86P

FINAL REPORT

For Order No. H-30968D

LAUNCH VEHICLE DESIGN PROCESS DESCRIPTION AND TRAINING FORMULATION

23 April 1999 through 15 August 1999

prepared for

MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, AL

NASA/George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

by

Aero Thermo Technology

6700 Odyssey Drive, Suite 206
Huntsville, Alabama 35806

13 August 1999

Table of Contents

AUTHORSHIP

The Avionics Design Function section was written by James Atherton, Charles Morris, Gray Settle, and Marion Teal.

The Materials and Manufacturing Design Function sections were written by Paul Schuerer.

The Compartmentalization section and the Training Course Formulation section were developed by James Blair, Robert Ryan, and Luke Schutzenhofer.

INTRODUCTION

A primary NASA priority is to reduce the cost and improve the effectiveness of launching payloads into space. As a consequence, significant improvements are being sought in the effectiveness, cost, and schedule of the launch vehicle design process. In order to provide a basis for understanding and improving the current design process, a model has been developed for this complex, interactive process, as reported in the references. This model requires further expansion in some specific design functions. Also, a training course for less-experienced engineers is needed to provide understanding of the process, to provide guidance for its effective implementation, and to provide a basis for major improvements in launch vehicle design process technology.

The objective of this activity is to expand the description of the design process to include all pertinent design functions, and to develop a detailed outline of a training course on the design process for launch vehicles for use in educating engineers whose experience with the process has been minimal.

Building on a previously-developed partial design process description, parallel sections have been written for the Avionics Design Function, the Materials Design Function, and the Manufacturing Design Function. Upon inclusion of these results, the total process description will be released as a NASA TP (Reference 1). The design function sections herein include descriptions of the design function responsibilities, interfaces, interactive processes, decisions (gates), and tasks. Associated figures include design function planes, gates, and tasks, along with other pertinent graphics.

Also included is an expanded discussion of how the design process is divided, or compartmentalized, into manageable parts to achieve efficient and effective design.

A detailed outline for an intensive two-day course on the launch vehicle design process has been developed herein, and is available for further expansion. The course is in an interactive lecture/workshop format to engage the participants in active learning. The course addresses the breadth and depth of the process, requirements, phases, participants, multidisciplinary aspects, tasks, critical elements, as well as providing guidance from previous lessons learned. The participants are led to develop their own understanding of the current process and how it can be improved. Included are course objectives and a session-by-session outline of course content. Also included is an initial identification of visual aid requirements.

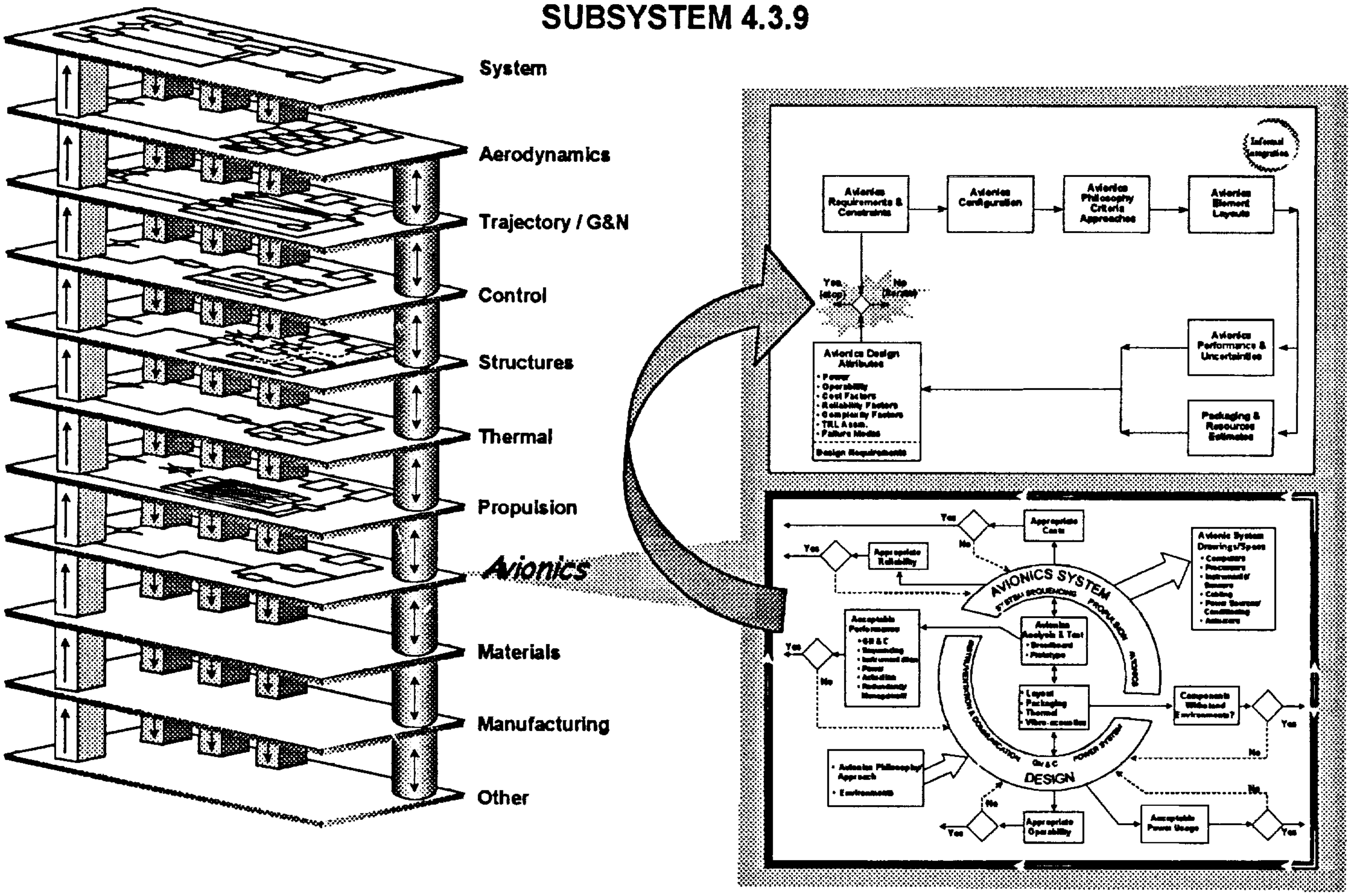
DESIGN FUNCTION DESCRIPTIONS

DESIGN FUNCTION DESCRIPTIONS

In this section, design function descriptions are developed for the design functions of Avionics, Materials, and Manufacturing. The writeup format is consistent with that of Reference 1, so that the sections may be inserted into the Reference 1 document to complete its design function narrative.

AVIONICS

SUBSYSTEM 4.3.9



4.3.9 Avionics Design Function

In the illustration on the previous page, the connection between the "design process technical integration" and the avionics design function is shown. 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, which 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 subdisciplines 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 paper, the *avionics* subsystem includes all vehicle electrical and electronic systems, such as guidance, navigation and control (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 <u>Avionics Design Function Plane</u>

The avionics design function includes responsibility for designing the electrical and electronic hardware and the 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 4.3.9-1. 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.

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, determines 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 4.3.9-2.

A listing of inputs and outputs for the avionics design function process along with discipline activities and products is shown in Figure 4.3.9-3. This process flow diagram addresses design considerations for the elements and which comprise the total avionics system, and is consistent with the flow diagram of the avionics plane. Figure 4.3.9-4 is a Work Breakdown Structure (WBS) for the design process for a typical avionics subsystem, the data management subsystem (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. Figures 4.3.9.3 and 4.3.9-4 are an adaptation of the process flow diagrams and task WBS charts of Reference 68.

The design and development of the avionics software and the Electrical Ground Support Equipment (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

Gates for the avionics design process are shown on Figure 4.3.9-5. 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 guidance, navigation and control, 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 leads 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.

4.3.9.3 Avionics Tasks

The top-level avionics design activities are summarized on Figure 4.3.9-6 and are described below. The design activities include both flight and ground support equipment.

Task 1: Requirements Allocation

Requirements allocation 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.

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.

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.

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 test beds 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 test beds 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 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, which is 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

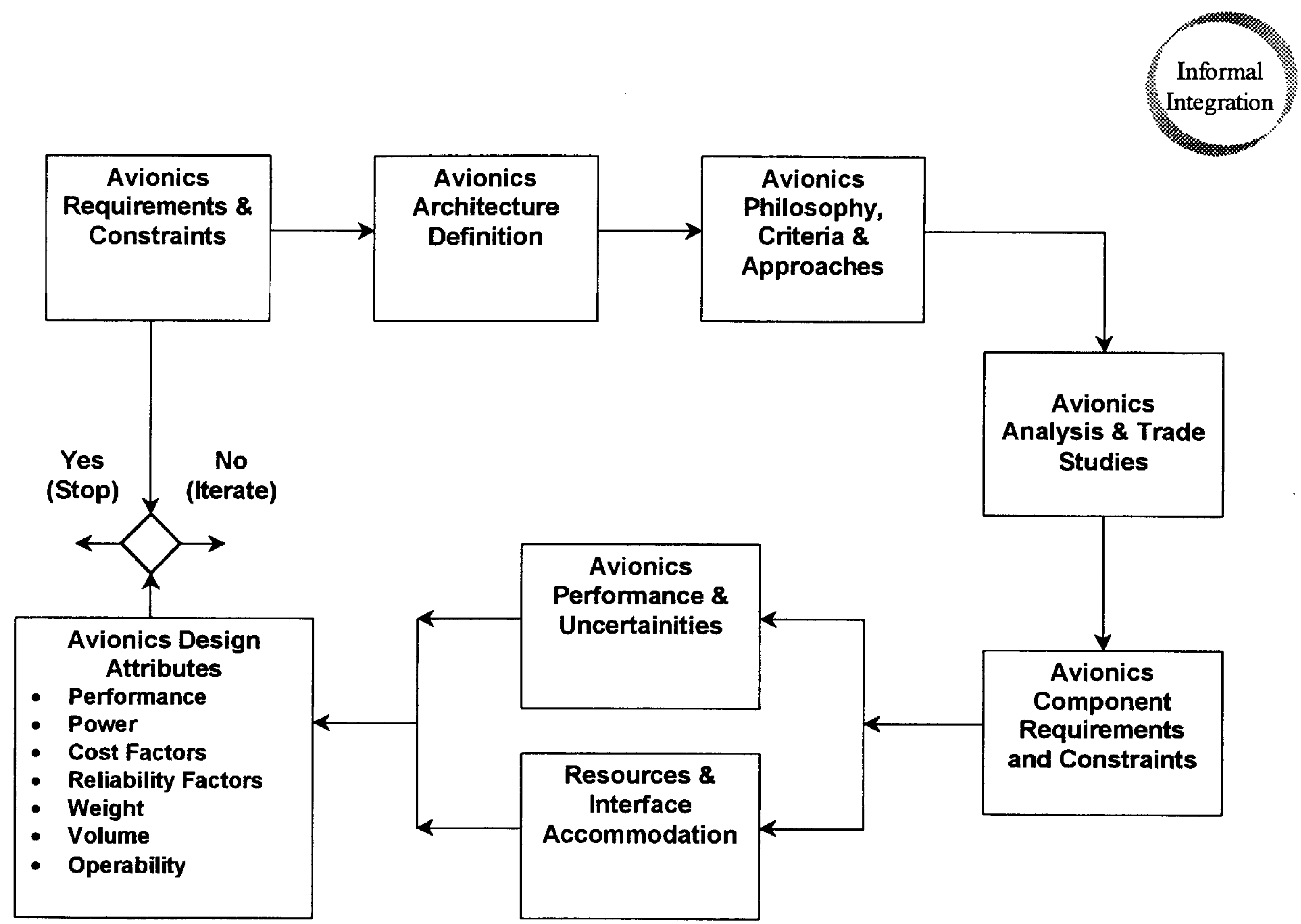


Figure 4.3.9-1 Avionics Design Function Plane

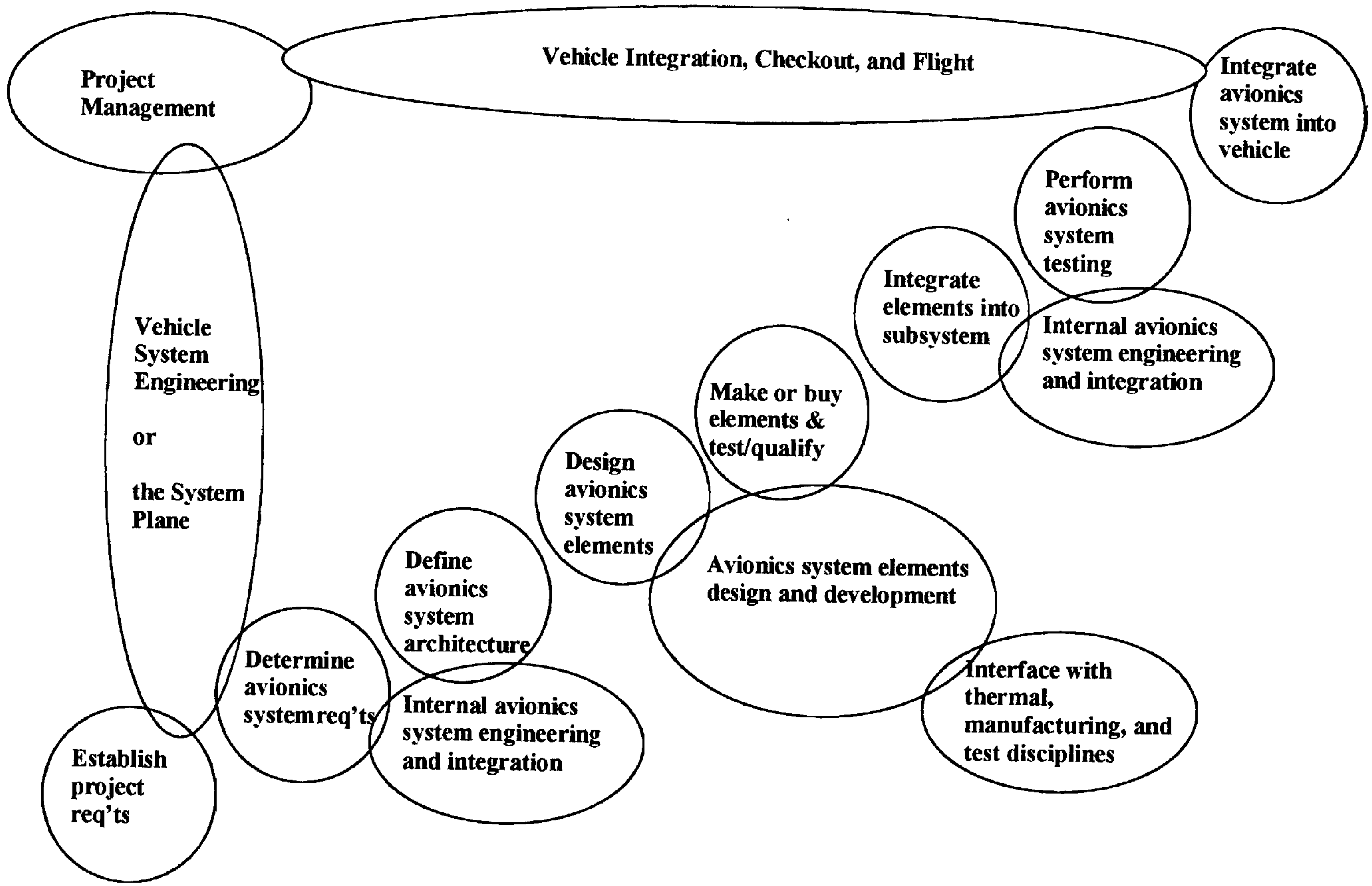


Figure 4.3.9.2 Avionics Systems Design Process Interactions

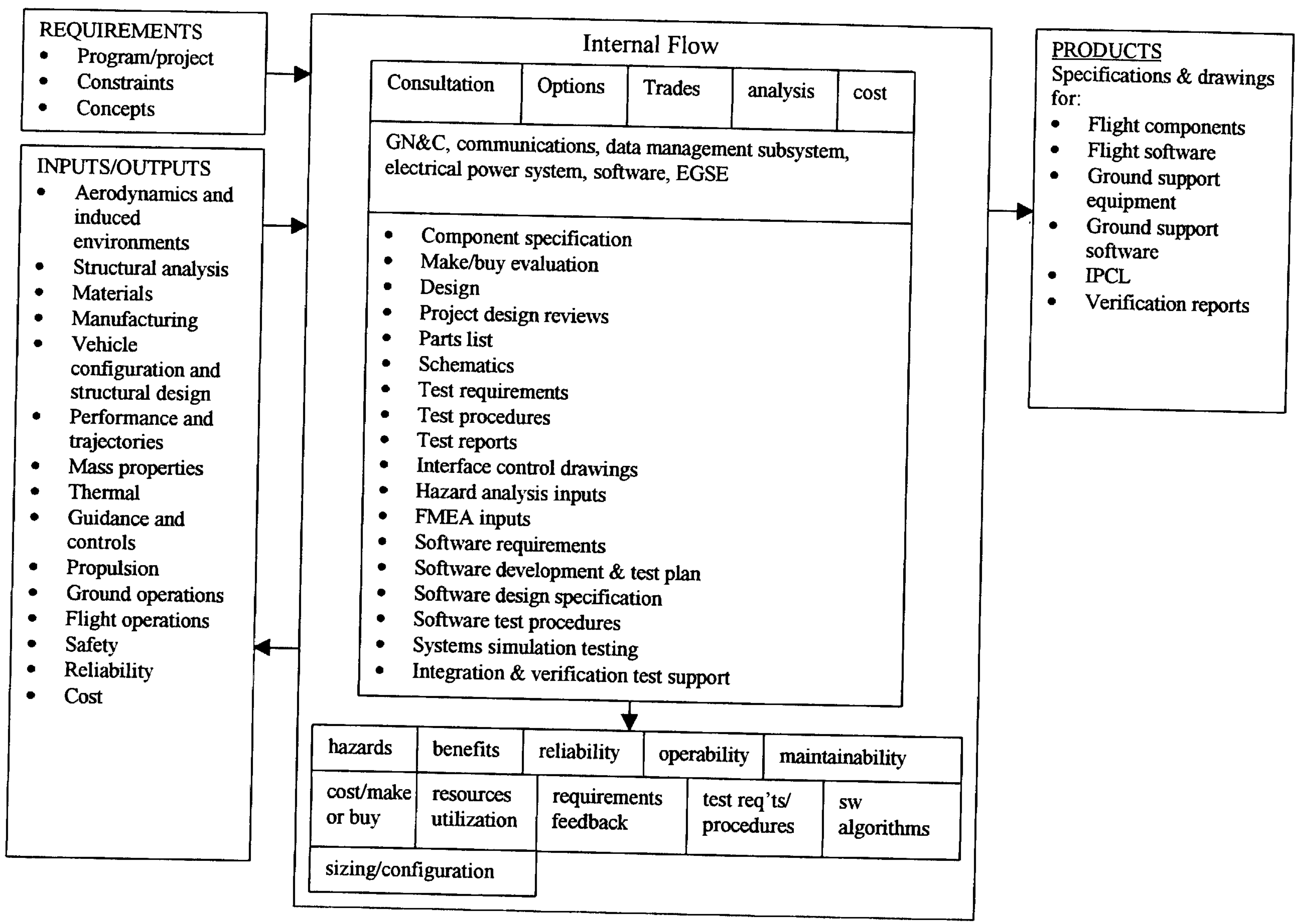


Figure 4.3.9-3 Avionics Process Flow Diagram

INPUTS	WBS	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 Requirements
	3.10.3.1.1 Components
	3.10.3.1.2 Avionics system inputs
	3.10.3.2 Design
	3.10.3.2.1 Trades and analysis
	3.10.3.2.2 Subsystem design
	3.10.3.2.3 Components
	3.10.3.3 Documentation
	3.10.3.3.1 Parts list
	3.10.3.3.2 Schematics
	3.10.3.3.3 Released drawings
	3.10.3.4 Test
	3.10.3.4.1 Test requirements
	3.10.3.4.2 Test procedures
	3.10.3.4.3 Component tests
	3.10.3.4.4 Subsystem tests
	3.10.3.4.5 Test reports
	3.10.3.5 Subsystem/component GSE
	3.10.3.5.1 GSE trades and analysis
	3.10.3.5.2 GSE design
	3.10.3.5.3 GSE test
	3.10.3.5.4 GSE documentation
	3.10.3.6 Project/program reviews
		• Subsystem design specifications
		• Flight components specifications
		  • Computer
		  • Command receivers
		  • Data processors
		  • Remote data acquisition units
		  • Storage devices
		• Ground support equipment specifications
		  • Subsystem design
		  • Components
		• Released drawings
		  • Test Specifications and procedures

Figure 4.3.9-4 WBS 3.10.3 Data Management Subsystem

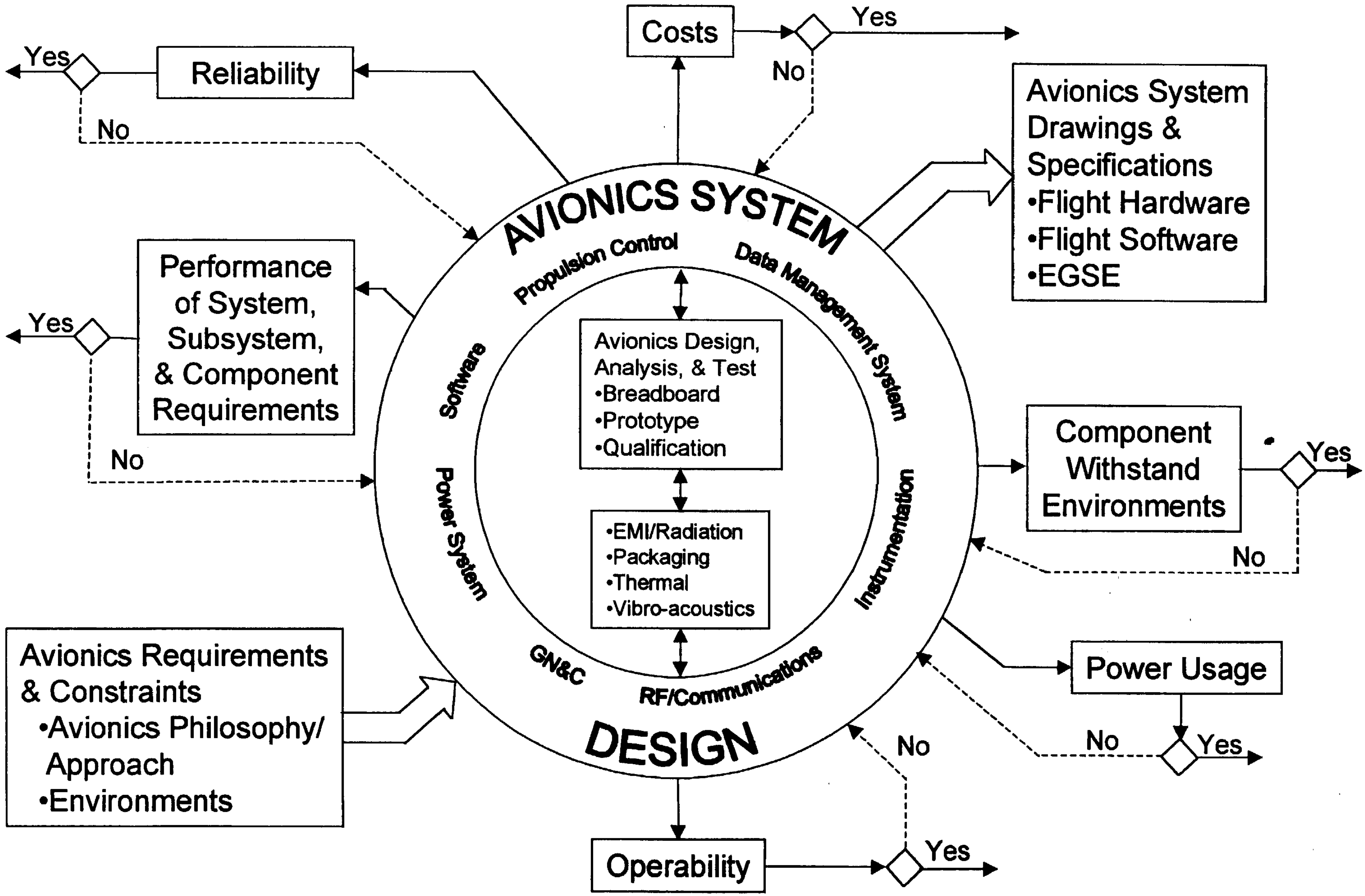


Fig. 4.3.9-5 AVIONICS SYSTEM DESIGN FUNCTION GATES

Multidisciplinary Activity	Interacting Disciplines	Tasks
I. Requirements Allocation	• System • GN & C • Propulsion • Natural Environments • Thermal • Operations	1. Consult with System to aid in initial requirements allocation of cost, reliability operability, maintainability, etc. 2. Consult with Control, Navigation & Guidance, Propulsion, and any internal "system" group to obtain avionics hardware/software/EGSE performance requirements 3. Obtain environmental requirements both Natural and Induced Environments 4. Feed back attributes to System and to "system" groups. Provide trade data and consultation for revised allocation if required.
II. Avionics Architecture	• System • Control • Navigation & Guidance	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
III. Avionics Subsystem Design 173	• System • Internal Avionics Subsystems	1. During detailed design, maintain close coordination with "system" groups that specify hardware/software requirements. 2. For subsystems, including EGSE, and component which are to be made vs. 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.
IV. Verification	• System • GN & C • Propulsion • Natural Environments • Thermal • Operations	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.

