter and uncertainty definition cannot be overemphasized.

ORGANIZATION SYSTEMS DYNAMICS LABORATORY	MARSHALL SPACE FLIGHT CENTER **AFSIG REVIEW**	NAME R. RYAN
CHART NO.: 15		DATE APRIL 1986

Parameter Matrix

Discipline

Trajectory Performance
Pogo
Flutter
Control
Thermal
Liftoff Clearance (Drift)
Separation
Loads
Environments
  Overpressure
  Acoustic
  Shock
  Winds
Propulsion
Dynamics
Criteria
Failure Modes

Event

Prelaunch
Launch
Max Q
Max G
Pre-SRB Separation
SRB Separation
Post-SRB Separation
Second Stage Ascent
ET Pre-Separation
ET Separation
Total Ascent

Figure 97. Parameter matrix.

ORGANIZATION SYSTEMS DYNAMICS LABORATORY	MARSHALL SPACE FLIGHT CENTER **BASIC PARAMETERS**	NAME R. RYAN
CHART NO.: 16		DATE APRIL 1986

SRM Propulsion

Analysis Tolerance

- TC227A–75 Thrust Versus Time Curve Per SE–019–083–2H
  (SRB System Data Book) for Bulk Grain Temperatures
  (TC227H Is Proposed as Update)

$\begin{cases} \text{ETR} - 81 \ ^\circ\text{F (Mean)}/ 83.4 \ ^\circ\text{F (Max)} \\ \text{WTR} - 52 \ ^\circ\text{F (Mean)}/ 44.5 \ ^\circ\text{F (Max)} \end{cases}$

- Flight-to-Flight Propellant Burning Rate

$\begin{cases} \pm 5.3\% \ \text{(One SRM)} \\ \pm 4.7\% \ \text{(Two SRM's)} \end{cases}$

- Thrust Level Development Uncertainty

$\pm 3\%$

- Thrust Oscillation (Dynamic Factor Assumed for
  Loads Analysis)

$\pm 5\%$

- Steady-State Thrust Mismatch Between Motors

85,000 lb (Ref. vol. X,
fig. 3.3.2.2e)

- Thrust Misalignment

$\pm 0.75^\circ$ Per SRB

- Flight-to-Flight Thrust Level Dispersion

$\begin{cases} \pm 5\% \ \text{Single Motor} \\ \pm 4.9\% \ \text{Both Motors} \end{cases}$

Aerodynamics

- Pressure Distribution Test Data Match with Aerodynamic
  Coefficient Test Data

$\pm 3\%$

- Elevon Deflection Schedule #6 (Hinge Moment Limiting
  Feedback) Per Rockwell Internal Letters ACDA/FSA/76–527
  and 531

$\Delta \delta_e o = f \ (\Delta C_{HM} = 0.02)$ Aero
Data Adjusted to New
$(\delta_e o + \Delta \delta_e o)$

- SD72–SH–0060–2 (Mated Vehicle Aero Design Data Book)

None

- Include Aerodynamic Tolerance Effects on Coefficients: Wind
  Tunnel Deviations Plus Power-on Deviations Plus Reynolds
  Number Effects

Values Per PRCB Briefing on
8/18/76 MCR 3378 "5.3 Ascent Load
Adjustments"

Figure 98. Basic parameters.

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
SYSTEMS DYNAMICS LABORATORY	**BASIC PARAMETERS** (Continued)	R. RYAN
CHART NO.: 17		DATE APRIL 1986

Main Propulsion System

Analysis Tolerance

- 3 SSME Thrust Level Throttling Range
- Thrust Oscillation (Dynamic Factor Assumed Only for Load Analysis)
- Equal Throttle Settings on All SSME's
- With One SSME Out, The Two Remaining SSME's Operate at 109% Thrust
- Thrust Misalignment
- Mixture Ratio (6:1)
- Variations in ET Propellant Load Left at Meco Result From Off–Normal SRM/SSME Performance and SSME Throttling History

50% (MPL) to 100% (FPL)
± 5%

None
None

± 3° Per SSME
None
None

Mass Properties

- Minimum Payload of 2,500 lb (Mission 3B)
- Maximum Payload of 32,000 lb (Mission 3A)
- Maximum Payload of 65,000 lb (Mission 1)

None
None
None

Flight Control and Guidance

- Rockwell Control #7 Per SD73–SH–0097–1 (Integrated Vehicle Flight Control System Data Book)
- Elevon Schedule #6 (Hinge Moment Limiting Feedback)
- Platform Misalignment
- Accelerometer Misalignment
- Accelerometer Null Offset (Time Variable)

- Accelerometer MDM Bias
- IMU Attitude Error
- Actuator Hysteresis
- Rate Gyro Misalignment

None

± 0.02 Hinge Movement Coefficient
± 0.5°
± 0.5°
0.010 to 0.025g (Pitch)
0.08 to 0.015g (Yaw)
0.0248
± 0.0083°
1.5 MA
± 2°

Figure 98. Basic parameters (continued).

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
SYSTEMS DYNAMICS LABORATORY	**BASIC PARAMETERS** (Continued)	R. RYAN
CHART NO.: 18		DATE APRIL 1986

Flight Control and Guidance (Continued)   **Analysis Tolerance**

- Rate Gyro Hysteresis   ± 0.02 deg/sec
- Rate Gyro MDM Bias   ± 0.12 deg/sec
- Rate Gyro Zero Offset   ± 0.15 deg/sec
- SRB and SSME Forward Loop Gain   ± 10%

External Environment

- 95% Seasonal Winds Based on Monthly Wind   None
  Ellipse Data for WTR and ETR (TMX–73319)
- Basic $q\alpha/q\beta$: 95th Percentile Wind Envelope
  Plus 3 m/sec Gust Plus 50th percentile Shear
  Random $q\alpha/q\beta$: FCS System Effects; 6 m/sec Gust
  (i.e., 9 m/sec Minus 3 m/sec) and Shear up to 99th Percentile

  Display $q\alpha/q\beta$ Envelopes: Basic Plus FCS Effects:
  Basic Plus 6 m/sec Gust and Shear Up to 99th Percentile

Vehicle Dynamics

- First 50 Bending Modes with 1% Damping   None
- Aeroelastic Effects   None
- Flutter Stability   None
  – First 20 modes
  – Control System Feedback Represented
  – Parametric Variation of Actuator Stiffness

Failure Modes
- Numbers 1, 2, or 3 SSME Out Anytime After Lift-off
- TVC Failure By-Pass Transient

Figure 98. Basic parameters (continued).

Analytical Approach   **Analysis Tolerance**

- Trajectory Logic Superimposes Engine–Out
  Squatcheloid on No–Failure Squatcheloid
- Conduct Loads Survey Around Squatcheloid Using
  Rigid–Body Squawkr Program to Calculate Max/Min
  Wing and Elevon Loads and ORB/ET and SRB/ET
  Fitting Loads
- Flexible–Body Dynamic Response Calculated for Final Loads

Combination Method

- $q\alpha/q\beta$ FCS Tolerance added ($\pm$ 700 psf–deg $q\alpha$; $\pm$ 700 psf–deg $q\beta$)
- 85% Gust Timed 6 sec After SSME Failure in 85% Max Shear
  or Full Gust 6 sec After SSME Failure Followed by Full
  Design Shear After SSME Failure. Sequence of Events
  Selected For Maximizing Loads
- SRB Thrust Dispersions:
- SD73–SH–0069–1, –2, –3, and –4 (Structural Design Loads
  Data Book)
- SD73–SH–0097–1 (Integrated Vehicle Flight Control System
  Data Book)

Figure 98. Basic parameters (continued).

ORGANIZATION SYSTEMS DYNAMICS LABORATORY	MARSHALL SPACE FLIGHT CENTER **BASIC PARAMETERS** **Lift Off**	NAME R. RYAN
CHART NO.: 20		DATE APRIL 1986

SRM Propulsion   **Analysis Tolerance**

• TC227A–75 Thrust Versus Time Curve Per SE–019–083–2H   { 90 °F (ETR)
  (SRB Systems Data Book) For Max/Min Grain   { 40 °F (WTR)
  Temperatures (TC227H I Proposed as Update)

• Thrust Level Development Uncertainty   ± 3%

• Steady-State Thrust Mismatch Between SRM's   35,000 lb

• Flight-to-Flight Thrust Level Uncertainty   { ± 5% Single Motor
                                                                { ± 4.9% Both Motors

• Thrust Buildup Rate Development Uncertainty   Ref: SDIL SRM76–037

• Thrust Misalignment   ± 0.50% (Both); 0.707° (One)

Aerodynamics

• Ground Wind Drag Coefficients Per SD72–SH–0060–2   None
  (Mated Vehicle Aero Design Data Book) and
  Rockwell Internal Letter SAS/AERO/75–430

Main Propulsion

• 3 SSME's at 100% Thrust (RPL) to 109% Thrust (RPL)   None

Figure 99. Liftoff load parameters.

ORGANIZATION SYSTEMS DYNAMICS LABORATORY	MARSHALL SPACE FLIGHT CENTER **BASIC PARAMETERS** **Lift Off**	NAME R. RYAN
CHART NO.: 21		DATE APRIL 1986

Mass Properties   **Analysis Tolerance**

• Minimum Payload of 2,500 lb (Mission 3B)   None

• Maximum Payload of 32,000 lb (Mission 3A)   None

• Maximum Payload of 65,000 lb (Mission 3A)   None

Miscellaneous

• SRB/MLP Holddown Bolt Preload (750,000 lb)   None

Flight Control and Guidance

• Rockwell Control No. 7 Per SD73–SH–0047–1   None
  (Integrated Vehicle Flight Control System
  Data Book)

• All Nozzles Gimbal But SRB Nozzle Gimbal $\left\{ \begin{array}{l} \pm 0.17° \text{ (SRB)} \\ \pm 0.23° \text{ (SSME)} \end{array} \right.$
  Limited to 2° for First 5 sec

• SRB Mistrim to 0° Until SSV Clears the Launch   None
  Pedestal

• STB TVC Misalignment   2 σ RSS Each SRB in
                                                             Worst Direction

External Environment

• 95% Wind Speed (One Hour Exposure)   None

• Peak Wind Speed   24 Knots (Max)

• Tuned Gust (Worst Case)   None

Figure 99. Liftoff load parameters (continued).

ORGANIZATION SYSTEMS DYNAMICS LABORATORY	MARSHALL SPACE FLIGHT CENTER **BASIC PARAMETERS** **Lift Off**	NAME R. RYAN
CHART NO.: 22		DATE APRIL 1986

Vehicle Dynamics

• First 50 Bending Modes with 1% Damping

Failure Models

• None

Analytical Approach

• Digital Simulation of Vehicle Flexible Body
Response Due to Applied Forces and Release of
Base Constraints

Combination Method

• Sequence of Events Selected or Max Loads (WOW)

• RSS Similar Uncertainties as a Group Then Add Groups
($\pm 2 \sigma$ Deviations) in Worst–On–Worst Combination

Documentation of Results

• SD73–SH–0069–1, –2, –3, and –4 Structural Design Loads
Data Book

Analysis Tolerance

None

Figure 99. Liftoff load parameters (continued).

APPENDIX C—GLOSSARY

Glossary Format: The glossary is divided into two sections. The first section is an alphabetical index of all terms, which identifies a group number where the definition is located. The definitions are given in the second section, grouped together with related terms to help clarify the definitions.

C.1 Alphabetical Index

C.2 Definitions

GROUP 1

Design stages. The design stages consist of conceptual design, preliminary design, detailed design, manufacturing, and systems integration and verification. These design stages are followed by the operational stage.