Figure 4.3.9-6 Avionics Design Function Tasks

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 both new materials and new processes development.

Composite materials including metallic, non-metallic, 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 sub-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.

4.3.10 Materials Design Function

"Materials" is considered a unique design 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 4.3.10.

4.3.10.1 Materials Design Function Plane

The materials design function plane is depicted in Figure 4.3.10.1. The output of this plane is the materials design, with all its inherent characteristics, for a component, element, subsystem, or system.

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 complement 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. Databases, 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 designs, develop further data where required and approve the material selections and specifications contained in the release drawings.

Material specialists interact directly with process engineers 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 where required.

The NxN diagram, and WBS elements 3.8, and 3.8.0 of reference 68 provide listings of inputs and outputs for the materials design function. The NxN diagram is shown in section 4.3.2. The materials WBS elements are reproduced herein as Figures 4.3.10.2 and 4.3.10.3.

4.3.10.2 Materials Design Function Gates

Gates for the materials design function are shown in Figure 4.3.10.4. They are (1) performance (2) environmental compliance (3) producibility/availability (4) cost/schedule.

Functional performance is determined by test, considering applied loads, service environments and service/cycle life. Environmental compliance requires a thorough researching of applicable OSHA/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 a 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.

4.3.10.3 Material Tasks

The top-level tasks of the materials plane are shown in Figures 4.3.10.5 and 4.3.10.6. They consist of (1) requirements determination and allocation (2) material selection and control (3) material development (4) material testing and analysis (5) failure analysis.

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 flow down 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 requirement 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, which 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 can not 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.

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 a more in depth 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 database on virtually all-conventional aerospace materials. This database 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.

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.

Task 4: Materials Testing and Analysis

Materials testing and materials analysis are performed to upgrade and supplement the design database. 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 compliment of standard assessment techniques for determining the physical and 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 in corrosive media and space radiation testing.

Certain materials are "batch sensitive", that is, vagaries in the production process result in materials that differ in service performance from batch to batch. Some non-metallic 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 is ultimately reviewed by material specialists for significance and accuracy. If it passes these screens it is then submitted for inclusion in the materials database.

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 failure 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.

4.3.11 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 4.3.11.

4.3.11.1 Manufacturing Design Function Plane

The manufacturing design function plane is depicted in Figure 4.3.11.1. The main output of this plane is the planning and documentation required for fabrication. Residing on the manufacturing plane are the sub-elements involved in the manufacturing activity. The significant sub-elements are described in limited detail in section 4.3.11.3. 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.

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 NxN diagram, and WBS elements 3.14 and 3.14.0 of reference 68 provide listings of inputs and outputs for the manufacturing design function. The NxN diagram is shown in section 4.3.2. The manufacturing WBS elements are reproduced herein as Figures 4.3.11.2 and 4.3.11.3.

4.3.11.2 Manufacturing Design Function Gates

Gates for the manufacturing design function are shown in Figure 4.3.11.4. They are (1) producibility (2) robustness (3) system performance (4) logistics (5) environmental compliance (6) cost and schedule.

Producibility is addressed early in the design of a component or assembly and continues throughout the design phase. 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 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.

4.3.11.3 Manufacturing Tasks

The primary tasks of the manufacturing plane are shown in Figures 4.3.11.5 and 4.3.11.6. 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 (6) parts fabrication and assembly.

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 "flow down" 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.

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 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.

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 their successful resolution required a coordinated effort between discipline specialists from the material supplier, the external tank contractor, the Marshall Space Flight Center, 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 requ ired 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.

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 "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.

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 on contract (3) the capability of the principal fabricator to perform a required function (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, the schedule, and the 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 International Standards Organization (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 the 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.

Task 6: Parts Fabrication and Assembly

The design of a component or assembly assumes 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 non-critical 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.

4.3.11.4 Manufacturing Implementation Function

The manufacturing design function provides the planning and documentation required for fabrication. 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 flow down of requirements from the system plane. But hardware production 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.

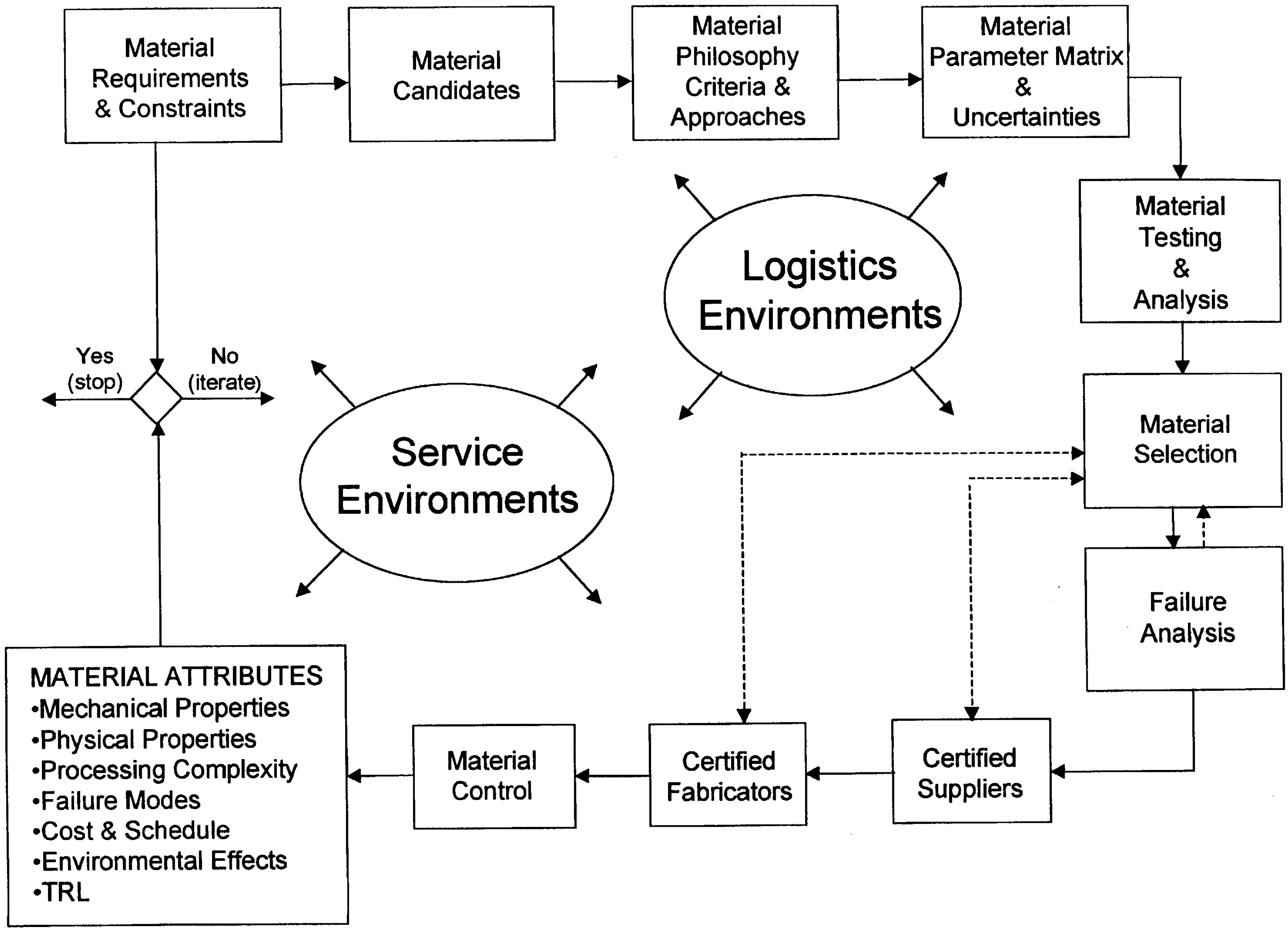


Fig. 4.3.10.1 MATERIALS DESIGN FUNCTION PLANE

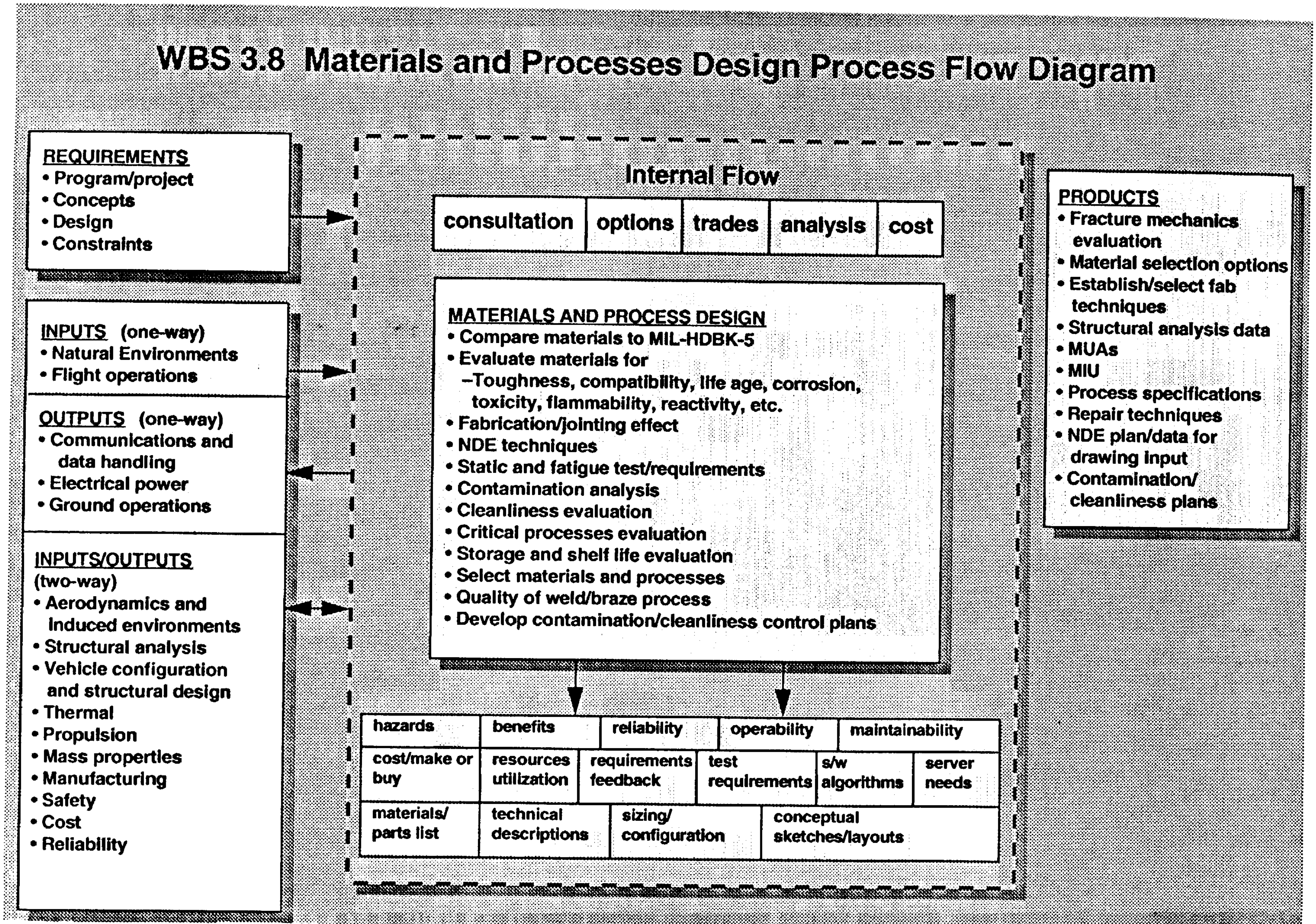


Figure 4.3.10-2 WBS 3.8 Materials and Processes Design Process Flow Diagram
(Reference 68)

WBS 3.8.0 – Materials

INPUT

- Drawings
- Component function
- Load/life requirements
- Environment
  - – temperature
  - – humidity
  - – pressure
- Accessibility
- Design engineering and strength requirements
- Special material requirements
- Material identification and usage list (MIUL)
- Assembly operations
- Environment restrictions

TASKS

3.8.1 Compare candidate materials to MIL-HDBK-5 data
3.8.2 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
3.8.3 Evaluate fabrication and joining effects
3.8.4 Develop NDE techniques
3.8.5 Conduct static and fatigue tests to obtain missing and needed data
3.8.6 Contamination analysis
3.8.7 Cleanliness evaluation
3.8.8 Critical processes evaluation
3.8.9 Storage and shelf life evaluation
3.8.10 Select materials and processes
3.8.11 Qualification of weld and braze specimens
3.8.12 Develop NDE techniques
3.8.13 Develop contamination and cleanliness control plans

Tools:
- NASA and MIL data bases

OUTPUT

- Fracture mechanics evaluation
- Material selection options
- Establishment and selection of fabrication techniques
- Data for structural analysis
- Material usage agreements (MUA)
- Materials selection and control plan
- Material identification and usage list — final (MIUL)
- 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

Figure 4.3.10-3 WBS 3.8 Materials Tasks (Reference 68)

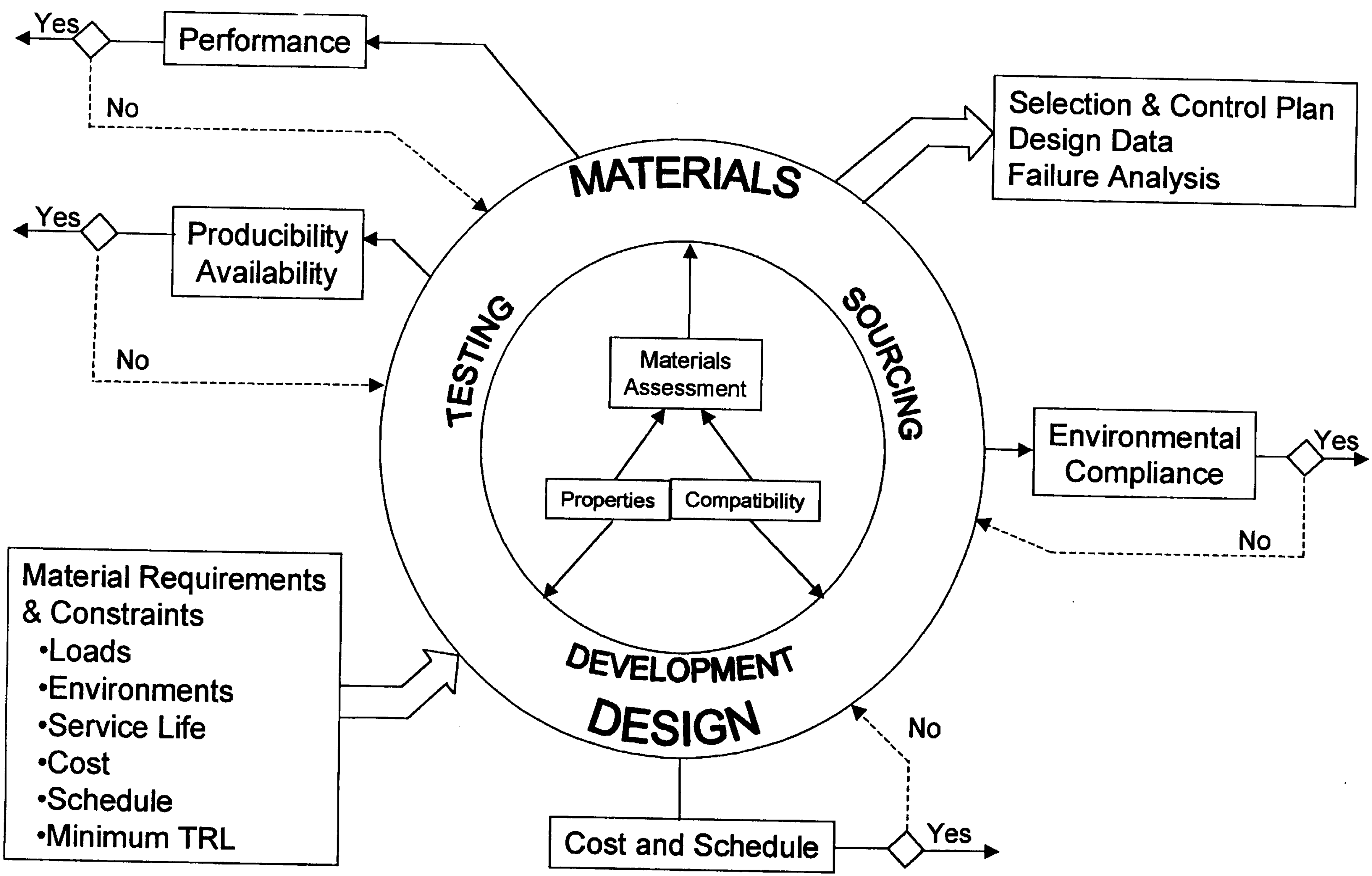


Fig. 4.3.10.4 MATERIALS DESIGN FUNCTION GATES

Multidisciplinary Activity	Interacting Disciplines	Tasks
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 non-conforming material issues, conduct trade studies, and where necessary, revise requirement and/or resource allocations.
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 databases. 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.
Materials Development	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.

Fig. 4.3.10.5 Materials Design Function Tasks

Multidisciplinary Activity	Interacting Disciplines	Tasks
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.
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.