Design phases. Historically, there have been five design phases that have been replaced by the design stages defined above.

- Phase A—Preliminary analysis
- Phase B—Definition
- Phase C—Design
- Phase D—Development
- Phase E—Operations.

Subprocesses. There are four "provide aerospace products and capabilities" subprocesses.

- Formulation—Define program
- Approval—Determine program readiness
- Implementation—Deliver program products and/or capabilities
- Evaluation—Assess the ability of program to meet its technical and programmatic commitments.

Conceptual design. That part of the design process where many feasible alternative concepts are determined for detailed study. It occurs early in the process when only top-level system parameters are known. Multicriteria decision-aiding techniques are used to reveal the best alternatives (could be a single alternative) from the many proposed concepts. The down-select decision is based on performance, cost, schedule, reliability, safety, operability, design uncertainty, and TRL figures of merit obtained from trade and sensitivity studies.

Preliminary design. This part of the design process follows conceptual design, and its purpose is to determine which of the selected alternative concepts is the best and then to establish a baseline design concept. In this stage, the configurations are further matured, and the significant subsystems are designed for inclusion in the assessment. In addition, refined analyses, simulations, and tests data are developed for trade and sensitivity assessments. All system support, manufacturing, test, and operations requirements are also defined. Refined and updated multicriteria decision-aiding techniques are used to reveal the best configuration based on performance, cost, schedule, reliability, safety, operability, and design uncertainty data obtained from trade and sensitivity studies relating to the launch vehicle, all supporting activities, and all supporting systems. This downselected configuration then becomes the baseline for detail design.

Detail design. During this part of the design process, the goal is to provide an engineering description (drawings, specifications, plans, etc.) of a tested and producible design. Additionally, plans are updated for final development, manufacturing, verification, and operations.

Manufacturing. During this part of the process, flight, facility, and GSE hardware and software are developed, manufactured/coded, and documented.

Systems integration and verification. This is the final stage of vehicle development. All systems (hardware and software) associated with the vehicle and operations are assembled, tested, and checked for compatibility, functionality, and verification that the design requirements and constraints are satisfied and the system is flight ready. All results are documented including anomalies and lessons learned.

Operations. Operations consists of two parts. The first part pertains to vehicle development. It is here that it is determined if the launch vehicle satisfies the mission need statement or not. If it does not, then flight constraints are required. The second part of operations occurs after all the flight constraints are determined. Then routine operations are established which include evaluation of results and documentation of anomalies and lessons learned.

Concept selection. Many alternative concepts are developed early in the design process. Initially, concepts are conceived, evaluated, and rejected or accepted based upon top-level system requirements. Multicriteria decision-aiding techniques are used to reveal the best alternatives from the many proposed concepts. The downselect decision is based upon discriminators such as performance, cost, schedule, reliability, safety, operability, design uncertainty, and TRL figures of merit obtained from trade and sensitivity studies. As the design process proceeds, additional knowledge related to the discriminators is acquired through analyses, simulations, and tests. This additional knowledge is applied with the multicriteria decision-aiding technique at various levels of system maturity until one concept is finally selected. The final concept selection usually occurs during or around PDR; however, some have occurred immediately after conceptual design. Then the selected concept proceeds to final design, development, and operations.

Design cycle. Each stage (e.g., conceptual design, preliminary design, etc.) of the design process is completed in a number of design cycles (iterations). For each design cycle during a particular design stage, the discipline functions develop knowledge and reduce risk (design uncertainty) through analyses, simulations, and testing at increasing levels of penetration as the design process proceeds from the conceptual design through the systems integration and verification stages. Through the process of formal and informal technical integration for each design cycle, the attributes determined by the design functions via the discipline functions are assessed at the system level. The focus of the assessment is conformance of the attributes to the overall system-levied requirements, constraints, philosophy, procedures, criteria, ground rules, etc., as well as their balance, interactive compatibility, consistency, and associated data trends. If the attributes are not consistent with the aforementioned and/or the appropriate level of maturity and risk has not been achieved, then another cycle is initiated and the design process repeated until a set of appropriately matured and balanced attributes with the required level of risk is achieved. At the initiation of each design cycle there could be changes in the requirements, constraints, philosophy, procedures, criteria, ground rules, etc., based upon results from the previous cycle.

Minidesign cycle. If a problem is indicated by analyses, simulations, testing, manufacturing, assembly, operations, etc., then after assessment, a redesign may be required. If the redesign is of a localized nature and does not impact the entire system, then the appropriate design and discipline functions execute the redesign also without perturbing the entire system. Technical integration can be accomplished via a change request guaranteeing that all the appropriate requirements are satisfied and balanced.

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Mission concept review (MCR). First formal review. Assesses mission objectives and concepts along with functional and performance requirements.

System requirements review (SRR). Demonstrates that the mission and system requirements are defined and understood. In addition, management techniques, procedures, agreements, etc., are evaluated.

Preliminary design review (PDR). Conducted when the basic design approach has been selected. Demonstrates that the preliminary design meets all the system requirements with acceptable cost, schedule, and technical risk. The design drawings are about 10 percent complete. The results of successful review are the "design to" baseline and the authority to proceed to final design.

Critical design review (CDR). Verifies that the design meets all the requirements and establishes a baseline for manufacturing. The design drawings are about 90 to 95 percent complete. The results of a successful review are the "build to" baseline and approval of the production and verification plans.

Design certification review (DCR). Evaluates the "as-designed" results from verification analyses, tests, and simulations to certify the design. Determines what requirements were met, reviews significant problems, and assesses corrective actions. This review is usually conducted after the manufacturing, assembly, and verification process.

Flight readiness review (FRR). Certifies that the system is flight ready and all flight objectives can be accomplished. This includes the launch vehicle, operational system, and all associated teams.