Fig. 4.3.10.6 Materials Design Function Tasks

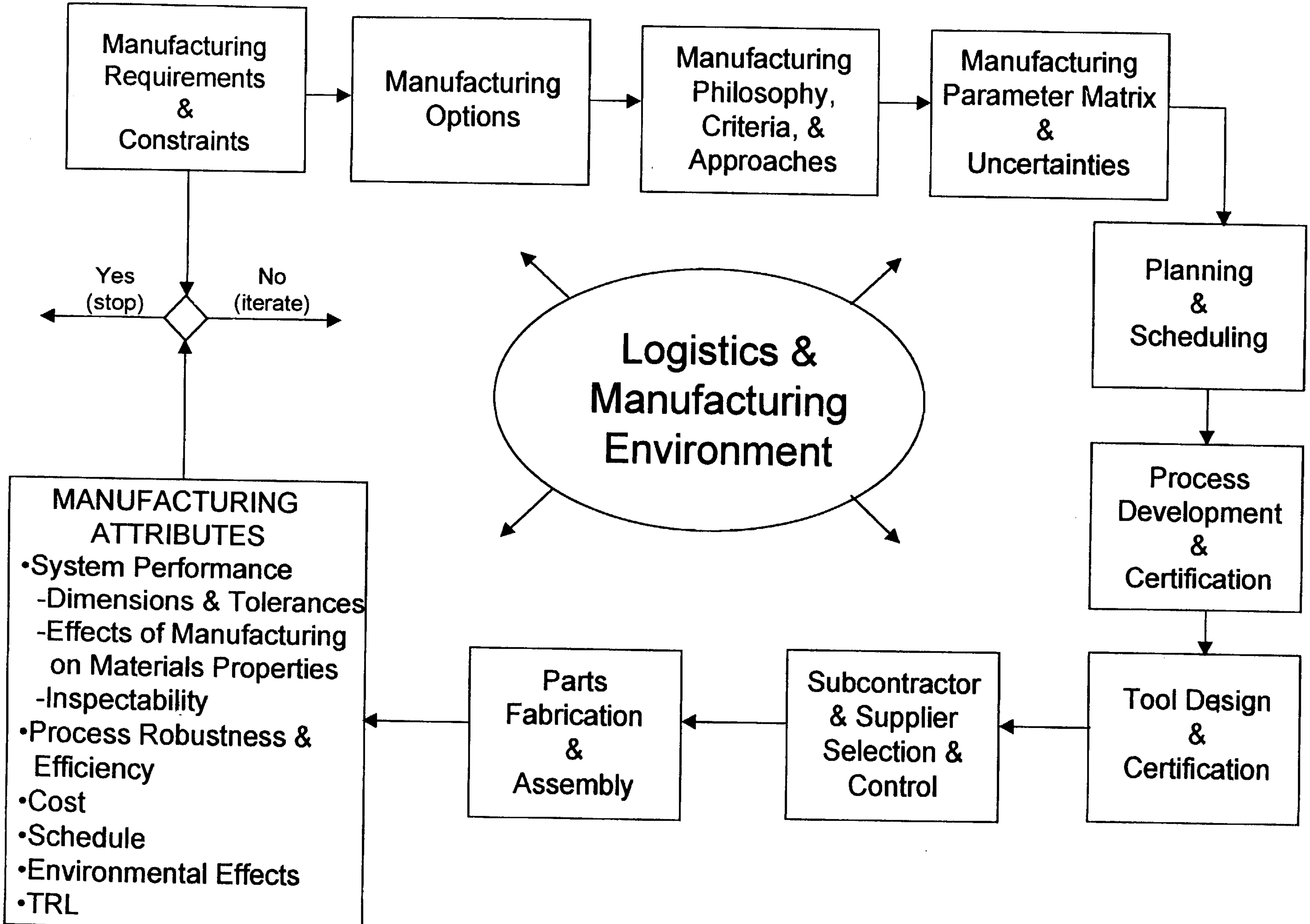


Fig. 4.3.11.1 MANUFACTURING DESIGN FUNCTION PLANE

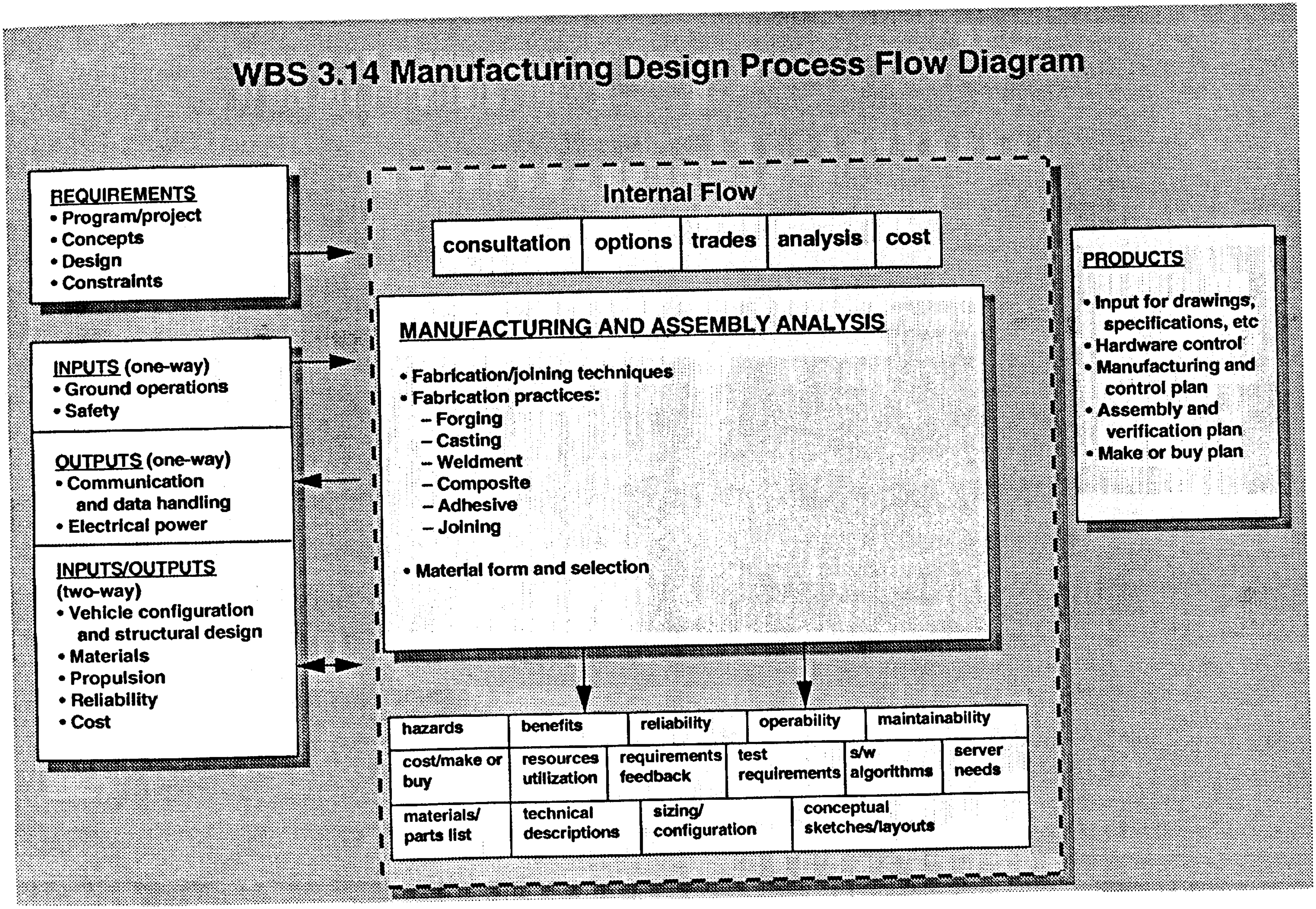


Figure 4.3.11-2 WBS 3.14 Manufacturing Design Process Flow Diagram (Reference 68)

WBS 3.14.0 – Manufacturing Processes

INPUT

- Drawings
- Component function
- Assembly operations
- Schedules
- Inspection and assurance requirements
- Cost restrictions
- NDE plan
- Cleanliness plan
- Contamination plan
- Quality plan

TASKS

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

Tools:
- NASA and MIL data bases

OUTPUT

- Input for drawings, notes, specifications, etc.
- Hardware control
- Manufacturing control plan
- Assembly and verification plan
- Make or buy plan input

Figure 4.3.11-3 WBS 3.14 Manufacturing Processes Tasks (Reference 68)

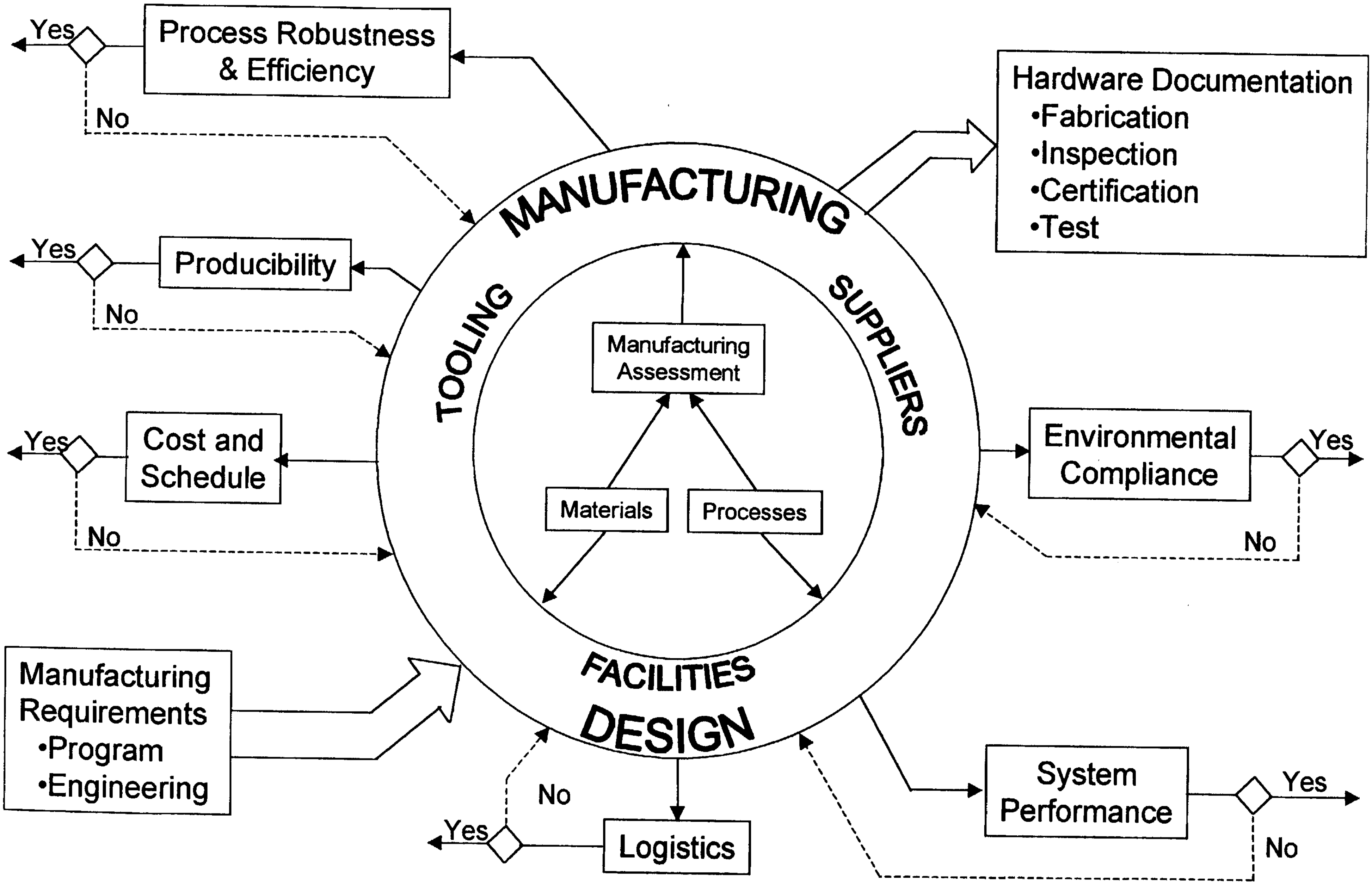


Fig. 4.3.11.4 MANUFACTURING DESIGN FUNCTION GATES

Multidisciplinary Activity	Interacting Disciplines	Tasks
Requirements Determination and Allocation	System Structures Thermal Propulsion Materials	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.
Planning and scheduling	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.
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
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.
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.

Fig.4.3.11.5 Manufacturing Design Function Tasks

Multidisciplinary Activity	Interacting Disciplines	Tasks
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.

Fig.4.3.11.6 Manufacturing Design Function Tasks

COMPARTMENTALIZATION OF DESIGN PROCESS

COMPARTMENTALIZATION OF DESIGN PROCESS

In developing the Training Course outline, it became apparent that the subject of design process compartmentalization had not been fully explained in the previous work of the references. A separate expansion of this topic is provided in this section.

The engineering design process has five major areas of emphasis that flow in sequential order: (1) requirements definition, (2) design, (3) build, (4) system integration and verification, and (5) operations, as shown on Figure 1.

The design process for launch vehicles is large and complex. At today's state of the art, the process must be divided into manageable parts for effective and efficient design. The question is: How and on what basis should the process be divided? Each division will require reintegration into a total system design. Integration is a challenge, and is often the source of problems and failures, so division should be made deliberately and rationally.

There are several bases for division, or compartmentalization. Since the launch vehicle is a highly coupled system, one basis is to divide the vehicle system into subsystems along lines of weak (or relatively weak) coupling. This reduces the difficulty of reintegration. These subsystems may be further divided into a hierarchy of sub-subsystems and components. Another basis is to take advantage of existing areas of expertise and state of the art (SOA) knowledge base which exist in the aerospace community that is going to participate in the design. The SOA information exists in three general areas: (1) Industrial specialization, (2) Governmental specialization, and (3) academic specialization. Figure 2 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 chart. These become the basis for the design process, the design activities. The design activities consist of (1) compartmentalization and decomposition of the hardware and tasks into workable units, (2) synthesis (concept utilizing the design), 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/decomposition 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 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 infracture, thus cutting cost and increasing quality. Government and academia decomposition 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. Decomposition, like 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.

Figure 3 illustrates an example compartmentalization, beginning with the Space Transportation System, and extending down through several levels of division. Focusing on the fuel tank as an example subsystem, this figure emphasizes the influence of industrial specialization. Figure 4 takes the compartmentalization to the next lower level.

Figures 5, 6, and 7 bring in the further specialization of academia, which is also reflected in the government and industry organizations. The previous compartmentalization diagram is shown on the left side of the figures. The design of each system, subsystem, sub-subsystem, part, etc. on the diagram typically requires multiple design functions and discipline functions as represented by the stack on the right side of the figures. In this context, the fuel tank, for example, is considered a system requiring integration of those design functions and discipline functions highlighted on Figure 6. The propellant utilization system, illustrated on Figure 7, is likewise considered a system, but it requires the integration of a smaller number of design functions and discipline functions as highlighted on that figure. Further down the tree, as the parts get more elemental, fewer design functions and discipline functions are involved. At sufficiently elemental level, the design is accomplished by the designer individually, usually through the use of handbooks, standards, etc. This is not to say that those more elemental parts are without multidisciplinary influences, but the handbooks and standards adequately cover these aspects with sufficient margin. Each design function must assure that its architecture is consistent across all levels of compartmentalization, from the smallest part to the largest system. For example, the thermal design function must produce an architecture of insulation and thermal protection that is consistent with the requirements of each small part of the propellant utilization system, up through the tankage, and up to the total launch vehicle system.

Vehicle Life Cycle Flow Chart

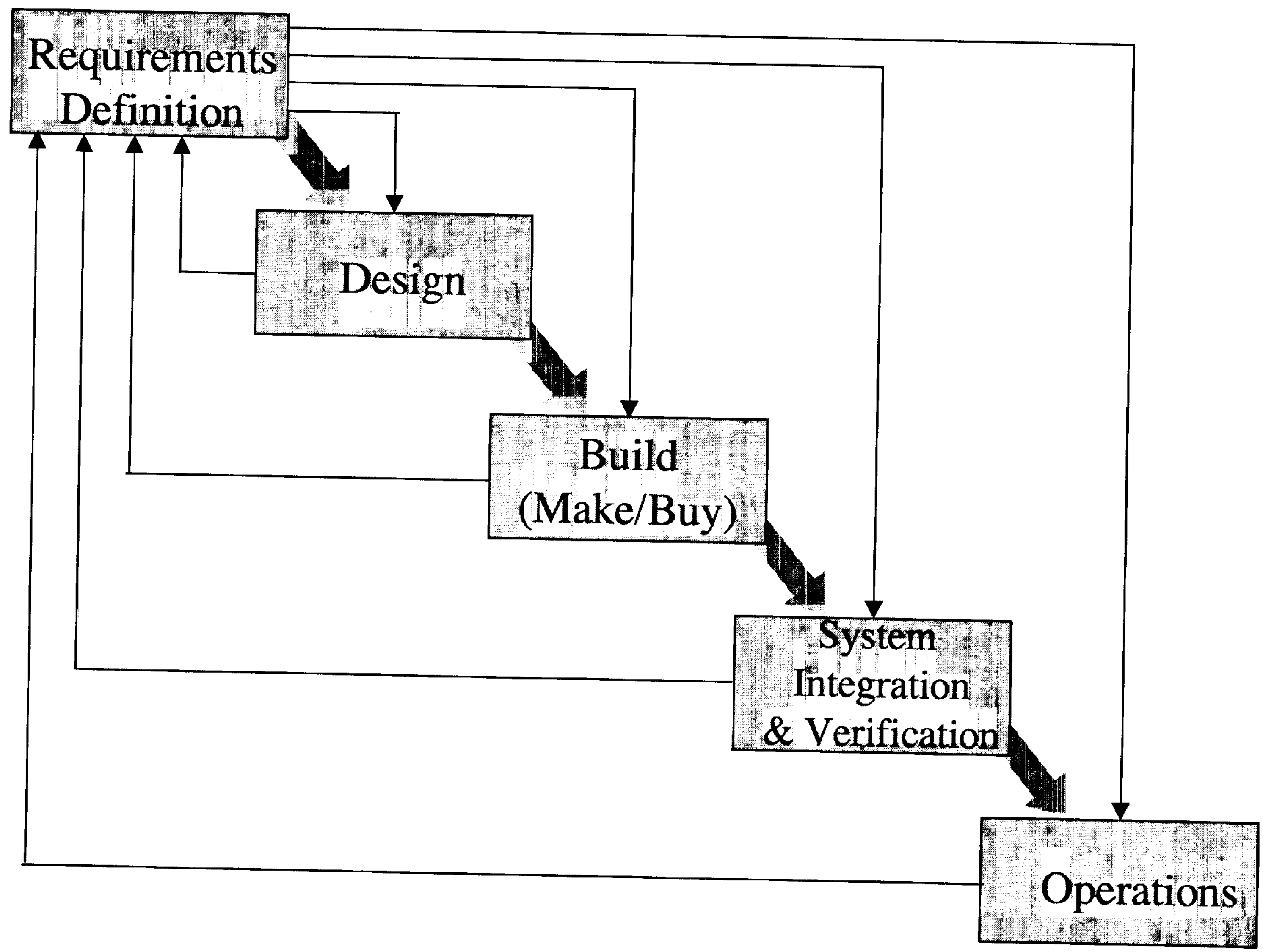
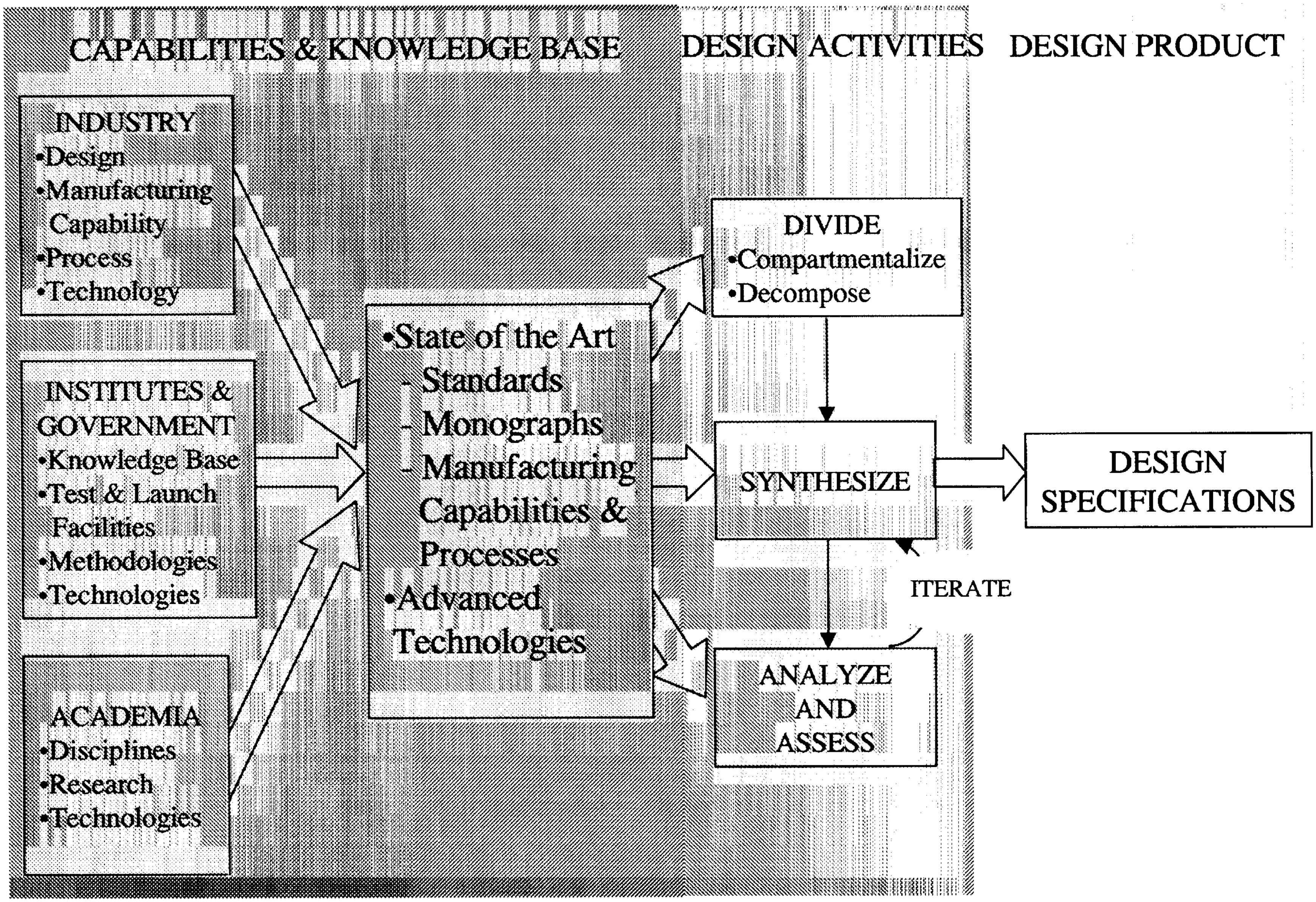
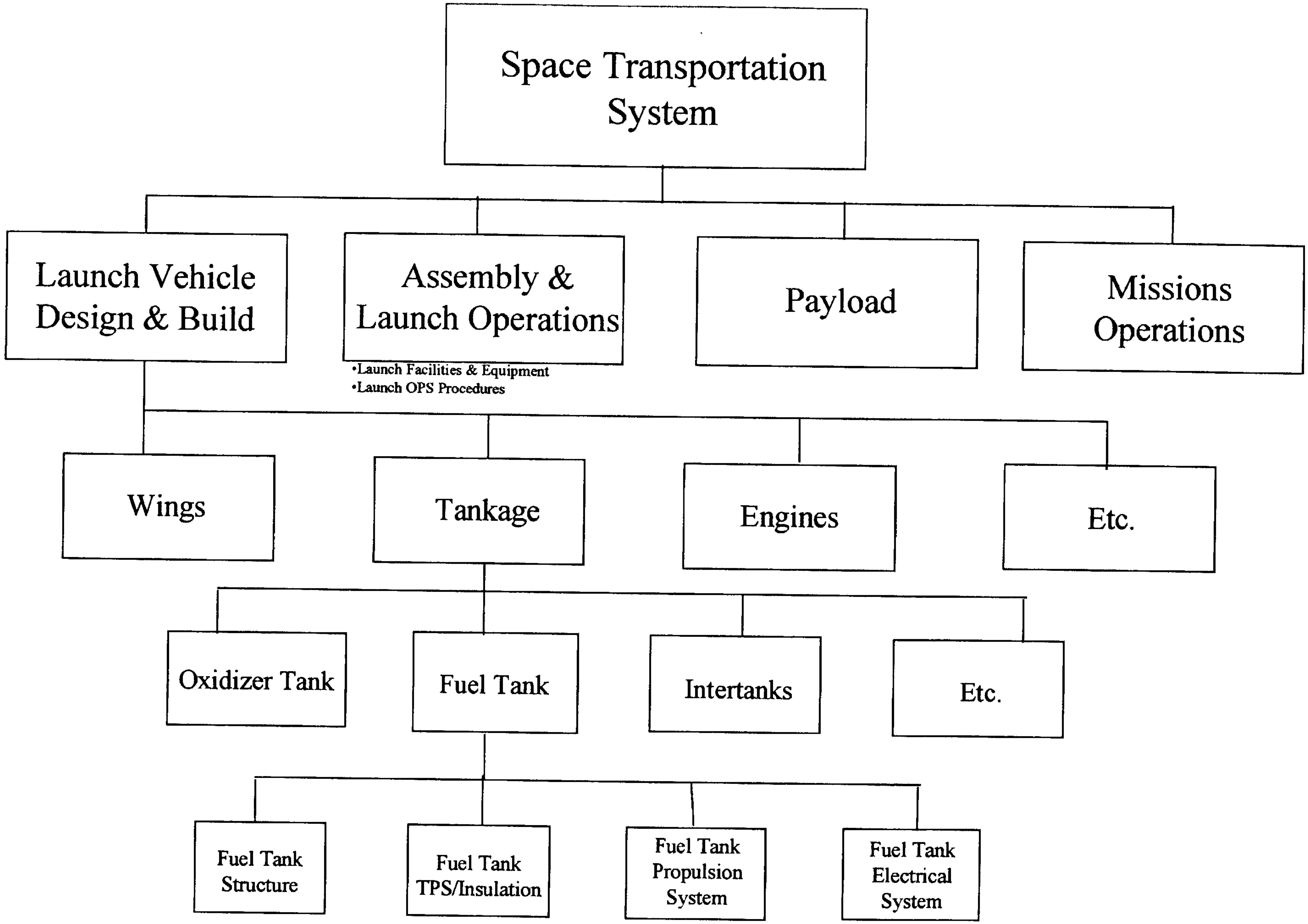