GROUP 2

Mission statement. The fundamental statement of need for a system; for example, a basic requirement for a launch vehicle to deliver xxx pounds of payload to a specified orbit at a reliability of at least yyy for a cost not to exceed $zzz.

Requirements. The conditions that the designed system must meet. Requirements specify what attributes the system must have. Requirements are "equalities;" that is, they require that the specified attribute equal a certain value. In more general usage, requirements are taken to mean the combined set of requirements, constraints, and derived requirements.

Constraints. The conditions that the designed system must be less than or must be greater than. Constraints are "inequality requirements" in that they require that the specified attribute be less than or greater than a certain value. Another type of constraint is that the TRL of any technology used in the design be greater than a specified TRL.

Derived requirements. Requirements or constraints that are not top-level requirements associated with the mission statement but which are created during the design process as a result of designing to meet the top-level requirements. They may be identified by a design function or discipline to be imposed on itself, or to be imposed on others.

Attributes. Properties of the designed system or subsystem. These may be performance properties, cost, reliability, etc. An attribute is a property that can be compared with a requirement or a constraint.

Performance. In this document, performance typically means the physical behavior of the launch vehicle or its subsystems, where that physical behavior has an effect on meeting the physical requirements imposed on the vehicle. Examples of measures of performance include payload-to-orbit, mass fraction, specific impulse of the propulsion subsystem, TPS mass density, etc. Performance is a physical attribute (or attributes) of the launch vehicle which is distinct from the life cycle attributes of cost, safety, reliability, operability, etc. Note also that this definition of performance is broader than the conventional usage of performance to strictly mean payload-to-orbit.

Life cycle attributes. Vehicle attributes other than performance as defined above. Life cycle attributes include cost, safety, reliability, operability, etc.

Technology Readiness Level (TRL). The maturity of a given technology, as measured by NASA's TRL scale; values ranging from 1 (least mature) to 9 (most mature).

Metrics. As used in this document, metrics are quantifiable measures of attributes (see following note).

(Note: "Quantifiable measure of attributes" is a definition of metrics applied in the recent past and applied in this document. There is, however, a move in the engineering community to apply specific definitions to certain parameters that quantify the system (see reference 19). In the past some of these terms have been used interchangeably. Specifically, three of these terms are (1) figures of merit, (2) technical performance measures (TPM's), and (3) metrics. In reference 19, figures of merit are used to quantify requirements. TPM's are used to track the progress of design and manufacturing. Metrics are measures related to the process, not the product.)

Gates. Events in the design process where an attribute of the design is compared with a requirement or constraint. To pass the gate, the design's attribute must meet the requirement or constraint; if it does not, the design must be changed or the requirement/constraint must be relaxed.

GROUP 3

Parts of a system. A system can be compartmentalized into parts. Usually this follows a hierarchy of compartmentalization into smaller and smaller parts. Generically, the system is compartmentalized into subsystems; the subsystems are compartmentalized into sub-subsystems, etc. Sometimes the various levels of the hierarchy are given specific names, such as in the following examples which are not unique:

Level	Specific Name
System	Launch vehicle
Subsystem	Propulsion
Element	Liquid engine
Component	Turbopump
Part	Turbine blade

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Design function. The activity of creating a design for a specific subsystem or system. The primary products of a system (top plane) design function are the specifications and drawings for its subsystem or system. The primary products of the other design functions (lower planes) are the descriptions of their respective aspects of the design, as fed to the system plane. See also the discussion in section 4.3.1.

Discipline function. The activity such as analysis, simulation, testing, etc., that is performed during the design process by specialists in the various technical areas of expertise. See also the discussion in section 4.3.1.

Compartmentalization. Separation of the design process into managable parts. There are three types of compartmentalization: (1) Separation of a system into subsystems (subsystems can be further compartmentalized into sub-subsystems); (2) separation of the design functions for each subsystem; and (3) separation of the design functions into the discipline activities necessary to achieve the design.

Reintegration. The process of recombining the compartmentalized parts of the design process to form a complete system design. Discipline functions are reintegrated into design functions, design functions are reintegrated into subsystems, and subsystems are reintegrated into the total system.

Requirement allocation. Identification and assignment of requirements by the system design function to the subsystems and lower design functions. Requirements are divided and allocated with the intent of producing a total design that will achieve the best balance among the subsystems and requirements.

GROUP 4

Technical Integration. The interactive activity among all participants in the design process, whereby the compartmentalized parts reintegrate into a balanced, successful total design. Technical integration is enabled by formal and informal information flow methods, by a system focus of all participants on how their part affects the total system, and by leadership that continually ensures that interactive aspects of the design are being addressed and balanced.

T-model. A representation of technical integration that consists of three parts. The horizontal crossbar portion of a "T" can be visualized as consisting of two parts as a result of a horizontal subdivision. The upper portion of the subdivision represents formal integration. Formal integration is accomplished by the leader via the systems plane. The lower portion of the crossbar represents informal integration. Informal integration is accomplished by design and discipline functions. The third portion of the T-model is the vertical leg of the T. This represents the activities of discipline engineers, and it signifies their indepth discipline capability with a systems perspective.

Formal Integration. A communication activity that consists of interactions between the system design function and all other design functions. It ensures that the attributes and uncertainties (developed by the design functions) satisfy the requirements, constraints, etc., and they are compatible. An associated activity of formal integration is resolving engineering conflict between design functions when incompatibilities, inconsistencies, unnecessarily high interactions and sensitivities, etc., occur. These activities are accomplished by the leader via the system plane.

Informal Integration. A communication activity that consists of interactions among discipline functions in a design function and interactions between design functions. The focus of these activities consists of data and information exchanges to determine the attributes and their uncertainties associated with the design function planes in an efficient and accurate manner.

Balancing Act. There are two types of balancing acts. The first relates to the system where the program requirements are balanced by the launch vehicle design and the operational design. The second relates to interactive discipline and design activities where trade balances are made among the subsystems, design functions, and disciplines to achieve the required attributes with acceptable uncertainties.