Figure 1



INFLUENCE OF AEROSPACE INFRASTRUCTURE AND SPECIALIZATION ON DESIGN

Figure 2



Example of Compartmentalization

Figure 3

Example of Launch Vehicle Hardware/Software Compartmentalization

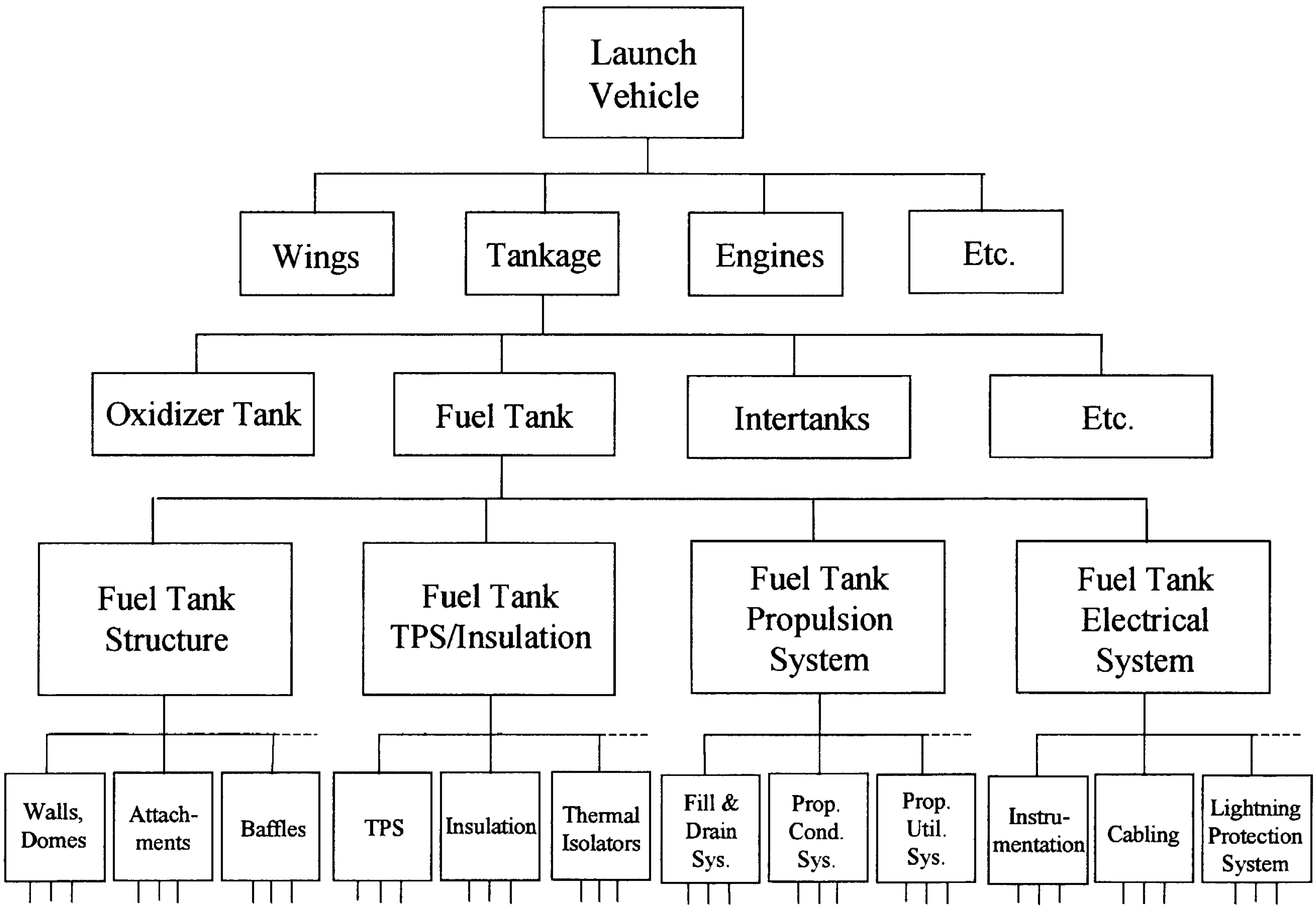


Figure 4

Example Compartmentalization - Launch Vehicle

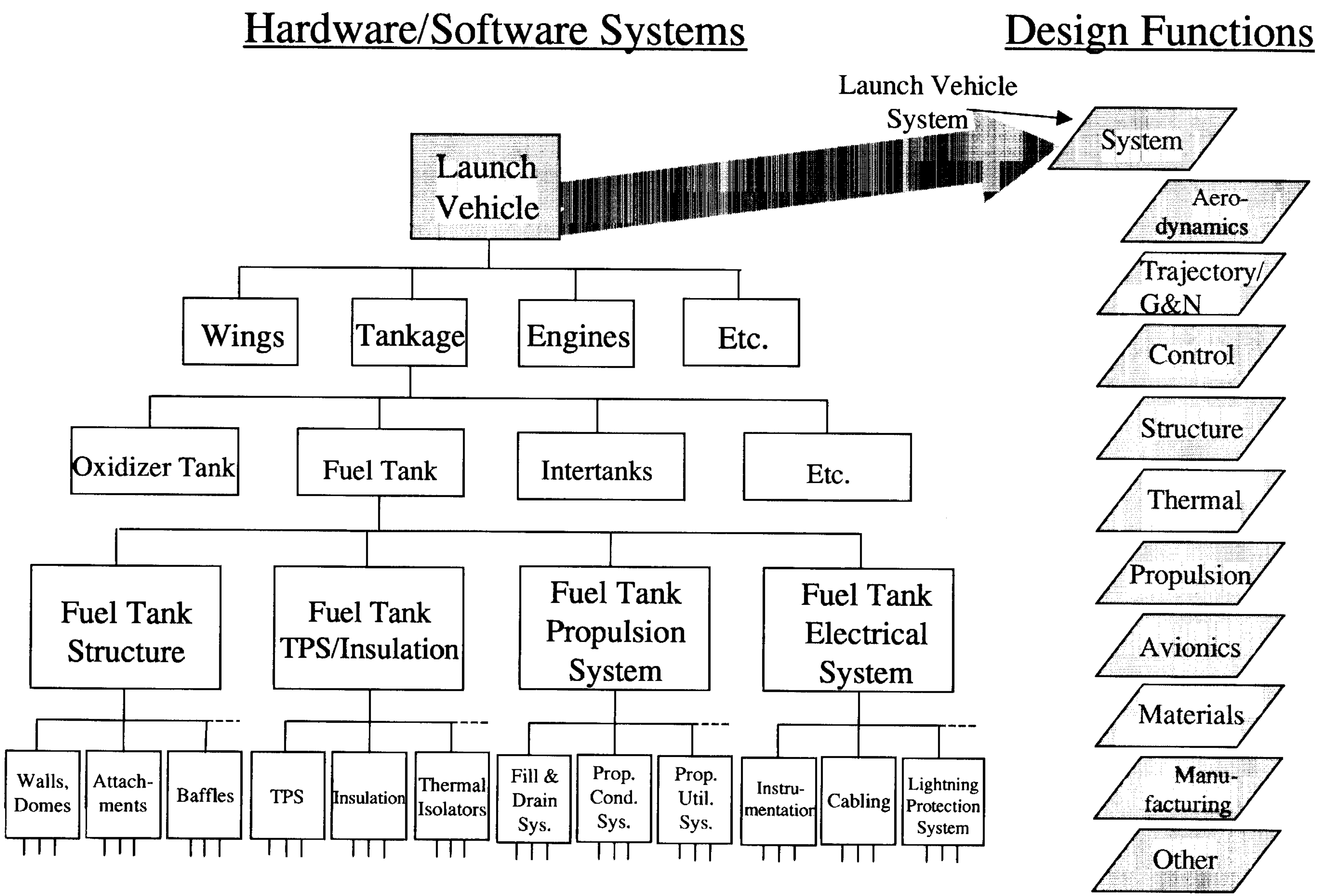


Figure 5

Example Compartmentalization - Fuel Tank

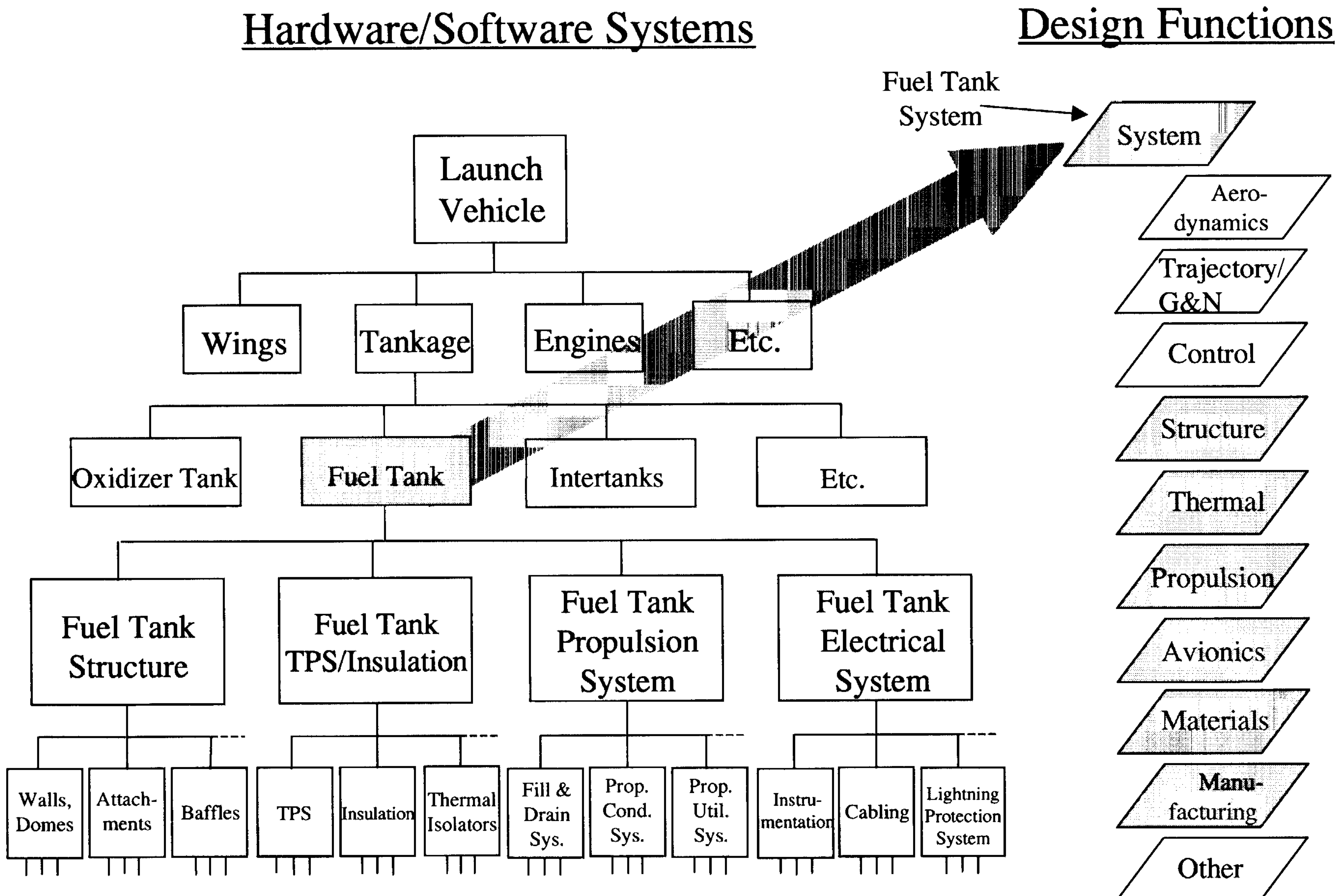


Figure 6

Example Compartmentalization - Propellant Utilization System

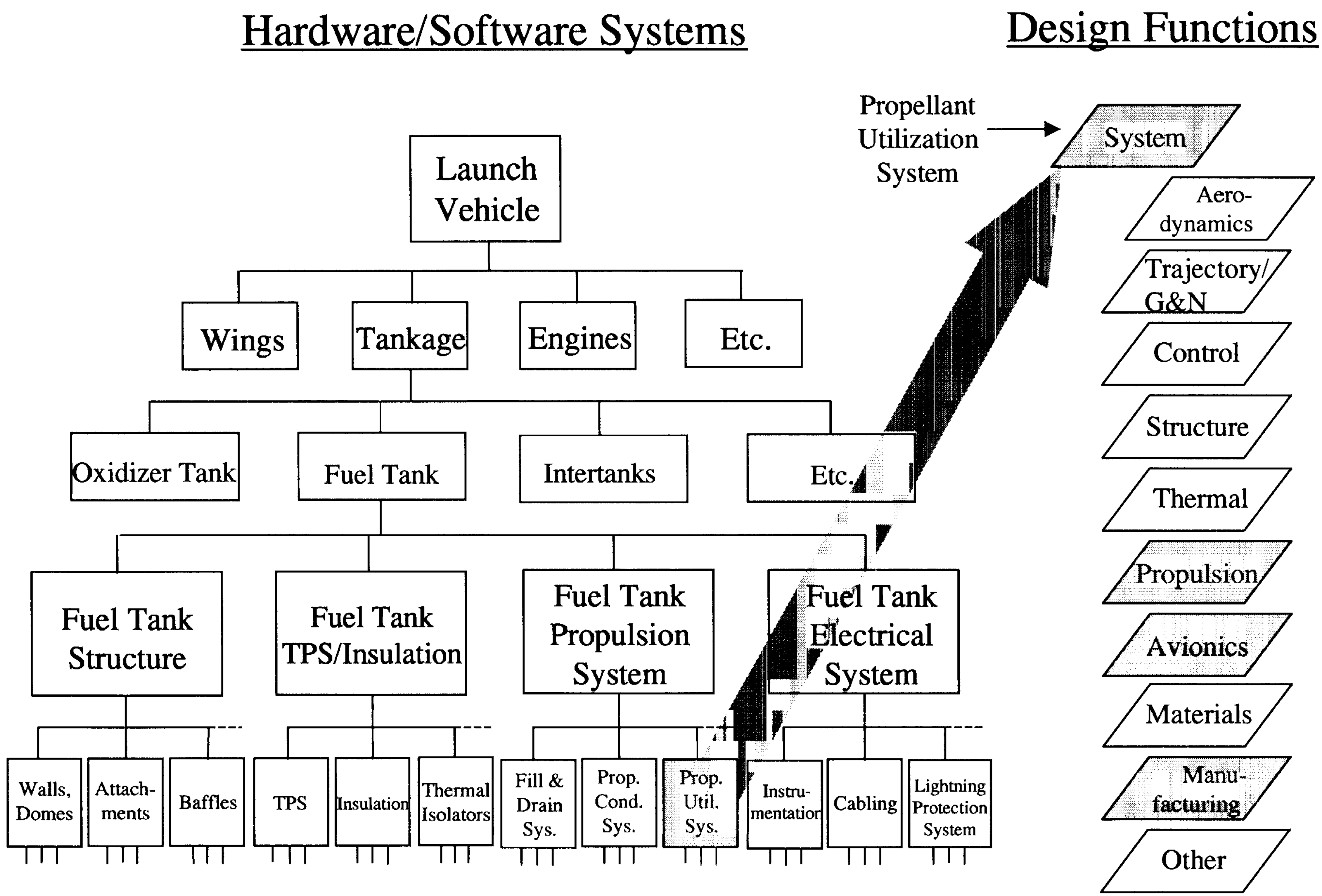


Figure 7

TRAINING COURSE FORMULATION

TRAINING COURSE FORMULATION

This section provides a detailed outline of a training course on the design process for launch vehicles for use in educating engineers whose experience with the process has been minimal. The course uses an interactive lecture/workshop format to engage the participants in active learning. The participants are led to develop their own understanding of the current process and how it can be improved. Included are course objectives, a session-by-session outline of course content, and an initial partial identification of visual aid requirements.

The outline provided herein is available for further expansion and development into the full course.

TRAINING COURSE OBJECTIVES

The course objectives include the following:

1. Provide a generic understanding of the launch vehicle design process.
2. Provide an understanding of the roles and responsibilities of the individuals involved in the process.
3. Identify key aspects of the process and provide guidance for its effective implementation.
4. Provide an understanding of the current environment for launch vehicle design, its state of the art, and mandates for improvement.
5. Stimulate ideas to improve the design process and have participants take ownership of the process.

TRAINING COURSE OUTLINE

Space Transportation System Design

Session 1 Lecture
(Design Process Characterization)

1. Motivation for Course
   a. Center's role and Administrator's mandate
   b. Need for space transportation systems improvement
   c. Challenge of launch vehicle design
      -Energy density
      -Integration

2. The Design Process
   a. Design life cycle
   b. Specialization/compartmentalization/decomposition
   c. Overview of design process
   d. Stack chat
      -Planes
      -Gates
      -Tasks
   e. NXN diagram
   f. Balancing Act

Session 2 Workshop
(Requirements Development and Information Needs)

<u>Activities</u>
a. Define purpose/goals of workshop
b. Develop Integrated Product Teams (IPT)
   -Tank System
   -Structures
   -Propulsion & Avionics
   -Thermal
c. Each team develop design requirements for its area
d. Each team develop information needs (inputs)
e. Presentation of results by each team
f. Compare teams' results with our prepared list

TRAINING COURSE OUTLINE -- continued

Session 3 Lecture
(Characterization Continued)

1. Design process connectivity and sequencing

2. Essentials – (list from report)
   a. Parameter matrix and uncertainty
   b. Sensitivity
   c. Failure modes (risk vs consequences)
   d. Judgements

Session 4 Workshop
(Trade Study Simulation)

<u>Activities</u>

a. Define purpose and goals of workshop (trade studies)
   -Tank System
   -Structural elements
   -Material selection
   -TPS/insulation
   -Selection of propellant system components
b. Teams define concepts to be traded
c. Teams define steps of trade process
d. Teams determine results of trade study
e. Teams down select to baseline
f. Teams report results of activities
g. Compare teams' results with our prepared list

Session 5 Lecture
(Expand description of trade studies)

1. Illustrate design attributes and associated metrics

2. How design choices are achieved
   a. Routine choices
      -Choice obvious
      -Choice has minor effect on attributes
      -Use of standard techniques of monographs

   b. Major or difficult choice
      -Not obvious
      -Has major effect on attributes
      -Do trade study

3. Definition and scope of trade study

4. Dealing with uncertainties, sensitivities, and margins
   a. Uncertainty and sensitivity

   b. Margins
      -Define relationship to uncertainties, sensitivities, safety factors, reserves, etc.
      -Margin/sensitivity with technology choice
      -Progression of margin with maturity of design
      -Example of attributes with margins and allocations

5. Interactions among subsystems

6. Risk assessment
   a. Define for technical, cost, and schedule
   b. Example for tank

7. Judgements

Session 6 Workshop
(Interfaces, Interactions, and Uncertainties Simulations)

1. Activities

a. Define purpose and goals of workshop
b. Assume configuration resulting from trade study is inadequate
   -Components missing
   -Interfaces incompatible and interface requirements not defined
   -Performance not met
     --Subsystem interactions not completely defined
     --Parameter uncertainties not fully taken into account
c. Based on inadequacies listed in b., whole group determine course of action

2. Probable course of action

d. Brainstorm component list and interface issues
e. Delegates from subsystem groups meet to identify interactions
f. Subsystem groups revisit (or visit) means of handling uncertainties and margins
g. Outline "5-column chart"
h. Assume comparison of margins and attributes with allocated requirement
i. List changes identified in comparison to baseline

Session 7 Workshop
(Lessons Learned and Improvements Thrusts)

Activities

Teams and entire group develop lessons learned and recommendations for process improvements
- -Each IPT
- -Group

Session 8 Lecture
(Approaches for improving space transportation systems)

1. Develop new hardware and software technologies
   a. Propulsion systems
   b. Structural systems
   c. Avionics systems
   d. Methods to manage losses

2. Develop new design process technologies
   a. Fine tune current design process---evolutionary
      -Data management
      -Electronic communications
      -Organizational structures
      -Parallel processing
      -Industrial specialization
      -Requirements management
   a. Subsystem seamless design process
      -For example; implement seamless structural design by unifying formulation of trajectory, control, stress, thermal, etc. analyses for specific mission events, i.e., lift off, max Q, docking, landing, etc.
   b. Total seamless design process------revolutionary
      -Approaches such as:
        --Virtual reality
        --Knowledge base expert systems
        --Inverse analyses

PARTIAL LIST OF VISUAL AIDS

A large number of visual aids will be required for teaching the course. These charts and forms will be developed as the detailed course is developed; however, material from previous work (in the References) will provide a significant initial resource from which the material may be drawn. In outlining the course sessions, a preliminary partial list of visual aids was identified, primarily from the reference documents, along with known sections of visual material that will need to be created. The following pages provide that initial list, with the existing charts being reproduced in reduced size to visually summarize the session content.

Chart - Need for Transportation Systems Improvement
(New, TBD)

Chart - Administrator's Mandate; Center's Role
(New, TBD)

Chart - Technology Areas to be Improved - Hardware/Software, Process
(New, TBD)

Chart - Course Objectives
(New, TBD)

Chart - Course Outline
(New, TBD)

Charts for Session I, 1a and 1b — Plus New Charts, TBD

Launch Vehicle Design Process
INTRODUCTION – DESIGN PROCESS SCENARIO

•Mission Statement: Insert a Specified Payload into a Specified Orbit To the Required Tolerances, within Cost, Reliability, Safety, Schedule and Operability Requirements and Operability Requirements

• Engineering Challenges:

·Design & Management Considerations

1. High Energy Densities
2. Propulsion Efficiency
3. Dry Weight Efficiency
4. Managing Losses
   a. Uncertainty
      e.g. Manufacturing Variables
      · Environmental Variables
   b. Interaction
      e.g. Multidisciplinary
      · Interfaces
      · Operations
   c. Failure to meet TRL Target

Design To Achieve

Project Requirements:

1. Performance
2. Cost
3. Reliability
4. Safety
5. Operability
6. Schedule

July 27, 1999

4

Challenge / Energy Chart
(New, TBD)

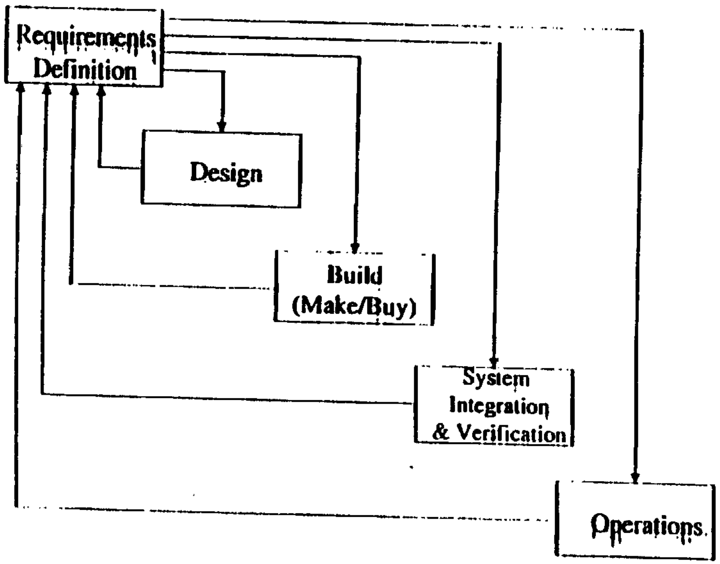
Challenge / Energy Chart
(New, TBD)

Challenge / Integration Chart
(New, TBD)

Challenge / Integration Chart
(New, TBD)

Charts for Session I, 1c-- Plus New Charts, TBD

Vehicle Life Cycle Flow Chart



July 27, 1999

6

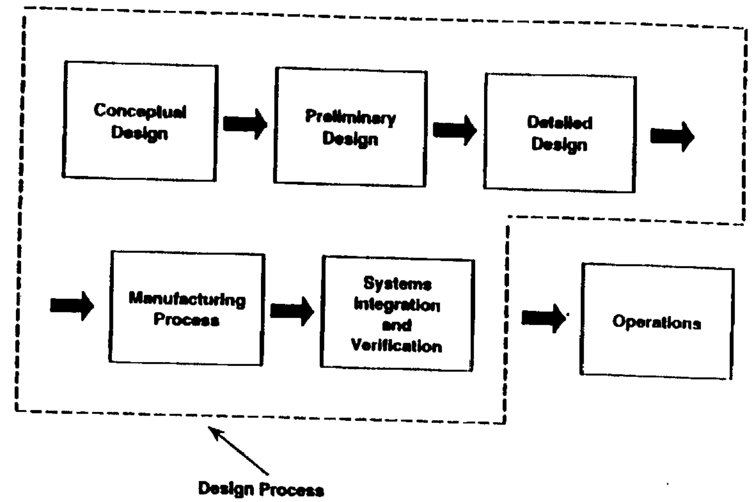
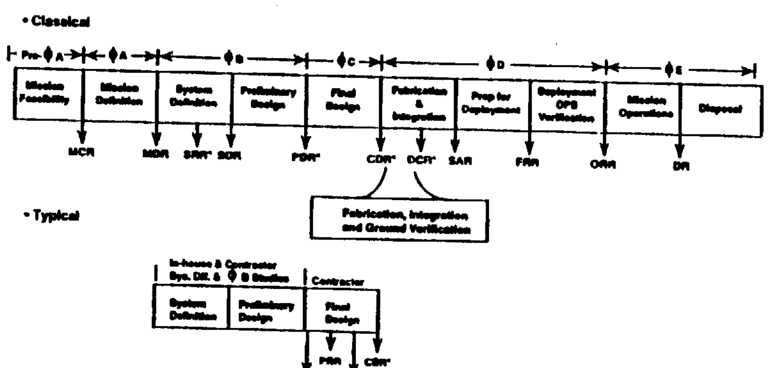


Figure 4.1-1 Systems Engineering – Project Stages



* CDR - Critical Design Review
* DCR - Design Certification Review
DR - Disposal Review
FRR - Flight Readiness Review
MCR - Mission Concept Review
MDR - Mission Definition Review

ORR - Operational Readiness Review
*PDR - Preliminary Design Review
PRR - Preliminary Requirements Review
SAR - System Acceptance Review
SDR - System Definition Review
*SRR - System Requirements Review

Figure 4.1-2 Major Project Phases

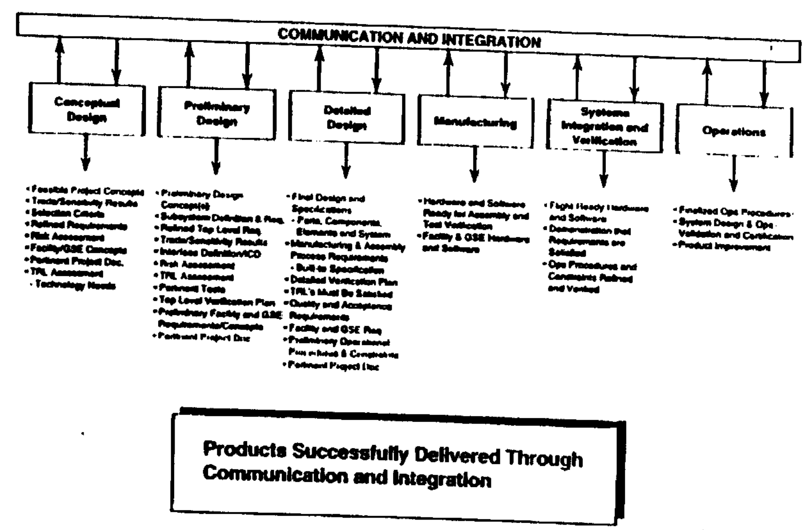


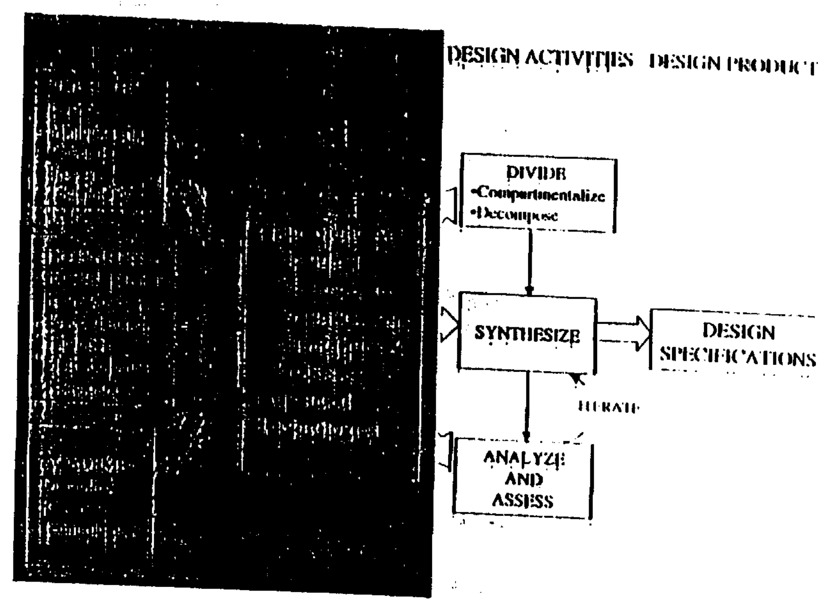
Figure 4.1-3 System Engineering – Project Main Products

Charts for Session I, 2a– Plus New Charts, TBD

Launch Vehicle Design Process

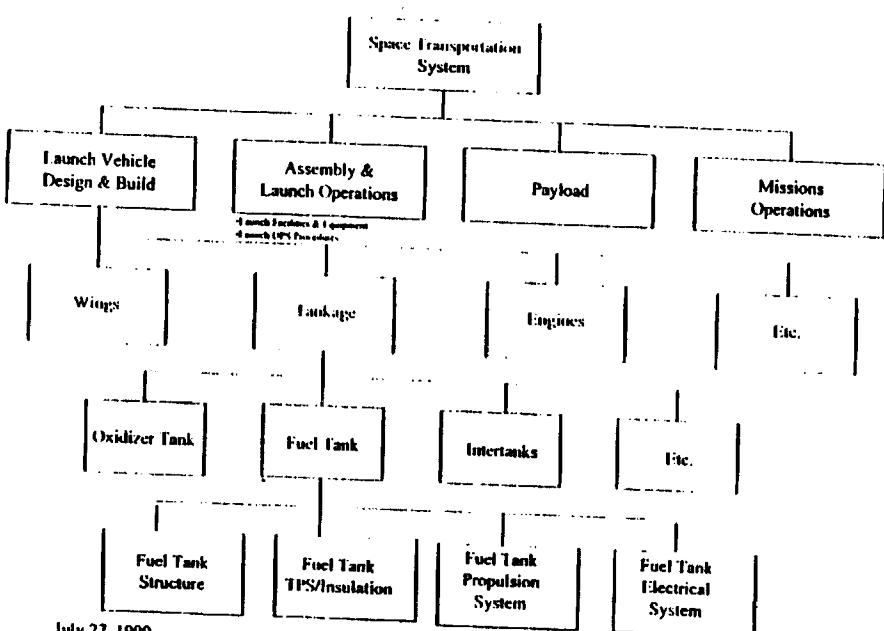
Compartmentalization, Decomposition, and Technical Integration

- Aerospace Infrastructure And Specialization
- Compartmentalization, Decomposition, And Reintegration
- Example
- Technical Integration Of System, Design, And Discipline Functions



July 27, 1999

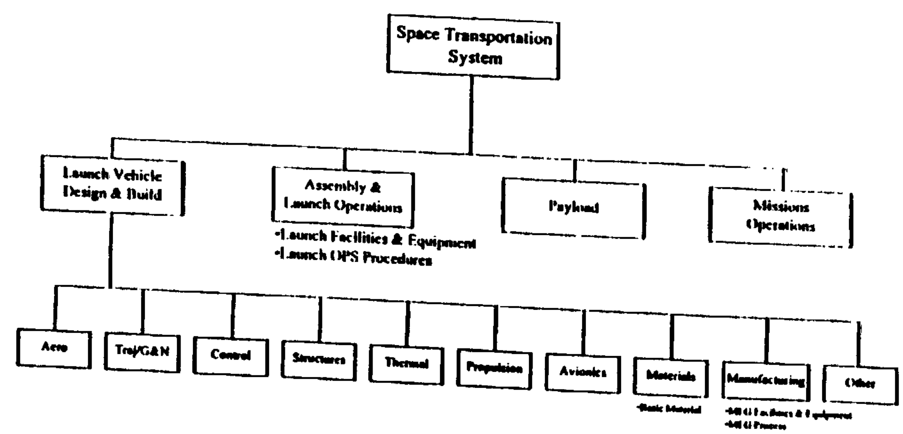
13



July 27, 1999

Example of Industrial Compartmentalization

14

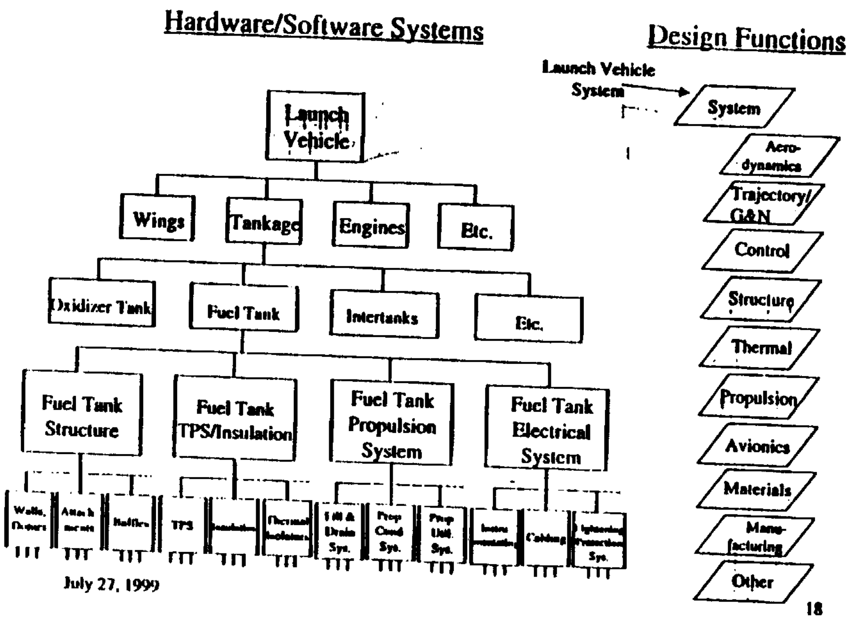


July 27, 1999

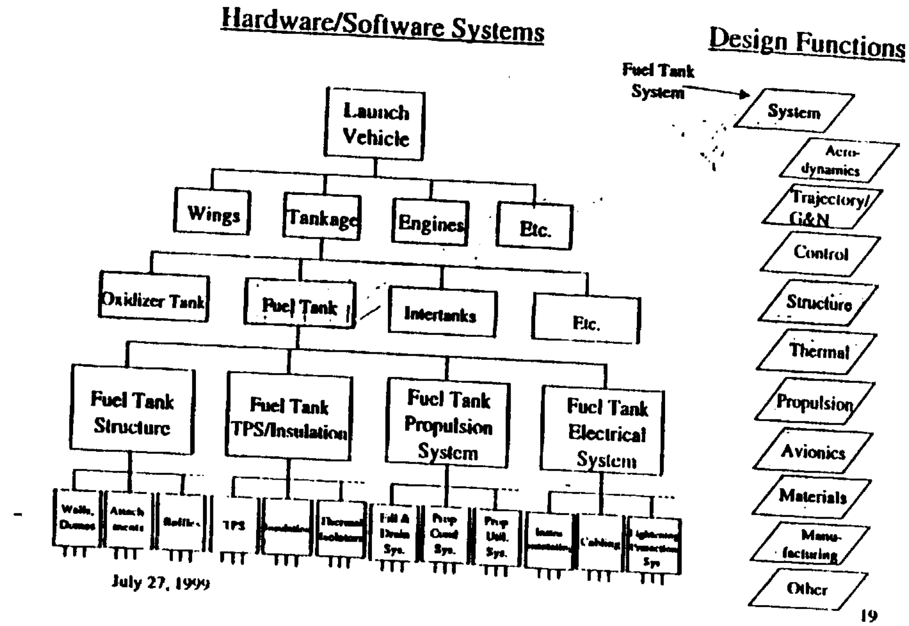
Top-Level Design Function Compartmentalization

Charts for Session I. 2b-- Plus New Charts TBD

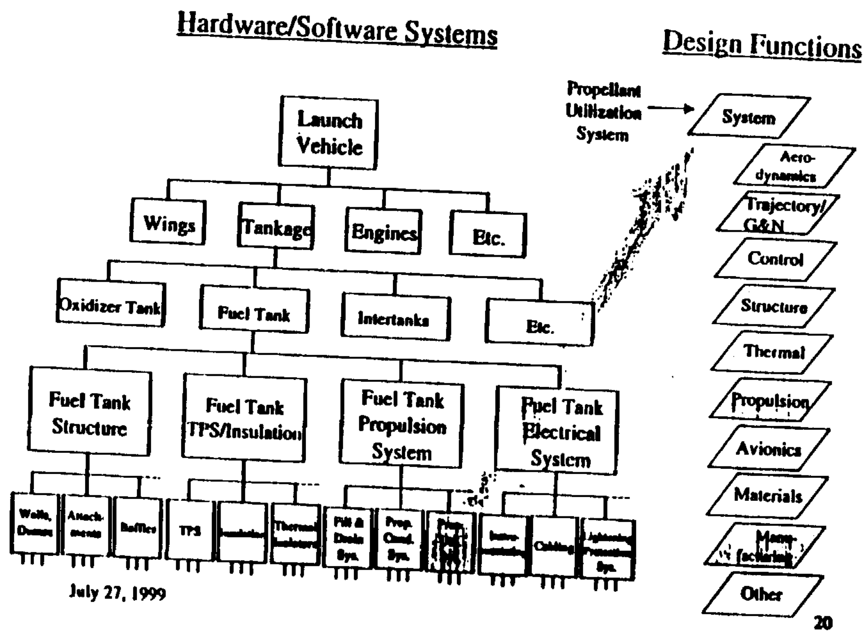
Example Compartmentalization - Launch Vehicle



Example Compartmentalization - Fuel Tank



Example Compartmentalization - Propellant Utilization System



Charts for Session I, 2b-- Plus New Charts, TBD

Launch Vehicle Design Process

Definitions

- **Subsystem compartmentalization: Based on Industrial Specialization**
  - -Physical Vehicle System Subdivided into a Number of Subsystems and So On
    - --Subsystems Composed of Hardware and/or Software
  - -Design Functions Subdivided to Provide Design Specification for the Hardware and/or Software Subsystems
    - --E.G. Systems, Structures, Propulsion, Avionics, Etc.
- **Design Functions**
  - -Designers Conceive Candidate Subsystem Configurations which are Assessed to Determine Design Attributes, i.e., Performance, Cost, Etc.
  - -Designers Products are Hardware and Software Drawings and Specifications which Define Their Subsystem
    - --E.G. Systems Design Function, Structures Design Functions, Etc.
- **Discipline Functions**
  - -Disciplines are Technical Areas of Specialization; They Perform Analyses, Simulations, Tests, Etc. for a Given Subsystem Design
    - --E.G. Structural Analyses
      - a. Structural Dynamics
      - b. Stress
      - c. Durability
      - d. Vibroacoustics

17

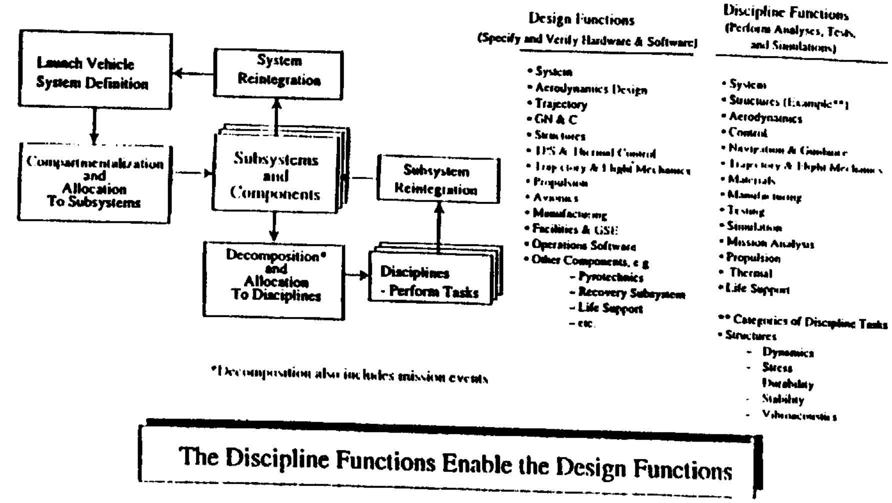


Figure 2.1-4 Design Process Compartmentalization/Decomposition/Reintegration

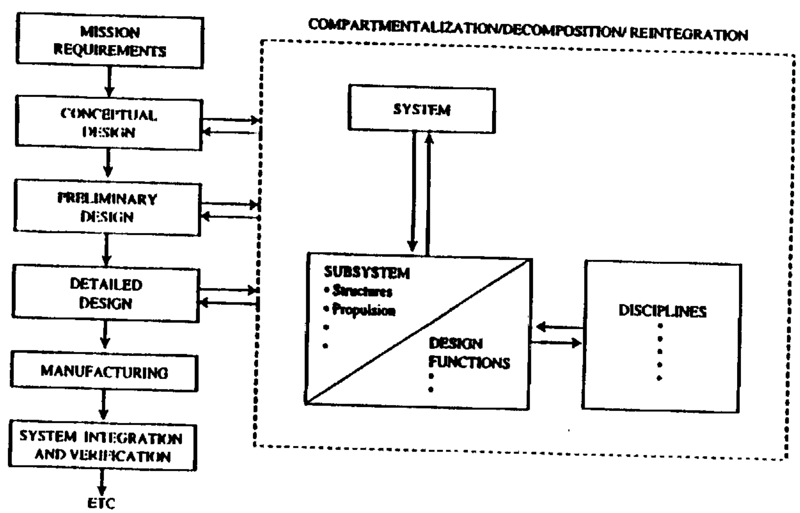
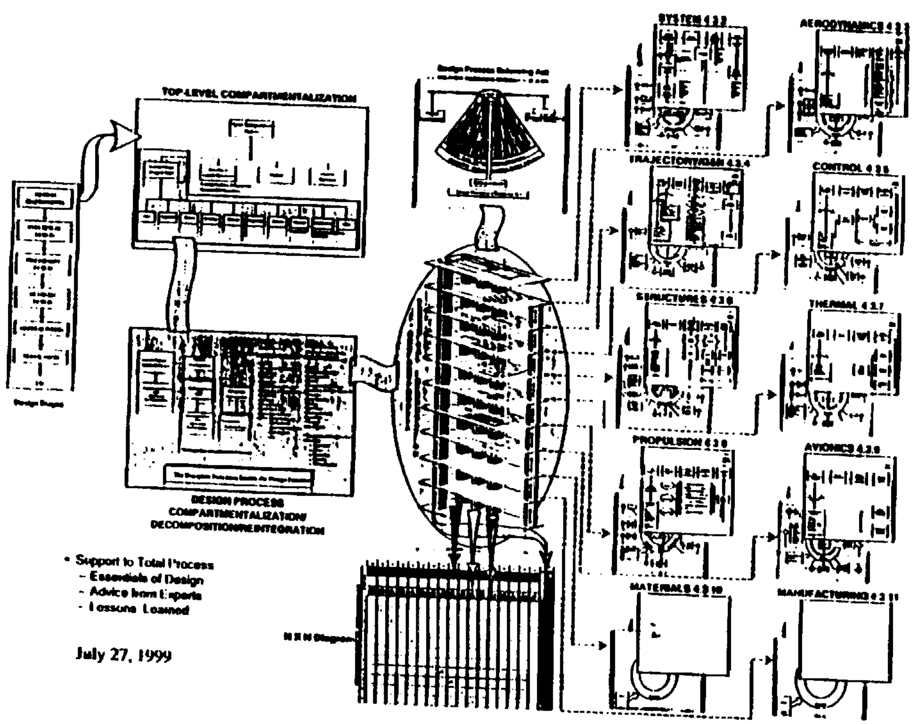