Risk Assessment. An evaluation process that addresses technical, cost, and schedule risk. It uses an estimate of probabilities of success versus consequences of failure.

GROUP 5

Parameters (design). Design measures that fall into two categories: (1) One that the designer can control and (2) one that the designer cannot control. The controllable parameters are measures that characterize the design; e.g., independent variables of the design process. The latter parameters are environmental inputs where the designer has control only over how they are characterized.

Uncertainty. A general term for the estimated amount by which the observed or calculated value of a quantity may depart from the true or mean value.

Sensitivity. A measure of a system of functional relationships, a hardware system, or a software system that can be defined as the amount that the dependent variables differ from their reference values (baseline) when one of the independent variables differs from its reference value (baseline). The specific calculus depends upon the application.

Margin. The difference between the value that a variable must not exceed (its requirement limit) and the predicted maximum value of that variable, including known parameter variations. Margin is the measure of headroom available in meeting the requirement, and may be included to allow for contingencies or unmodeled uncertainties.

GROUP 6

Planes. In the design process model delineated in this document, a plane represents a design function. The plane contains the various activities that are executed within the design function.

Conduits. Pathways between planes that represent information flow among the design functions.

Gates. Events in the design process where an attribute of the design is compared with a requirement or constraint. To pass the gate, the design's attribute must meet the requirement or constraint; if it does not, the design must be changed or the requirement/constraint must be relaxed.

Tasks. Specific activities accomplished by design functions or discipline functions.

IxI matrix. A matrix that defines information flow among subsystems and between a subsystem and its next higher level system. Interface inputs, outputs, and connectivity are shown.

NxN matrix. A matrix that defines information flow among design functions and disciplines, showing inputs, outputs, and connectivity.

Work Breakdown Structure (WBS). An organized listing of the areas of work (tasks) required to produce a design.

REFERENCES

1. Utterback, J.: *Mastering the Dynamics of Innovation*, Harvard Business School, Boston, MA, 1994.

2. Humphries, W.R; Holland,W.; and Bishop, R.: "Information Flow in the Launch Vehicle Design/ Analysis Process," *NASA/TM—1999-209877*, MSFC, December 1999.

3. Pugh, S.: *Total Design*, Addison-Wesley Publishing Co., New York, NY, 1991.

4. "NASA Systems Engineering Handboook," *NASA SP–6105*, June 1995

5. Gordon, J.E.: *Structures, or Why Things Don't Fall Down*, Decapo Press, 1986.

6. Pye, D.: *The Nature of Design*, Reichold Book Corp., New York, NY, 1969.

7. Blanchard, B.; and Fabrycky, W.: *Systems Engineering and Analysis*, Prentice Hall, Englewood Cliffs, NJ, 1990.

8. "System Engineering Handbook," 2nd ed., *MSFC–HDBK–1912A*, MSFC, December 1994.

9. "Project Management Handbook," *MM 7120.2A*, MSFC, 1989.

10. "NASA Program and Project Management Processes and Requirements," *NASA NPG 7120.5A*, April 3, 1998.

11. Wheelwright, S.C.; and Clark, K.B.: "Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality," New York: Free Press, 1992.

12. Fleeter, R.: Launchspace Magazine.

13. Jenkins, D.R.: *Space Shuttle—The History of Developing the National Space Transportation System*, Walsworth Publishing, Marceline, MO, 1997.

14. Ryan, R.S.: "Lessons Learned in Propulsion System Design," AIAA Joint Propulsion Conference, San Diego, CA, July 1995.

15. Gordon, J.E.: *The New Science of Strong Materials*, Princeton University Press, Princeton, NJ,1988.

16. Petroski, H.: *To Engineer Is Human: The Role of Failure in Successful Design*, St. Martin Press, New York, NY, 1982.

17. Petroski, H.: *Design Paradigms: Case Histories of Error and Judgment in Engineering*, Cambridge University Press, 1994.

18. Greenleaf, R.F.: *Servant Leadership,* Paulist Press, New York, NY, 1977.

19. Moody, J.A.; Chapman, W.L.; Van Voorhees, F.D., and Bahill, A.T.; *Metrics and Case Studies for Evaluating Engineering Designs*, Prentice Hall, 1997.

BIBLIOGRAPHY

Abramson, N.: "Dynamic Behavior of Liquid in Moving Containers," *NASA SP–106*, 1996.

Admire, J.R.; Tinker, M.L.; and Ivey, E.W.: "Residual Flexibility Test Method for Verification of Constrained Structural Models," *AIAA Journal*, Vol. 32, No. 1, January 1994.

Admire, J.R.; Tinker, M.L.; and Ivey, E.W.: "Mass-Additive Model Test Method for Verification of Constrained Structural Models," *AIAA Journal*, Vol. 31, No. 11, November 1993.

Akao, Y.; et al.: *Quality Function Deployment*, Productivity Press, Cambridge, MA, 1990.

Akao, Y.: *Quality Function Deployment, Integrating Customer Requirements into Product Design*, Cambridge University Press, Cambridge, MA, 1988.

Anon.: *From Earth to Orbit*, National Academy Press, Washington, DC, 1992.

Anon.: "Spacecraft Design and Operations Problems," *SAE SP–636*, Aerospace Technology Conference, October 1985.

Asimow, M.: *Introduction to Design*, Prentice Hall, Englewood Cliffs, NJ, 1962.

Augustine, N.R.: "Augustine's Laws," *AIAA*, New York, NY, 1983.

Bamford, R.M.; and Trubert, M.: "A Shock Spectra and Impedance Method to Determine a Bound for Spacecraft Structural Loads," *AIAA–75–811*, May 1975.

Bamford, R.M.; Wada, B.K.; and Gayman, W.H.; "Equivalent Spring-Mass System for Normal Modes," *JPL TM No. 33–380*, February 1971.

Bendat, J.S.; and Piersol, A.G.: *Engineering Applications of Correlation and Spectral Analysis*, Wiley Interscience, New York, 1980.

Bendat, J.S.; and Piersol, A.G.: *Random Data, Analysis and Measurement Procedures*, Wiley Interscience, New York, 1986.

Biggs, R.E.: "Propulsion System Failure Analysis—A Methodology," *AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference and Exhibit*, Nashville, TN, pp. 1492–3796, July 6–8, 1992.

Blair, J.C.; and Ryan, R.S.: "The Role of Criteria in Design in Management of Space Systems," *AIAA–92–1585*, March 1992.

Bookout, P.S.: "Statistically Generated Weighted Curve Fit of Residual Functions for Model Analysis of Structures," *NASA TM–108481*, NASA, Washington, DC, February 1995.

Braun, R.D.; Powell, R.W.; Lepsch, R.A.; Stanley, D.O.; and Kroo, I. M.: "Comparison of Two Multidisciplinary Optimization Strategies for Launch-Vehicle Design," *AIAA Journal of Spacecraft and Rockets* 32:3, May/June 1995.

Bruhn, E.F.: *Analysis and Design of Flight Structure*, John Wiley & Sons, New York, 1993.

Chamis, C.C.: "Probabilistic Structural Analysis Methods for Space Propulsion System Components," *Probabilistic Engineering Mechanics*, Vol. 2, No. 2, pp. 100–110, 1987.

Christensen, D.L.: "Advances in the Application of Systems Engineering Procedures," *AIAA–96–4433*, 1996.

Cikanek, H.A.: "Characteristics of Space Shuttle Main Engine Failures," *AIAA-87-1939*, AAIA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego, CA, July 1987.

Collins, J.: *Failure of Materials in Mechanical Design—Predictions, Prevention*, 2d ed., John Wiley & Sons, New York, 1993.

Craig, R.R.; and Bampton, M.C.C.: "Coupling of Substructures for Dynamic Analysis," *AIAA Journal* 61:7, July 1965.

Crandall, S.H.; and Mark, W.D.: *Random Vibration in Mechanical Systems*, Academic Press, New York, 1963.

Cross, N.: *Engineering Design Methods*, Wiley, New York, 1989.

Cyr, K.J.: "The Role of Cost Analysis in Manned Spacecraft Development," *SAE 901863*, Aerospace Technical Conference, October 1990.

Deming, E.: *Out of the Crisis*, Massachusetts Institute of Technology, Cambridge, MA, 1989.

Den Hartog, J.P.: *Mechanical Vibrations*, McGraw-Hill, New York, NY, 1956.

Dieter, G.E.: *Engineering Design—A Materials and Processing Approach*, 2d ed., McGraw-Hill, New York, NY, 1991.

Drucker, P.F.: *Managing for Results*, Harper & Row, New York, NY, 1984–86.

Dym, C.L.: *Engineering Design—A Synthesis of Views*, Cambridge University Press, 1994.

Ehrich, F.F.; and Childs, D.: "Self Excited Vibration in High-Performance Turbomachinery," *Mechanical Engineering*, pp. 66–79, May 1984.

Ertas, A.; and Jones, J.C.: "The Engineering Design Process."

Ferebee, R.C.: "Application of a Computerized Vibroacoustic Data Bank for Random Vibration Criteria Development," *NASA TP 1998*, NASA, March 1982.

Ferguson, E.S.: *Engineering and the Mind's Eye*, Massachusetts Institute of Technology, Boston, MA, 1992.

Flugel, C.; and Weisbrich, A.: "Voice of Customer Conversion Steps," *Japan Business Consultants*, Ann Arbor, MI, 1990.

Fox, J.: *Quality Through Design*, McGraw-Hill, New York, NY, 1993.

"Fracture Control Requirements for Payloads Using the Space Shuttle," *NASA–STD–5003*, October 1996.

"Fracture Control Requirements for Space Station," *SSP 30558–B*, June 1994.

French, M.: *Invention and Evolution, Design in Nature and Engineering*, Cambridge Press, New York, NY, 1994.

Garrick, I.E.; "Aeroelasticity—Frontiers and Beyond," 13th Von Karman Lecture, *AIAA Journal of Aircraft*, 113:9, September 1976.

Garrick, I.E.; and Reed III, W.H.: "Historical Development of Flutter," *AIAA–81–0591–CP*, Atlanta, GA, April 1981.

Geissler, E.D. (Editor): "Vehicle Response to Atmospheric Disturbance," Wind Effects on Launch Vehicles, *AGARDograph* 115, February 1970.

Goldberg, B.E.; et al.: "Systems Engineering "Toolbox" for Design Oriented Engineers," *NASA Report 1358*, MSFC, December 1994.

Greenwood, D.T.: *Principles of Dynamics*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1965.

Handy, C.: *The Age of Paradox*, Harvard Business School, Boston, MA, 1995.

Harris, C.M.; and Crede, C.E., Eds: *Shock and Vibration Handbook*. McGraw-Hill, New York, 1976.

Himelblau, H.: "Guidelines for Dynamic Environmental Criteria."

Hopkins, J.: "Approaches to Reduced Launch Operations Costs," *SAE 901877*, Aerospace Technical Conference, October 1990.

Hubka, V.; and Eder, W.E.: *Design Science*, Springer-Verlag, London, 1996.

236

Humphries, R.; Wegrich, R.; Pierce, E.; and Patterson, W.: "A Survey of Spacecraft Thermal Design Solutions." NASA MSFC, October 1991; ESA and AST, *Fourth European Symposium on Space Environmental Control Systems*, Florence, Italy, October, 1991.

Hurty, W.C.: "Dynamic Analysis of Structural Systems by Component Mode Synthesis," *JPL Technical Report No. 32–530*, January 1964.