Figure 2.1-8 Design Process Flow Summary

Charts for Session I, 2b-- Plus New Charts, TBD



• Support to Total Process
  - Essentials of Design
  - Advice from Experts
  - Lessons Learned

July 27, 1999

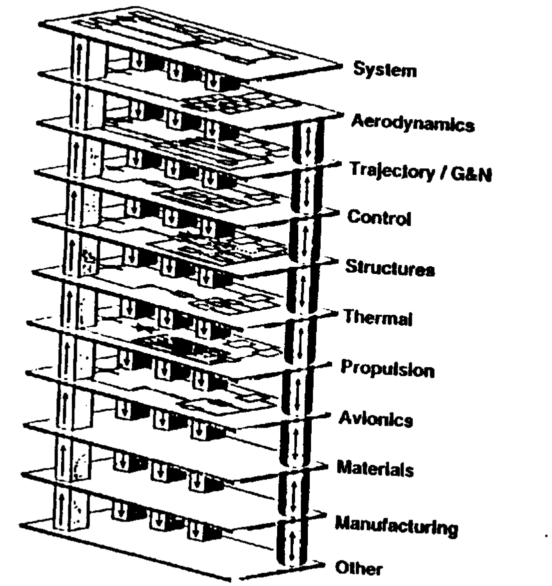
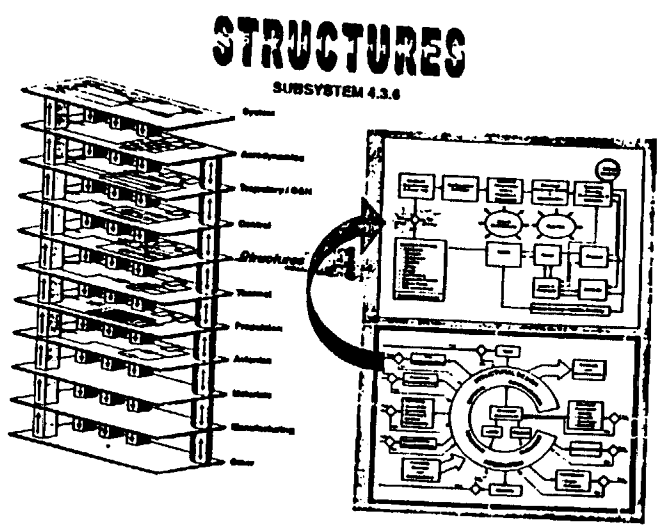


Figure 2.1-5 Technical Integration of System, Design, and Discipline Functions



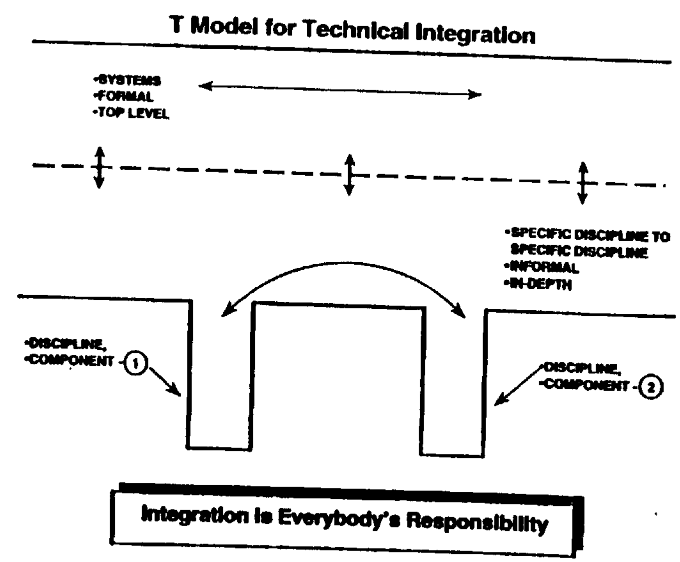


Figure 4.2-1 Technical Integration – T Model

Charts for Session I, 2c and 2d— Plus New Charts, TBD

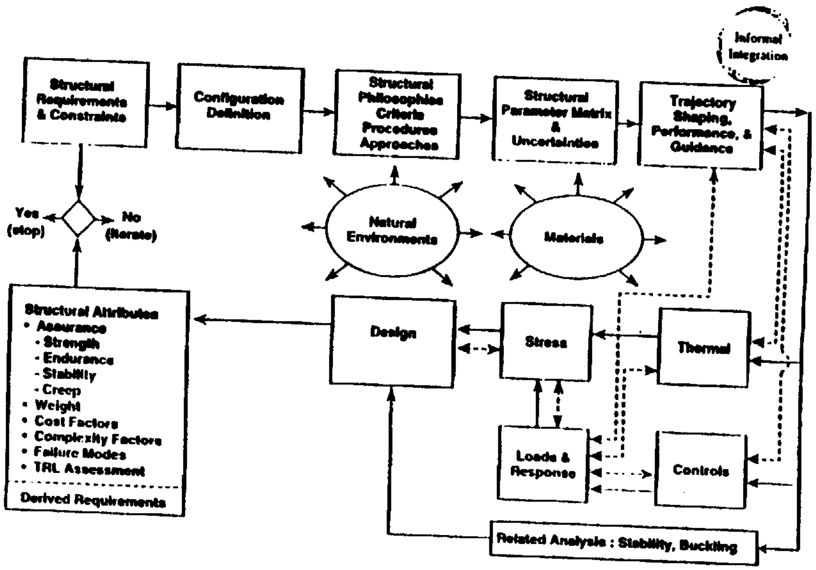


Figure 4.3.6-1 Structures Design Function Plane

Multidisciplinary Activity	Interacting Disciplines	Tasks
III. Detailed Stress Analysis	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
IV. Detail 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 update design to accommodate requirements change, reduced margins and issues. Provides trade date and recommendations to program on issues.
V. 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. Flow up anomalies to system for design changes or changes in operational constraints and procedures 4. Final structural validation achieved in development flight tests.

Figure 4.3.6-7 Structures Design Function Tasks – continued

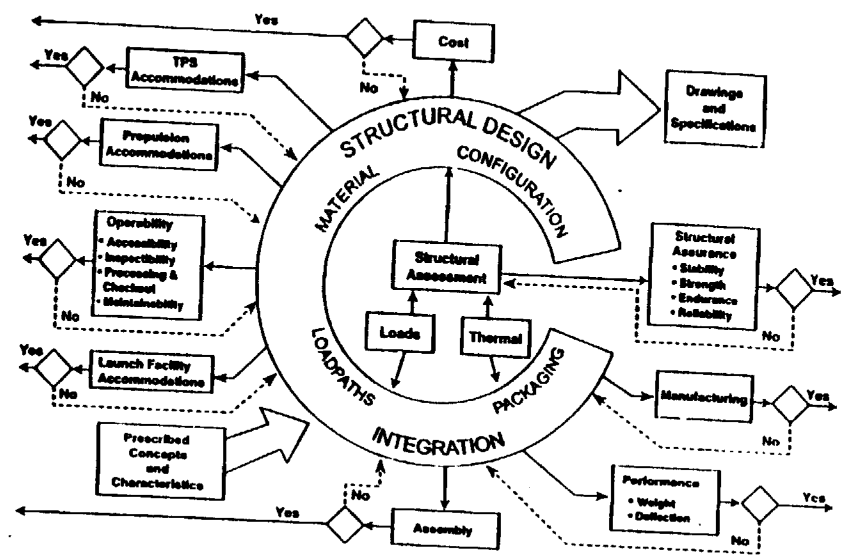
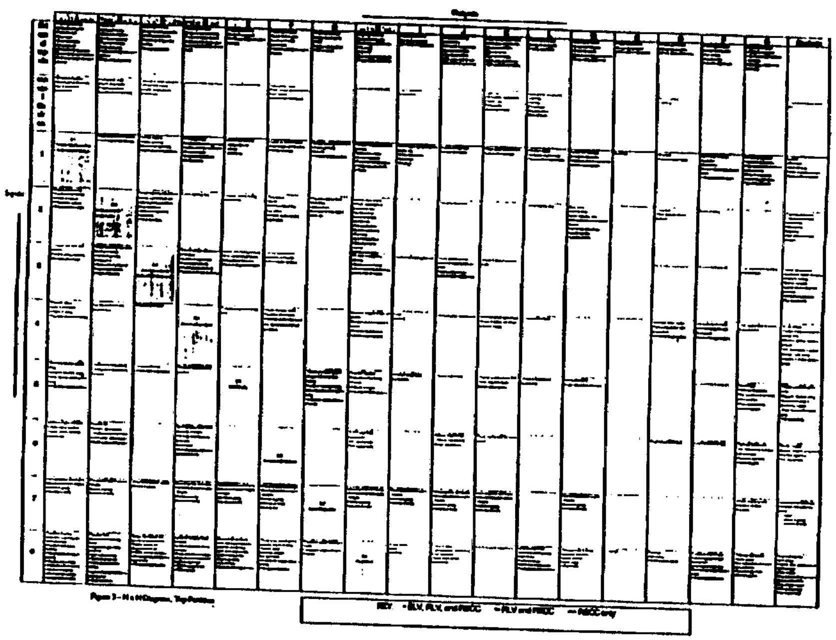


Figure 4.3.6-3 Structure Design Function Gates

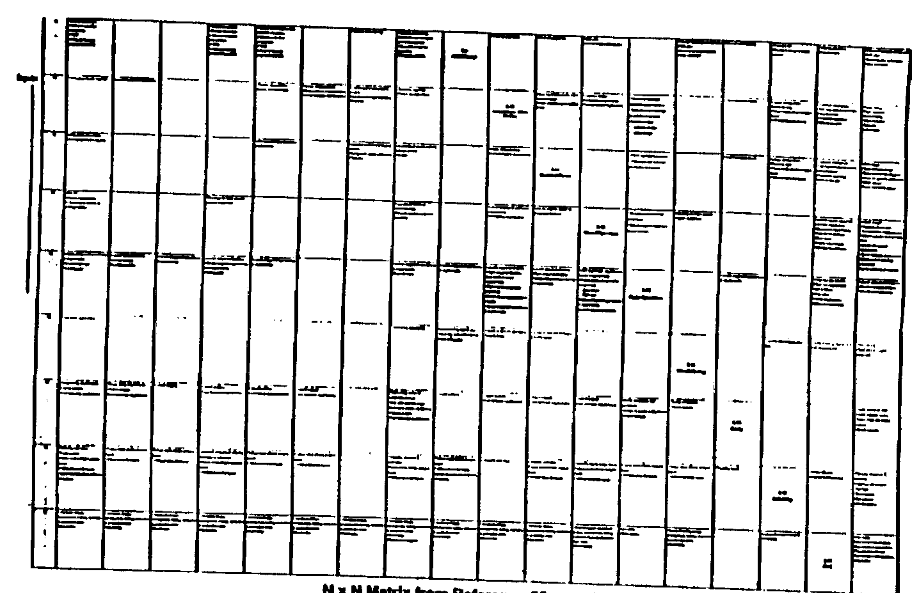
Multidisciplinary Activity	Interacting Disciplines	Tasks
I. Requirements Allocations	Mass Properties System Control Trajectories Materials Propulsion Aerodynamics	1. Consult with system to obtain operations philosophy, constraints, cost, mass fraction, etc. 2. Obtain initial configuration definition 3. Provide to systems, 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
II. Performance 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 "g", 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

Figure 4.3.6-6 Structures Design Function Tasks

Charts for Session I, 2d– Plus New Charts, TBD



NxN Matrix from Reference 68



N x N Matrix from Reference 68 - continued

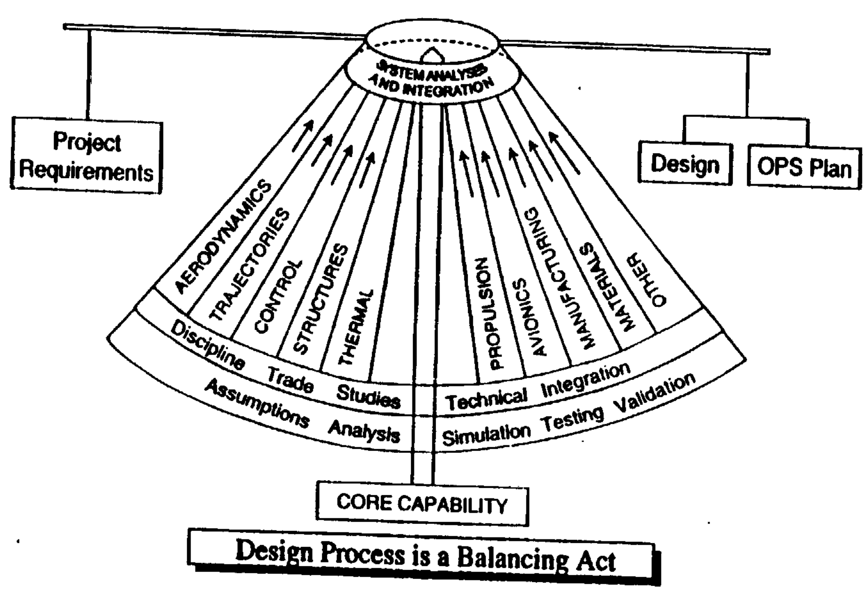


Figure 4.3.1-2 Design Process Balancing Act

Charts for Session I, 2e and 2f-- Plus New Charts, TBD

Charts - Workshop Definition - Requirements Definition and Information Needs (New, TBD)

TYPICAL FUEL TANK REQUIREMENTS

Top-Level System Requirements	Environmental Accommodation

Weight
Mass fraction
Cost
Reliability
Safety
 	
Geometric Characteristics
 	
System configuration
Volume of propellants
    LH2
    LOX
Length
Diameter
SRB/Orbiter connections
Aerodynamic shape
c.g. position
	Loads
	    Internal pressure
	    Flight loads
	    Cryoshrinkage
	    Transportation and handling loads
	Thermal
	    In-flight aeroheating
	    Propellant conditioning
	    Ice/frost avoidance
	    Thermal isolation for attachments
	    Compartment temperature requirements
	Ability to withstand on-pad and in flight weather
	    Rain
	    Wind
	    Salt spray
	    Lightning
	Aerodynamic venting
	Protuberance accommodation

TYPICAL TANK REQUIREMENTS - continued

Materials Requirements	Requirements from Other Systems

Materials availability
Materials properties limitations
Materials compatibility with LOX and LH2
Compatibility with EPA regulations
 	
Requirements from Propulsion System
 	
Propellant types, densities
Purge system requirements
Fill and drain system requirements
    Flow rates
    Minimum ullage volume
    Level sensors
    Diffusers
Propellant conditioning requirements
    Temperature limits
    Pressurization, pressure maintenance
Feed system requirements
    Flow rates
    Anti-vortex baffle and siphon
Propellant utilization system requirements
    Level and depletion sensors
Other instrumentation
Supporting electronic systems
	Minimum pressure requirements for structural stability
	Anti-slosh baffles
	Umbilicals and disconnects
	Range safety destruct system
	Separation system
	
	Operational Constraints
	
	Capable of being handled without damage to insulation
	Access provisions
	<u>Verification</u>
	<u>Transportation</u>
	<u>Assembly</u>
	<u>On-Pad</u>
	    Hazardous gas protection
	        Hazardous gas detection
	        Facility purge gas supply
	        Accommodation of LH2 boiloff
	    Ice/frost debris avoidance
	<u>In-flight</u>
	    Debris avoidance

R-4

TYPICAL TANK REQUIREMENTS - continued

Manufacturing Constraints	Interface Characteristics (ICD's) Structural, Fluid, Electrical

Facility availability
Facilities compatibility
    Dimensions—Maximum diameter, etc.
Manufacturing processes constraints
    Forming, machining, welding, etc.
 	
Verification Requirements
Strength tests
Dynamics tests
Vibroacoustics tests
Fracture tests
TPS integrity tests
Functional tests
    Valves, instrumentation
    Propulsion system tests
    Etc.
	ICD's with other vehicle elements; Assembly, Storage, & Processing Facilities; Launch Pad, LPS Computational System
	
	Discipline-Imposed Requirements
	
	Structures requirements and criteria – includes fracture control
	Thermal criteria and philosophy
	TPS criteria
	    Strength
	    Performance
	Materials characterization criteria
	Materials compatibility requirements

TYPICAL TANK REQUIREMENTS - continued

Additional Requirements for Cryotank Reusability

Additional service life for tank structure, insulation, TPS, and components
    Design for fatigue and fracture over full service life

Inspectability for required between-use inspections

Ability to clean before reuse

Insulation and TPS integrity assurance before reuse

Ability to refurbish components subject to failure (e.g., valves, instrumentation)

If tank structure is composite,
- Damage tolerance
- Damage-evident
- Permeability limits
- Composite-metal joints
  - Accommodation of thermal expansion and contraction

Reproof periodically

Charts for Session 2, Plus New Charts, TBD

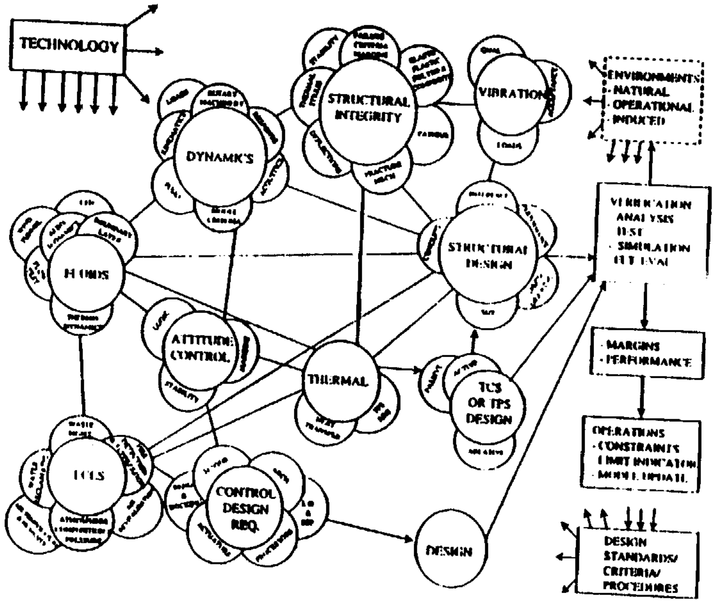


Figure 2.1-6 Design/Discipline Interactions

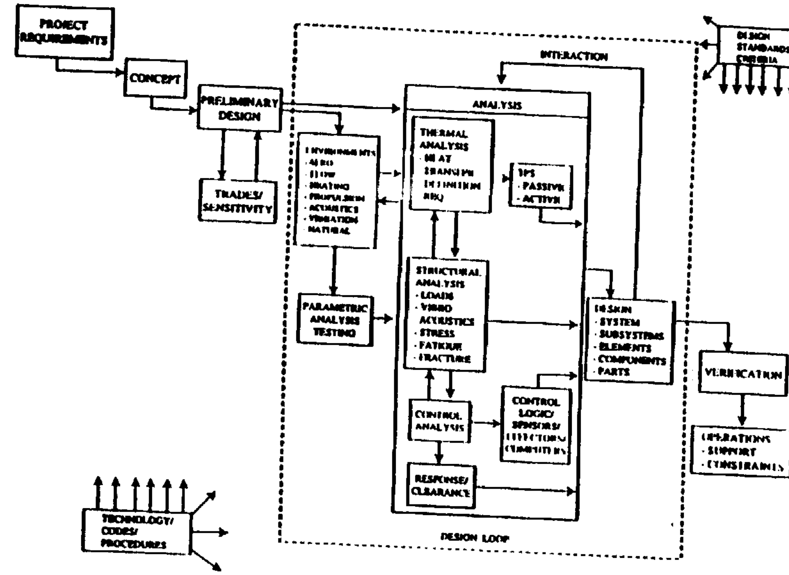
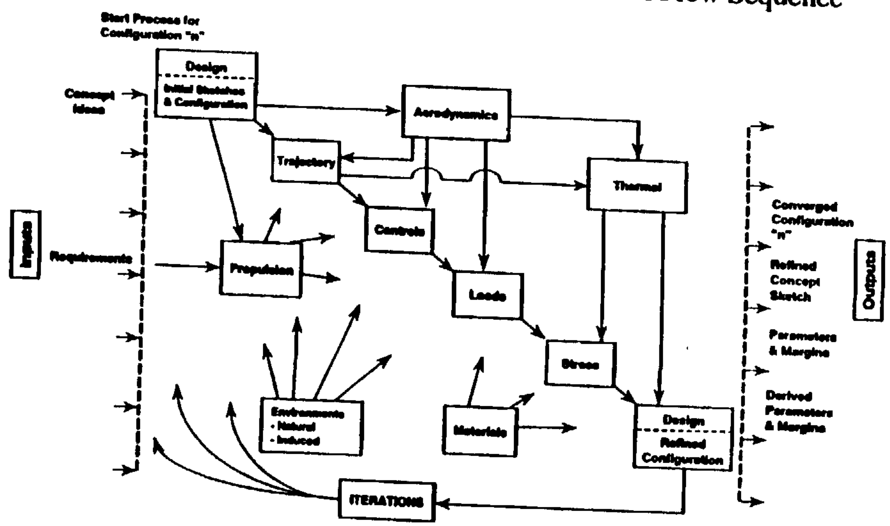
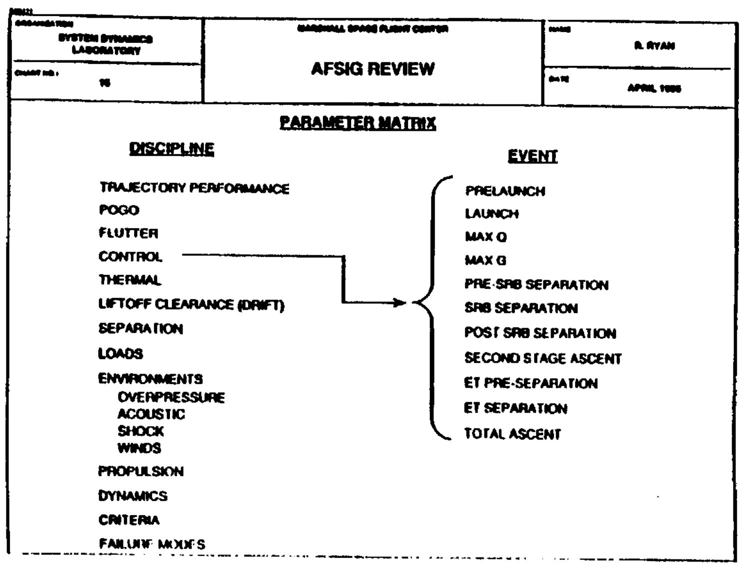


Figure 2.1-7 Structural Design Process Flow

Conceptual Design Phase – Sizing and Functional Flow Sequence



Charts for Session 3, Part 1 – Plus New Charts, TBD



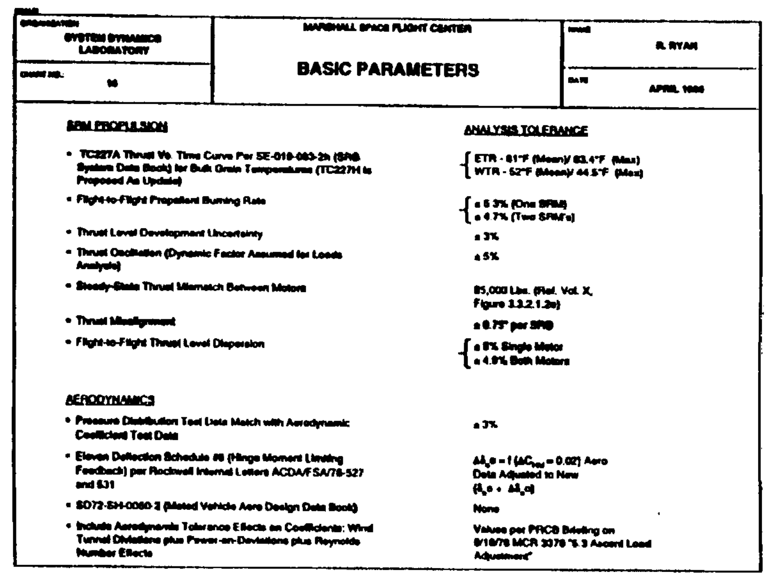
SYSTEM DYNAMICS LABORATORY | MARSHALL SPACE FLIGHT CENTER | R. RYAN

CHART NO. 16 | AFSIG REVIEW | APRIL 1986

PARAMETER MATRIX

DISCIPLINE	EVENT
TRAJECTORY PERFORMANCE	PRELAUNCH
POGO	LAUNCH
FLUTTER	MAX Q
CONTROL	MAX G
THERMAL	PRE-SRB SEPARATION
LIFTOFF CLEARANCE (DRIFT)	SRB SEPARATION
SEPARATION	POST SRB SEPARATION
LOADS	SECOND STAGE ASCENT
ENVIRONMENTS	ET PRE-SEPARATION
OVERPRESSURE	ET SEPARATION
ACOUSTIC	TOTAL ASCENT
SHOCK	
WINDS	
PROPULSION	
DYNAMICS	
CRITERIA	
FAILURE MODES	

Figure 6.2-3 Space Shuttle AFSIG –Example Parameter Matrix Event



SYSTEM DYNAMICS LABORATORY | MARSHALL SPACE FLIGHT CENTER | R. RYAN

CHART NO. 16 | BASIC PARAMETERS | APRIL 1986

SRM PROPULSION	ANALYSIS TOLERANCE
• TC227A Thrust Vs. Time Curve Per SE-019-083-2h (SRB System Data Book) for Bulk Grain Temperatures (TC227H is Proposed As Update)	ETR - 61°F (Mean)/ 83.4°F (Max); WTR - 52°F (Mean)/ 44.5°F (Max)
• Flight-to-Flight Propellant Burning Rate	± 5.3% (One SRM); ± 4.7% (Two SRM's)
• Thrust Level Development Uncertainty	± 3%
• Thrust Oscillation (Dynamic Factor Assumed for Loads Analysis)	± 5%
• Steady-State Thrust Mismatch Between Motors	85,000 Lbs. (Ref. Vol. X, Figure 3.3.2.1.2a)
• Thrust Misalignment	± 0.75° per SRB
• Flight-to-Flight Thrust Level Dispersion	± 8% Single Motor; ± 4.9% Both Motors
AERODYNAMICS	
• Pressure Distribution Test Data Match with Aerodynamic Coefficient Test Data	± 3%
• Elevon Deflection Schedule #6 (Hinge Moment Limiting Feedback) per Rockwell Internal Letters ACDA/FSA/78-527 and 531	$\Delta\delta_e\alpha = f(\Delta C_{hel} = 0.02)$ Aero Data Adjusted to New $(\delta_e\alpha + \Delta\delta_e\alpha)$
• 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 9/18/78 MCR 3078 "5.3 Ascent Load Adjustment"

Figure 6.2-4 Space Shuttle AFSIG – Example Parameter Variations

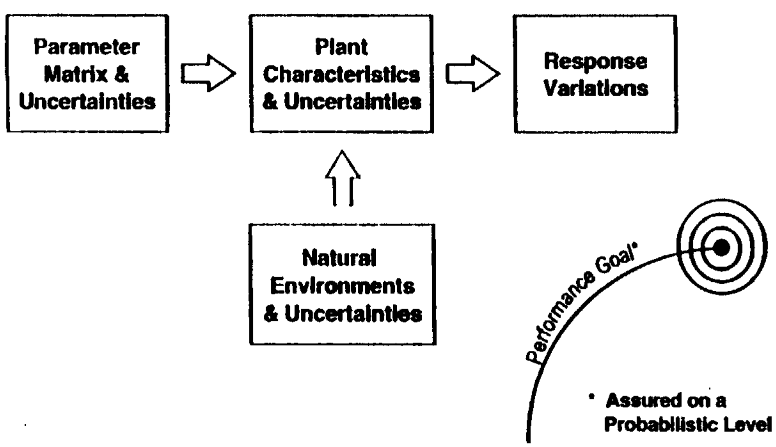


Figure 6.2-7 Overall Concept for Flight Mechanics

Charts - Parameter Matrix and Uncertainties

Chart - Essentials
(New, TBD)

Chart - Sensitivity
New, (TBD)

Chart - Risk/Consequences
New, (TBD)

Charts - Judgements -Ref. "Probing Questions"
New, (TBD)

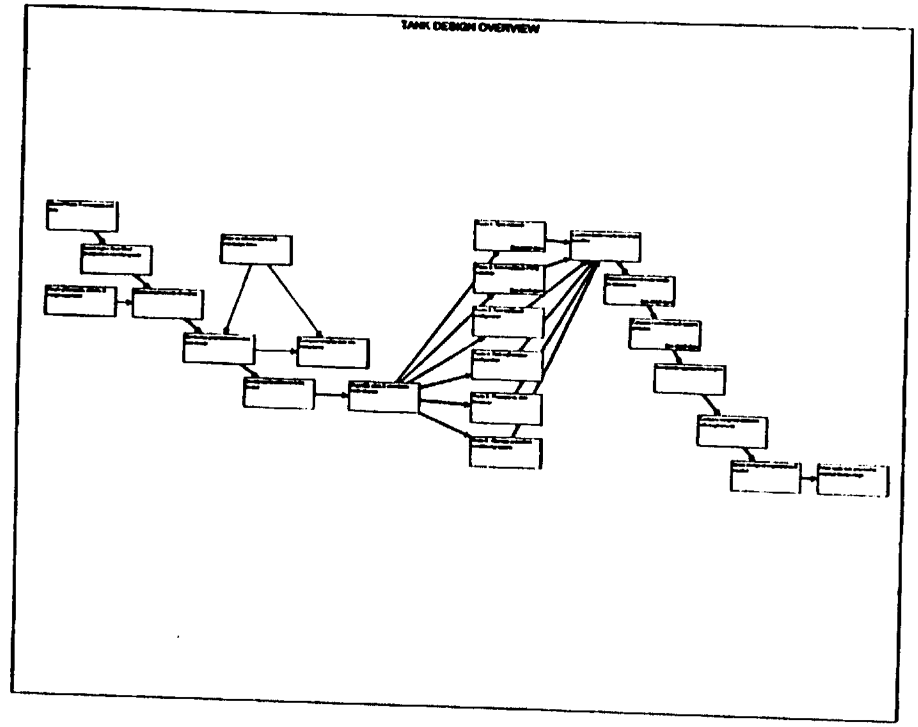
Charts for Session 3, Part 2 – Plus New Charts, TBD

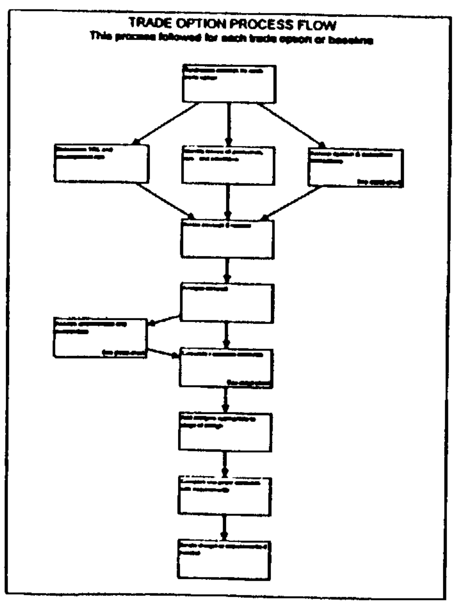
Charts - Workshop Definition - Trade Studies (New, TBD)

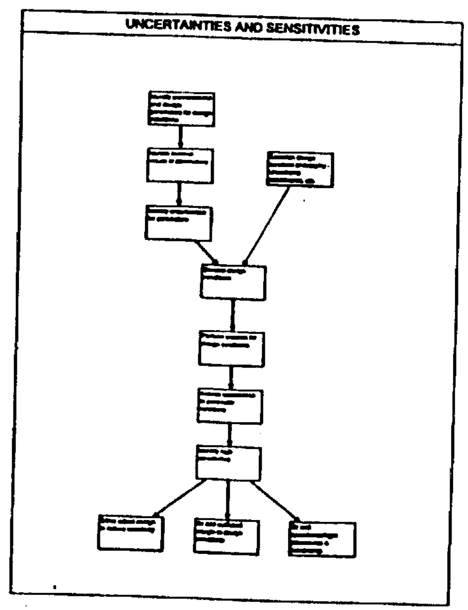
TRADE STUDIES

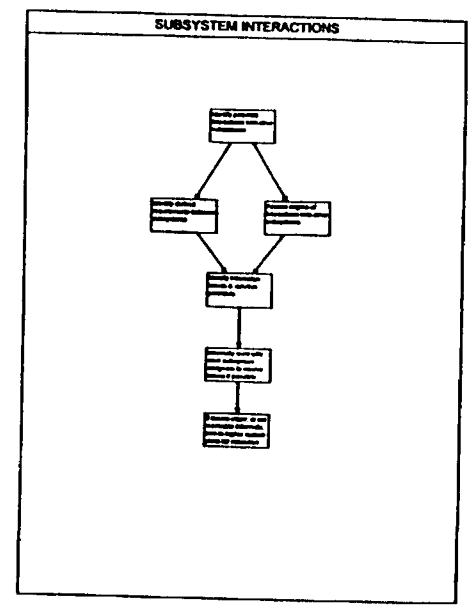
- Design issues involving the more significant choices of design variables require trade studies to identify the best options
- Trade studies involve considerable analysis (and possibly tests)
- Results of one trade study can influence outcomes of other trades
- Potential trade studies for the tank design example include
  - Tank material selection*
  - Tank insulation / TPS selection*
  - Bulkhead configuration
  - Wall section configuration
  - Pressure vs. skin thickness
  - Alternate propellant conditioning system configurations

* The first two trade studies are detailed in Design Task Sequence section

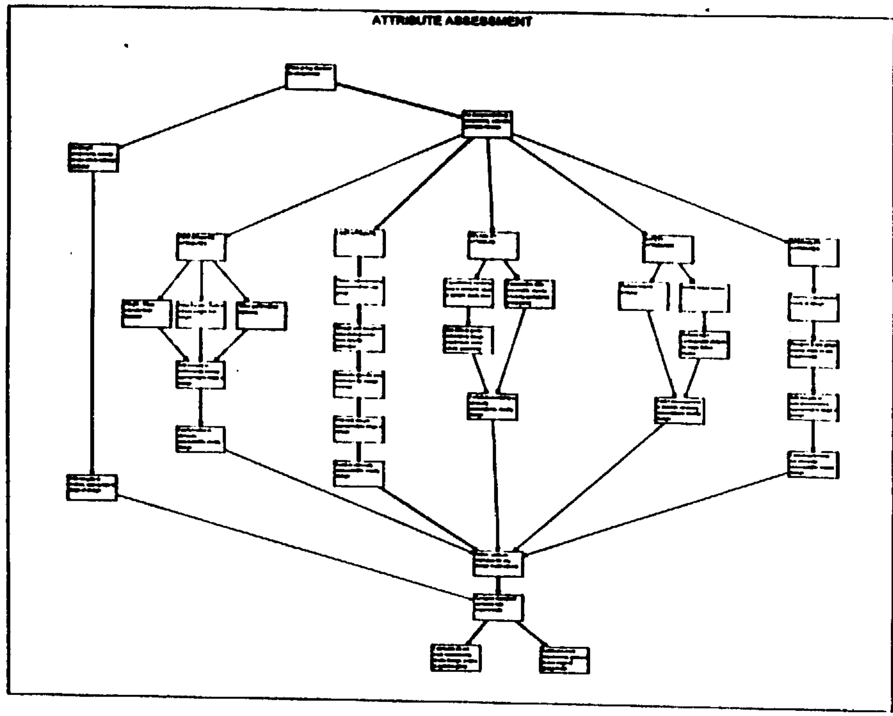


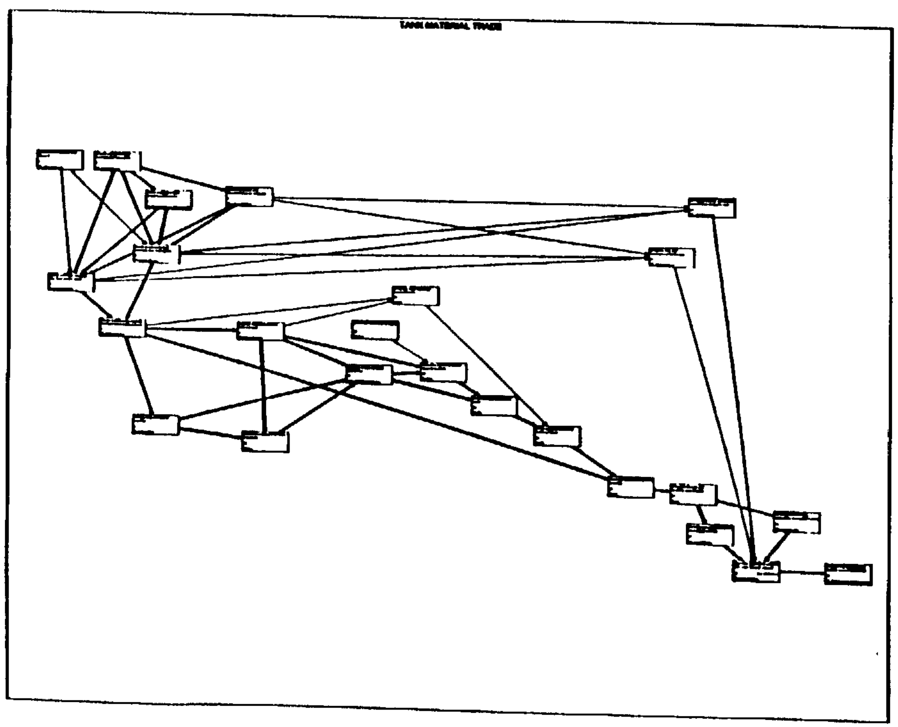


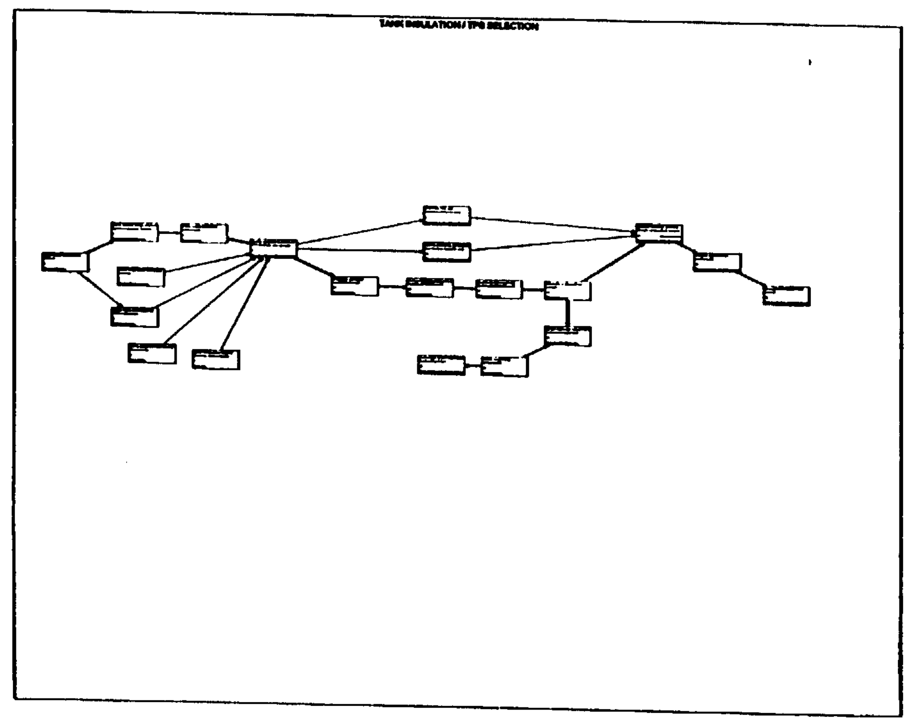




Charts for Session 4, Plus New Charts, TBD







Charts for Session 4, continued, Plus New Charts, TBD

DESIGN ATTRIBUTES

Attributes [Design characteristics viewed from system level]	Metrics [Measures of the attributes]
Performance Attributes	
A. Structure	
Tank weight	Pounds
Tank mass fraction	Usable propellant weight / Tank gross weight (full)
B. Insulation / TPS	
Ascent/reentry aeroheating level accommodated	Q; Q-dot ?
Natural environment temp/humidity range accommodated	Degrees; RH
Damage tolerance (rain, hail, handling, etc.)	High/Medium/Low
Insulation / TPS weight	Pounds
C. Fill, drain, and purge system	
Time to purge, fill, drain	Minutes
System weight	Pounds
D. Propellant Conditioning and Pressurization System	
Propellant pressure / temperature limits maintained	Psi / degrees
Tank structural pressure limits maintained	Psi
System weight	Pounds
E. Propellant Utilization System	
Minimum propellant residuals	Pounds
Maximum propellant residuals	Pounds
System weight	Pounds

A-3

DESIGN ATTRIBUTES - continued

Attributes	Metrics
Performance Attributes - continued	
F. Slosh Baffles	
Minimum damping provided (function of fill level)	Percent of critical damping
Weight of baffles	Pounds
G. Other Systems (as required)	
Technology Maturity Attributes	
Technology Maturity	TRL number
Development Risk	High/Medium/Low Risk
Cost Attributes	
Development cost	$
Production and assembly cost of first unit	$
Recurring cost of reuse	$ per flight
Reliability Attribute	
Reliability	Estimated probability of no failure

A-4

DESIGN ATTRIBUTES - continued

Attributes	Metrics
Safety Attributes	
Hazards	Number and severity of hazards
Failure modes	Number and severity of failure modes (On-ground; In-flight)
Operability Attributes	
Turnaround time between flights	Days
*Amount of labor required for turnaround**	*Man-hours*
*Skills required for turnaround**	*Number and levels of technician skills*

**Italicized items also factor into cost attribute.*

A-5

Charts - Design Attributes and Metrics

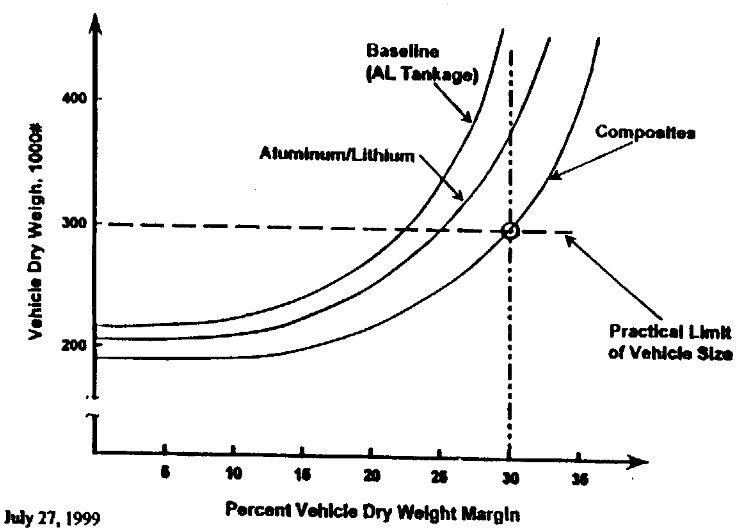
Charts - How are Design Choices Made New, (TBD)

Chart - Definition & Scope of Trade Studies New, (TBD)

Charts for Session 5, Plus New Charts, TBD

Charts - Dealing with Uncertainties, Sensitivities, and Margins New, (TBD)