Ibrahim, S.R.; and Mikulcik, E.C.: "A Method for the Direct Identification of Vibration Parameters from the Free Response," *The Shock and Vibration Bulletin* 47, Part 4, September 1977.

"Loads Analysis of Spacecraft and Payloads," *NASA-STD–5002*.

Lovingood, J.A.: "A Technique for Including the Effects of Vehicle Parameter Variations in Wind Response Studies," *NASA TM X–53042*, May 1964.

"Management of Major System Programs and Projects," *NASA NMI 7120*.4, November 1993.

McCarty, J.; and Murphy, J.M.: "An Assessment of Liquid Propulsion in the United States," *AIAA*, July 1989.

Melosh, R.J.; Deither, P.A.; and Brennan, M.: "Structural Analysis and Matrix Interpretive Systems (SAMIS) Program Report," *JPL TM No. 33–307*, December 1966.

Metals Handbook, 9th ed., Volume II, Failure Analysis and Prevention, Failures of Rolling Element Bearings, American Society for Metals, Metal Park, OH, pp. 490–514, 1979.

Miller, I.; Freund, J.E.; and Johnson, R.A.: *Probability and Statistics for Engineers*, 4th ed., Prentice Hall, Englewood, Cliffs, NJ, 1990.

Mintzberg, H.: *Mintzberg on Management*, Free Press, New York, 1988.

Niu, M.C.Y.: *Composite Airframe Structures,* Hong Kong Comlit Press, Hong Kong, 1992, Rev. 1996.

Noor, A.K.; and Venneri, S.L.: "New and Projected Aeronautical and Space Systems, Design Concepts and Loads," *ASME*, New York, 1994.

O'Hara, K.: "Liquid Propulsion System Reliability—Design for Reliability," *AIAA–89–2628*, July 1989.

Pack, H., Jr.; and Young, L.E.: "Solar Array Flight, Dynamic Augmentation Experiment," *NASA TP 2690*, NASA, Washington, DC, February 1987.

Pahl; and Beitz: "Engineering Design," The Design Council, Springer-Verlag, London, 1984.

"Payload Test Requirements," *NASA-STD–7002*, July 1996.

"Payload Vibroacoustic Test Criteria," *NASA–STD–7001*, June 1996.

Peters, T.; and Waterman, R.: *In Search of Excellence,* Warner Books, New York, NY, 1985.

Phadke, M.S.: *Quality Engineering Using Robust Design,* Prentice Hall, Englewood Cliffs, NJ, 1989.

Pikey, W.; and Pikey, B.; Eds: "Shock and Vibration Programs, Reviews, and Summaries," *SVM10,* The Shock and Vibration Information Center, United States Department of Defense, 1975.

"Program/Project Management," *NASA NPD 7120.4A,* November 14, 1996.

Rao, J.S.: *Rotordynamics,* 2d ed., J. Wiley, 1991.

Rao, S.S.: *The Finite Element Method of Engineering,* Pergamon Press, New York, NY, 1982.

Ravindra, M.K.; and Galambos, T.V.: "Load and Resistance Factor Design for Steel," *Journal of the Structural Division,* Vol. 104, No. ST 9, pp. 1337–1353, 1978.

Ricks, E.; Klein, M.; and Reynolds, J.: "Derivation of Improved Load Transformation Matrices for Launchers-Spacecraft Coupled Analysis, and Direct Computation of Margins of Safety," Proc. Intl. Conf.: "Spacecraft Structures and Mechanical Testing," *ESA SP–289,* January 1989.

Ryan, R.S.; Nurre, G.S.; Scofield, H.N.; and Sims, J.L.: "Dynamics and Control of Large Space Structures," *Journal of Guidance, Control and Dynamics,* Vol. 7, No. 5, September–October 1984.

Ryan, R.S.: "Practices in Adequate Structural Design," *NASA 2893,* January 1989.

Ryan, R.S.: "Systems Analysis Approach to Deriving Design Criteria (Loads) for Space Shuttle and Its Payloads," *NASA TP 1949 and 1950,* December 1981.

Ryan, R.S.; Jewell, R.; Bugg, F.; Ivey, W.; McComas, R.; Kiefling, L.; and Jones, J.: "Dynamic Testing of Large Space Systems," *NASA TM–78307,* September 1980.

Ryan, R.S.: "The Role of Failure/Problems in Engineering: A Commentary on Failures Experienced - Lessons Learned," *NASA TP–3213,* March 1992.

Ryan, R.; and Verderaime, V.: "Launch Vehicle Systems Design Analysis Applied," *AAIA–93–1140,* February 1993.

Ryan, R.; and Verderaime, V: "Systems Design Analysis Applied to Launch Vehicles," *NASA TP–3326,* February 1993.

Ryan, R.; Schutzenhofer, L.; Jones, J.; and Jewell, R.: "Elimination of Discrete Frequency Acoustical Phenomenon Associated with the Space Shuttle Main Engine Oxidizer Valve Duct System," *10th Shock and Vibration Symposium,* Colorado Springs, CO, October 1979.

Ryan, R.S.; et al.: "Dynamic Testing of Large Space Systems," *NASA TM–78307*, September 1980.

Ryan, R.S.: "Fracture Mechanics Overview," JANNAF Nondestructive Evaluation Subcommittee Meeting, *CPIA Publication 514*, NASA Langley Research Center, May 1989.

Ryan, R.S.; and Townsend, J.: "Application of Probabilistic Analysis/Design Methods in Space Programs: The Approaches, The Status, and the Needs," *AIAA–93–1381*, SDM AIAA/ASME, LaJolla, CA, April, 1993.

Ryan, R.S.; Mowery, K.; and Tomlin, D.D.: "The Dynamic Phenomena of Tethered Satellite," *NASA TP 3347*, NASA, Washington DC, February 1993.

Ryan, R.S.: "Fracture Mechanics Overview," *JANNAF Nondestructive Evaluation Subcommittee Meeting*, Langley Research Center, May 2–4, 1989.

Ryan, S.G.: "Limit Cycle Vibrations in Turbomachinery," *NASA TP 3181*, December 1991.

Safie, F.; and Fox, E.P.: "A Probabilistic Design Analysis Approach for Launch Systems," *AIAA–91–3372*, June 1991.

Salomone, T.A.: "What Every Engineer Should Know About Concurrent Engineering," Marcel Dekker, Inc., 1995.

Scharton, T.: "Vibration-Test Force Limits Derived from Frequency-Shift Method," *AIAA Journal of Spacecraft and Rockets* 32:2, March–April 1995.

Schock, R.: "Solar Array Flight Dynamic Experiment," *NASA TP 2598*, NASA, Washington, DC, May 1986.

Schutzenhofer, L.A.; McConnaughey, P.K.; and McConnaughey H.V.: "Role of CFD in Propulsion Design—Government Prospective," *AIAA–90–1825*, 1990.

Senge, P.: *The Fifth Discipline, The Art of the Learning Organization*," Doubleday, New York, NY, 1990.

Shen, F.; and Pope, D.: "Design and Development of Composite Fairing Structures for Space Launch Vehicles," *SAE 901836*, Aerospace Technology, October 1990.

Sobieski, S.; and Goetz, R.C.: "Synthesis of Aircraft Structures Using Integrated Design and Analysis Methods," Status Report, NASA, Langley Research Center, VA.

"Space Shuttle Launch System Evaluation Advisory Team (LSEAT) Integrated Support Plan," *NSTS 03211*, Rev. B, Johnson Space Center, NASA, December 5, 1991.

"Space Vehicle Design Criteria (Structures), Buckling of Thin-Walled Doubly-Curved Shells," *NASA BP–8032*, August 1959.

"Space Vehicle Design Criteria (Structures), Buckling of Thin Walled Truncated Cones," *NASA BP–8019*, September 1986.

"Space Vehicle Design Criteria (Structures), Buckling Strength of Structural Plates," *NASA BP–8068*, June 1971.

"Space Vehicle Design Criteria (Structures), Discontinuity Stresses in Metallic Pressure Vessels," *NASA BP–8083*, November 1971.

"Space Vehicle Design Criteria (Structures), Design-Development Testing," *NASA SF–8084*, May 1970.

"Space Vehicle Design Criteria (Structures), Fracture Control of Metallic Pressure Vessels," *NASA BP–8040*, May 1980.

"Space Vehicle Design Criteria (Structures), Preliminary Criteria for the Fracture Control of Space Shuttle Structures," *NASA SF–8095*, June 1971.

"Space Vehicle Design Criteria (Structures), Stress-Corrosion Cracking in Metals," *NASA BP–8032*, August 1985.

"Space Vehicle Design Criteria (Structures), Structural Design Criteria Applicable to a Space Shuttle," *NASA BP–8087*, January 1971.

Steward, D.V.: *Systems Analysis and Management*, Petrocelli Books, Inc., New York, NY, 1981.

"Structural Design and Test Factors of Safety for Spacecraft Hardware," *NASA–STD–5001*, June 1996.

"Structural Design and Verification Requirements—ISSA," *SSP 30559–B*, June 1994.

Sullivan, R.: "A Coupled Solution Method for Predicting the Thermostructural Response of Decomposing, Expanding Polymeric Composites," *Journal of Composite Materials*, Vol. 27, No. 4, 1993.

"System Engineering Handbook," 2d ed., *MSFC–HDBK–1912A*, MSFC, December 1994.

Taguchi, G.: *Introduction to Quality Engineering*, American Supplier Institute, Inc., Dearborn, MI, 1986.

Ullman, D.: *The Mechanical Engineering Design Process*, McGraw-Hill, New York, 1994.

Ulrich, K.; and Eppinger, S.: *Product Design and Development*, McGraw-Hill, New York, 1994.

von Pragenau, G.: "Damper Seals for Turbomachinery," *NASA TP–1987*, March 1982.

Wallace, P.J.: *The Technique of Design*, Sir Isaac Pitman & Sons Ltd., London, England, 1952.

Walton, M.: *The Deming Method*, Periger Books, Putman Publishing Co., New York, NY, 1986.

240

Wirsching, P.J.; et al.: "An Overview of Reliability Methods in Mechanical and Structural Systems," *28th Annual Structures, Structural Dynamics, and Materials Conference*, April 1987.

Wirshching, P.H., and Ortiz, K.: "Reliability Methods in Mechanical and Structural Design," *13th Annual Seminar and Workshop*, Univ. of Arizona, Tucson, AZ, January 1992.

Woodson, T.T.: *Introduction to Engineering Design*, McGraw-Hill, New York, 1996.

Zarestsky, E.: "Life Factors for Rolling Bearings," *STLE Publications SP–341*, 1992.

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13. ABSTRACT (Maximum 200 words)

Engineering design is a challenging activity for any product. Since launch vehicles are highly complex and interconnected and have extreme energy densities, their design represents a challenge of the highest order. The purpose of this document is to delineate and clarify the design process associated with the launch vehicle for space flight transportation. The goal is to define and characterize a baseline for the space transportation design process. This baseline can be used as a basis for improving effectiveness and efficiency of the design process. The baseline characterization is achieved via compartmentalization and technical integration of subsystems, design functions, and discipline functions. First, a global design process overview is provided in order to show responsibility, interactions, and connectivity of overall aspects of the design process. Then design essentials are delineated in order to emphasize necessary features of the design process that are sometimes overlooked. Finally the design process characterization is presented. This is accomplished by considering project technical framework, technical integration, process description (technical integration model, subsystem tree, design/discipline planes, decision gates, and tasks), and the design sequence. Also included in the document are a snapshot relating to process improvements, illustrations of the process, a survey of recommendations from experienced practitioners in aerospace, lessons learned, references, and a bibliography.

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