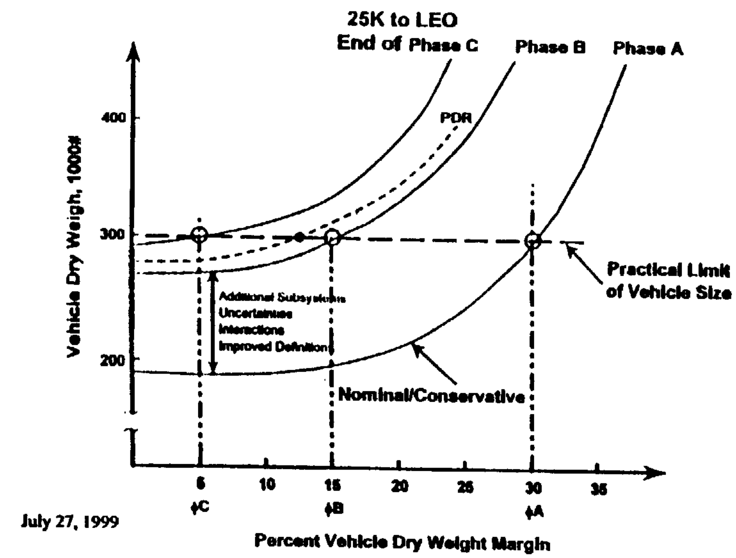
SSTO Metric Example: Impact of Technologies - ϕA



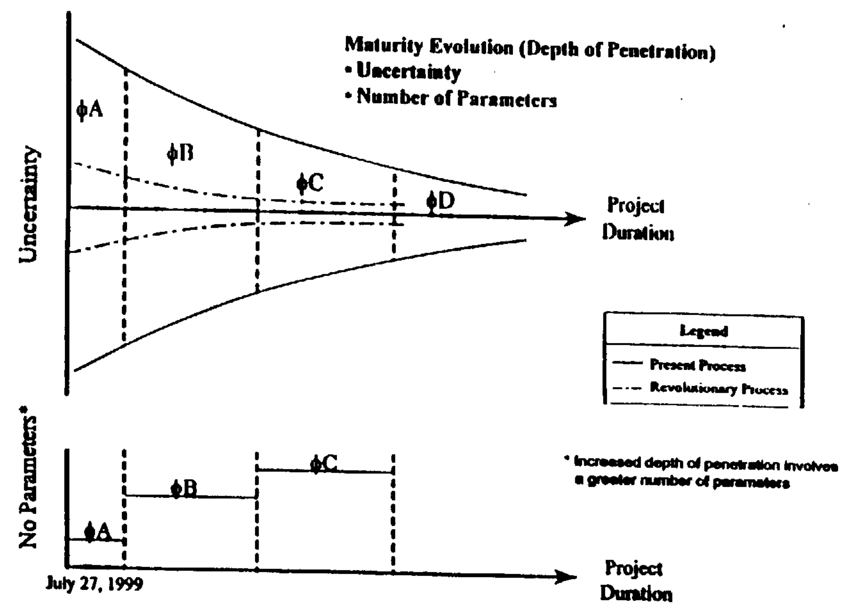
July 27, 1999

Chart - Five-Column Attributes/Metrics/Margins/ /Allocations/ Margined Attributes Numerical Example - Tank New, (TBD)

STTO Metric Example: Idealized Impact of Design Phases



July 27, 1999



July 27, 1999

Chart - Risk Assessment – Technical/Cost/Schedule
New, (TBD)

Chart - Risk vs. Consequences - Tank Example
New, (TBD)

DEFINITION OF METRICS
Factors for Judging Maturity and Margins

DESIGN PHASE

	A	B	C
• Sensitivity - Magnitude - Rate ②	Trends	Quantification of Trends	Quantified ①
• Interactions	Flight Performance - Rules Of Thumb	Identified - Other Systems ③	Quantified ④
• Control Of Environment		Baseline Potential Approaches ④	Select, Integrate, And Quantify
• Number Of TRL's ≥ 6	Less Than 2	Quantify	Mature To Acceptable Level ③⑤
• Pedigree of Data - Assumptions - Analyses & Simulation Tests	Historical Course Limited ⑦	Quantified ⑥ 80% Pedigree Start Development Test	Verified Comprehensive ⑦ Complete Dev. Test
• Drawings & Specifications	Vu Graph	Overall System and Subsystem Layouts	Detail Drawing - 10% BDR Release ⑧ - 90% CDR

① If unacceptable, iterate (Judgement)
② e.g. Load Relief
③ Technology Test
④ Specific for a Vehicle
⑤ Verification Of All Analyses Relating To Hardware/Software Completed in φD
⑥ All Discipline Gates Satisfied φCA φD
⑦ e.g. Pogo, Flutter, Controllability/Control Stability, Sloshing, Others Evolve From Analysis/test
⑧ Closeness to CDF Nonlinearity

Charts for Session 5, continued, Plus New Charts, TBD

Charts - Workshop Definition -
Interfaces, Interactions, and Uncertainties Simulations
(New, TBD)

Chart - Simulation Assumptions
(New, TBD)

Chart - Stimulation of Action Plan
(New, TBD)

Charts for Session 6, Plus New Charts, TBD

Charts - Workshop Definition -
Lessons Learned and Improvements Thrusts
(New, TBD)

Chart - Stimulation of Brainstorming for Lessons Learned and Improvements Thrusts
(New, TBD)

Lessons Learned - Major Topics

- Although Engineering Skills Are Essential; People Skills Are Mandatory for Achieving Successful Products
- Manage to Ensure Good Technical Integration
- Manage to Ensure Proper Concept Selection
- Requirements and Constraints Greatly Influence Design
- All Design Is a Balancing Act Between Conflicting Requirements. You Get Some of What You Want with Some of What You Don't Want
- Consideration of System Sensitivities and Uncertainties is Crucial to the Design Process
- Engineers' Judgment and Creativity is Essential to the Design Process
- Design Process is Complex and Laborious - Improve it Wherever Possible

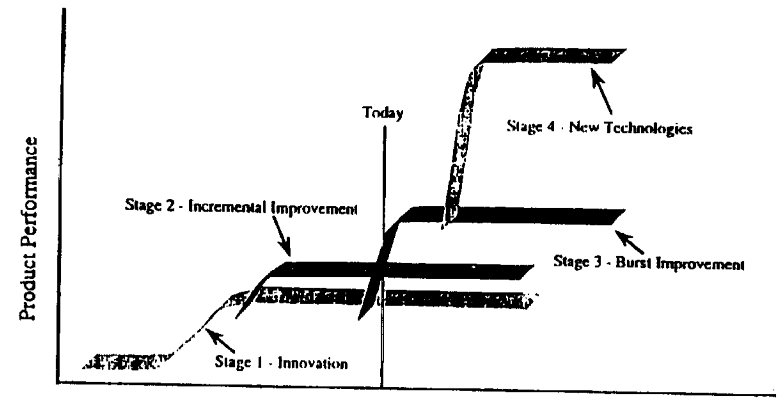
Chart for Response and Expansion of Team Brainstorming Plus Detailed Lessons Learned Charts, as Appropriate

Charts for Session 7, Plus New Charts, TBD

Chart - Categories of Hardware / Software Technologies and Design Process Technologies (New, TBD)

PATTERN OF TECHNOLOGY ADVANCEMENT

- Technologies typically develop and advance in a step-wise pattern.
  - Illustrated on following chart (Ref. Utterback)
  - As products based on existing technologies mature, there are minor evolutionary improvements, with occasional bursts stimulated by need or threat.
  - The products based on existing technologies are then overtaken by new revolutionary technologies, having a different paradigm. This is where the major advances occur.
- At what stage is launch system design technology today?
  - As indicated on chart, the existing design process technology for launch systems has matured, and is subject to evolutionary improvements (e.g., as provided by electronic data transfer).
  - Achieving major advances in design capability will require new, revolutionary design technologies.



Product Evolution Cycle

Charts - Characterization of Product Evolution Cycle

CURRENT SHORTCOMINGS AND NEED

Shortcomings: Current launch system design process falls short in at least these areas:

- Process is fragmented, producing designs that are less than optimal.
- Resulting design is too costly and too operationally intensive.
- Synthesis is an idea-driven process, which may miss promising concepts.
- Design process involves numerous sequential steps and iterations.
- Design process takes too long.

POTENTIAL SOURCES OF REVOLUTONARY IMPROVEMENTS

Revolutionary technology advances obviously can not be created on command; however, exploring and delineating potential sources, categories, high-leverage areas, and related fields can provide a framework and stimulus for their development.

Where does one look for revolutionary improvements? Possibilities include:

- Our experience base
- Identification of "design drivers" and high-leverage areas
- Existing research in field of system design (MDO)
- Other fields (e.g., software development)

Charts for Session 8, Plus New Charts, TBD

Charts - Potential Evolutionary Improvement Thrusts (New, TBD)

Charts - Potential Revolutionary Improvement Thrusts

CONCEPTUAL DESIGN PROCESS TECHNOLOGY

- High leverage of Conceptual Design phase
  - Estimated 80% of life cycle cost locked in by concept selected
  - Advances in conceptual design process will have major payoff
- Consider the three major activities of conceptual design:
  - Idea (concept) generation – *ideation*
  - Expansion of idea into consistent system concept – *sizing*
  - Assessment of attributes to enable downselection – *attribute prediction*
- These activities addressed on following charts

DESIGN PHILOSOPHY IMPROVEMENTS

- Design philosophy is the framework for the design process, inherently exercising major influence over the design process and its results.
- Changes in design philosophy should be explored for their potential to advance design process capability.
- Design philosophy areas that could be explored include:
  - Probabilistic Design
  - Nonlinear Design
  - Requirements and Criteria

HIGH LEVERAGE AREAS FOR TECHNOLOGY DEVELOPMENT

- <u>High-Leverage Areas:</u> Revolutionary advances in the following areas would provide major advances in design capability.
  - Reduction of process fragmentation - Move toward more seamless design in
    - -- Subsystem compartmentalization
    - -- Discipline decomposition
    - -- Objective function elements – performance, cost, reliability, etc.
    - -- Design for all mission events
    - -- All design phases
  - More-direct synthesis
    - -- Conversion of requirements to concepts
    - -- Translating requirements to design
    - -- Ideation
    - -- Visualization of design space
  - Improved Conceptual Design process
    - -- High percentage of life-cycle costs locked in by this phase
    - -- Better ideation
    - -- Higher fidelity representations
    - -- Better convergence process for downselection

INVERSE ANALYSIS

The term "Inverse Analysis" as applied to the design process means a synthesis approach that derives a design or system from its desired attributes (requirements);
i.e., Given these attributes, what system will produce the attributes?

An online Literature Search produced the following results

- ACCESS INTENSITY OF ACTIVITIES (Search logic results)

– Aerospace Inverse Problems	3
– Inverse Engineering	24
– Inverse Design	346
– Inverse Problems	2748

Charts for Session 8, continued, Plus New Charts, TBD

Multidisciplinary Optimization (MDO) Taxonomy*

1. DESIGN FORMULATION AND SOLUTIONS

1a. Design Problem Objectives	- Move from Feasible to Improved to Optimal to Pareto (Multi-objective) - Accommodate Problem Statement evolution
1b. Design Problem Decomposition & Organization	- Done for efficiency. Needs to converge to high-fidelity result
1c. Optimization Procedures	- Typical problem is nonlinear, nonconvex, both discrete and continuous

2. ANALYSIS CAPABILITIES AND APPROXIMATIONS

2a. Breadth and Depth Requirements	- Breadth: Include all constraints, disciplines, flight conditions *[and life cycle items, e.g., cost]* - Depth: Need highest fidelity throughout process *[Need appropriate fidelity" would be more correct]* Understand physics.
2b. Effective inclusion of High-Fidelity Analysis/Test	- Level 1: Empirical equations - Level 2: Intermediate models (e.g., beam theory, panel aerodynamics) - Level 3: SOA, hi-fi models (e.g., FEA, CFD). Costly in time and $. - "May be highest challenge" to drive to Level 3 - Other approaches are decomposition (above) & approximation/correction (below)
2c. Approximation and Correction Process	- "May be single most important need" - Approaches are (Local) Taylor series, (Global) Response surfaces and neural nets or Level 1,2 models corrected by Level 3 or Reduced order methods
2d. Parametric Geometric Modeling	- Sharable common vehicle description - Automatic model changes (morphing) Problems: - When morphing, doesn't change topology as would best industrial practice. Structural members become curved vs. straight, etc. - Needs to be CAD compatible - CAD not now robust enough for topology optimization. DARPA (PMTK)
2e. Analysis and Sensitivity Capability	- Currently have mid-level models interfacing with optimizers and single discipline hi-fi optimization, but with limitations - Needs: - Detailed nonlinear aero loads - Aeroservoelastic including controls - Robust CFD - Robust global/local structural sizing program including all major structural effects, such as: stress, buckling, durability, flutter, damage tolerance, etc. - Life cycle cost

Multidisciplinary Optimization (MDO) Taxonomy* - continued

3. INFORMATION MANAGEMENT AND PROCESSING

3a. MDO Framework and Architecture	- Currently minimal Off-the-Shelf. - Needs demonstrated, validated MDO software
3b. Data Bases and Data Flow & Standards	- Needs ability to handle huge amounts of data in multisite, heterogeneous environment - Obviously implies data standards
3c. Computing Requirements	- Is a major limitation, a formidable barrier - Probably requires massively parallel processing in a distributed computing system
3d. Design Space Visualization	- Designer can be more interested in design space than in optimal design point - Largest challenge is visualizing in greater than 3 dimensions - *[Would broaden this category as synthesis tool]*

4. MANAGEMENT AND CULTURAL IMPLEMENTATION

4a. Organizational Structure	- Advanced Development *[PD]* group usually does Conceptual Design - Should they be the integrator for high-fidelity design? - Currently, no one is in charge of MDO
4b. MDO Operations in IPD Teams	- IPD's need to use MDO as tool, and to direct MDO operations
4c. Acceptance, Validation, Cost, and Benefits	- Need cost/benefit of MDO as compared with conventional design
4d. Training	- Training needed; curriculum additions for MDO, etc.

* Extracted from AIAA 98-4737 "A Summary of Industry MDO Applications and Needs" Giesing and Barthelemy (Ref. 13)

OBSERVATIONS ON MDO AS SOURCE OF POTENTIAL REVOLUTIONARY IMPROVEMENTS

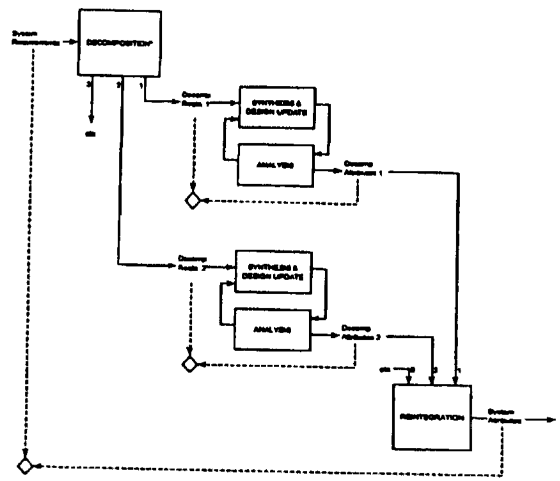
- The question then is: Is MDO too focused on the fine structure to provide stimulus for revolutionary advances?
- Despite the above shortcoming, MDO is the logical "home" for design process technology, and would provide a forum for revolutionary advances.
- The total MDO community might be stimulated toward greater advances by a focused, top-level goal, as has been stated by for NASA by the Administrator.

RECOMMENDATION

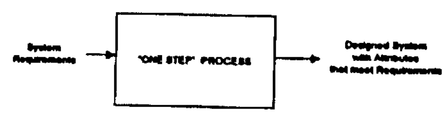
MDO should be studied and followed as providing a framework for evolutionary improvements, and as a potential stimulus for revolutionary advances.

Charts for Session 8, continued, Plus New Charts, TBD

CURRENT DESIGN PROCESS



IDEAL DESIGN PROCESS
(Distant Future)



*Decomposition currently is applied not only to vehicle system/subsystems, but also to disciplines, requirements accommodation (parts of objective function), operational events, etc., in order to divide the design process into manageable-sized parts.

47

3. ANALYSIS TECHNOLOGY - continued

C. Technology to address inclusion of life-cycle metrics

- Current state uses crude cost estimating relationships, reliability estimates done after-the-fact, and few measures of operability
- Reasonably reliable metrics currently depend on detailed definition of the design (and are still difficult in some cases)
- Need is for validated metrics which can be applied to the coarse definition of design which occurs early in the design process
- Such metrics will be essential to provide "design-to" capability for life cycle attributes

Charts for Session 8, continued, Plus New Charts, TBD

1. COMPARTMENTALIZATION / DECOMPOSITION and REINTEGRATION TECHNOLOGY

Compartmentalization / Decomposition is applied to many aspects or dimensions of the design. Five of these aspects or dimensions are expanded in the subsequent charts titled "Dimensions of Design Process". They are:

- Level or size of item to be designed
- Comprehensiveness of objective function
- Number of disciplines combined simultaneously in design
- System operational events simultaneously designed for
- Development phases that design process is applied to

These dimensions are delineated on the following two charts.

<u>Compartmentalization / Decomposition and Reintegration Technology Advancement Areas</u>

- Compartmentalization / Decomposition is best accomplished along lines of weak coupling.
  - Ability to accurately predict degrees of coupling could preclude some typical interdisciplinary or inter-subsystem problems
- Compartmentalization of subsystems necessitates allocation of requirements to those subsystems.
  - Improved requirement allocation approaches should have significant payoff.
- Reintegration usually entails a sequential process.
  - There are approaches to sequential optimization (e.g., LaRC's *DEMAID* program, Ref 25. See Figure on subsequent chart.).
- Advances in commonality and communication would advance the reintegration process.

2. SYNTHESIS AND DESIGN UPDATE TECHNOLOGY

Currently, any synthesis or design update depends strictly on the designer's ideas and experience base,
on an ad hoc basis.

The spectrum of technology advances in this area might be the following:

Increasing Technology

- Designer's ideas, ad hoc (current)
- Idea stimulus approaches; TRIZ*
- Convert judgments and rules-of-thumb into algorithms; expert systems*
- Automated Synthesis, e.g., using approaches like structural shape and topology optimization

3. ANALYSIS TECHNOLOGY

Analysis technology needs to be improved on several fronts, including fragmentation, fidelity, and life-cycle metrics.

A. Technology to reduce fragmentation:

Increasing Technology

- Analysis by individual disciplines, manual sequential (current)
- Analysis by individual disciplines, automated data flow
- Analysis on common models
- Combined disciplines, seamless analysis. Uses an integrated set of describing equations for multiple disciplines

B. Technology to improve fidelity

Increasing Technology

- Improvements in detailed analysis capability (current)
  - Typically pursued by individual disciplines
- Improvements in analytical tools which can be used in early design phases
- Potential of approximation / validation methods (cited in MDO field)
- Eventual high-fidelity representations that are computationally economic

CONCLUSIONS

- The current sequential design process is complex and costly.
- Revolutionary advances in design technology will be required to achieve needed major improvements in launch capability and cost.
- Must start from scratch and reformulate design process.
  - Fine-tuning will not meet long term project design goals.
- Revolutionary advances are usually the result of "nonlinear thinking" and idea conception, which are difficult activities to plan.
- However, identifying and developing revolutionary advances may be stimulated by
  - Examining the components and aspects of design technology
  - Considering "design drivers" and areas of high leverage
  - Looking at related categorizations and taxonomies
  - Considering significant major steps (themselves revolutionary) that may be undertaken in the direction of the eventual long-term goal of direct, unified design
    – An example of such a step is shown on the following chart

EXAMPLE OF POTENTIAL CANDIDATE INITIATIVE FOR SIGNIFICANT INITIAL ADVANCE IN DESIGN TECHNOLOGY

Title: Seamless multidisciplinary analysis of structural design

Category: Compartmentalization / Decomposition / Reintegration advance; Analysis advance

Disciplines: Trajectory, Control, Loads, Stress. Possibly Thermal.
Formulate a unified set of describing equations for above disciplines.
Include all inherent interconnecting terms.
Solve equations simultaneously to obviate sequential analyses and provide seamless analysis for these disciplines

Operational Events: Ascent atmospheric flight. Eventually extend to Liftoff, other flight events

Objective Function: Payload performance

Design Phase: Detailed design

RECOMMENDATIONS

- Vigorously pursue revolutionary advancements in launch vehicle design technology
- Further explore the areas and categorizations cited previously as idea generators
- Take a continual, step-wise approach to achieving revolutionary advancement in the design process.
  - Select one or more significant major steps to undertake immediately
    – For example, the Seamless Multidisciplinary Analysis of Structural Design initiative on previous chart.
- Concurrently, pursue other changes to design process, including
  - Improved communications / data exchange
  - Parallel processing
  - Localized MDO applied to parts of process
  - Revolutionize process through approaches such as
    -- Virtual reality
    -- Knowledge base / expert systems
    -- Inverse analysis
    -- Simultaneous engineering

Charts for Session 8, continued, Plus New Charts, TBD

RECOMMENDATIONS

The Design Function Descriptions as written herein should be added to the document of Reference 1 to complete its design function description.

The figures and discussion provided in the section on Compartmentalization of the Design Process may be included in narratives and presentations to expand the process description in this area.

The Training Course Formulation provided herein should be used as a basis for developing a course on the design process for launch vehicles. The course is intended to provide understanding of the process for those less experienced, and to serve as a basis for identifying needed improvements in the process, both incremental and major.

REFERENCES

1. NASA TP-XXXX, "Launch Vehicle Design Process: Characterization, Technical Integration, and Lessons Learned", J. C. Blair, W. R. Humphries, R. S. Ryan, and L. A. Schutzenhofer, Edition 1, September 1999.

2. "Technical Integration of the Design Process for Launch Vehicles, Its Characterization and Recommendations for the Future", J. C. Blair, W. R. Humphries, R. S. Ryan, and L. A. Schutzenhofer, Presented at the 1998 AIAA Defense and Space Programs Conference and Exhibits, Huntsville, AL, October 1998, and Presented at Intelligent Synthesis Environment Workshop, Huntsville, AL, March 1999.

3. "Space Transportation System Design: An Overview", Presentation to Dr. W. R. Humphries, NASA/MSFC, July 1998.

4. "Space Transportation System Design Process", Presentation to Science and Engineering, NASA/MSFC, October 1998.

5. "Space Transportation System Design: Design Process Tools", Presentation to Dr. W. R. Humphries, NASA/MSFC, March 1999.

6. "Survey of Innovative Design Technologies for Space Transportation Systems", Presentation to Dr. W. R. Humphries, NASA/MSFC, April 1999.

7. "Research in Subsystem Design Process", Final Report, Task H-30781-D, NAS8-97095, University of Alabama in Huntsville, August 1999.

8. "Study to Evaluate the Space Transportation System Design Process", John P. McCarty, Presentation to Dr. W. R. Humphries, NASA/MSFC, June 1999.

9. "Launch Vehicle Design Process: Characterization, Technical Integration, and Lessons Learned", J. C. Blair, W. R. Humphries, R. S. Ryan, and L. A. Schutzenhofer, Presented at Workshop on Launch Vehicle Design Process, NASA Ames Research Center, July 1999.