Preface

The NASA Engineering Management Council (EMC) was established in 1991 under NASA Management Instruction (NMI) 1152.62. The membership consists of senior management officials in engineering and quality assurance from each NASA Center,. One of these council's key functions is to develop policies and recommendations for NASA-wide programs. One of the key elements of NASA programs identified by the EMC is the mission design process used for developing new missions.

The guide has been developed in response to a request from the EMC to provide definition of the mission design process. It is intended to serve as a reference compendium of proven approaches to be used by those knowledgeable and experienced in NASA projects and aerospace technology. The basic processes, activities, and products described herein are applicable to the wide array of missions conducted throughout NASA. An abbreviated format of limited detail has been adopted in order to cover the essential topics in a reasonably sized document. Reference materials and other source data have been highly condensed. A listing of additional reading material is included as an Appendix.

The guide is <u>not</u> intended to constrain imagination and initiative in approaching the design of NASA missions. The guide should be used in formulating a study plan tailored to the mission under study.

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This guide is being distributed under the auspices of the NASA EMC.

Thomas E. Huber
EMC Chairman

Section 1. Introduction

1.1 Purpose of the Guide

This guide is to be used as a starting point for developing and executing a plan for conducting a mission design study, i.e., defining the mission and then designing the system(s), required to conduct that specific mission. The processes, activities, and products presented herein should not be held as a rigid prescription that must be met in every detail. Each Study Team should develop its own plans, processes, and products that are tailored to the particular mission under study. For larger missions, especially those requiring many organizations, the activities, processes, and resulting products are likely to be more formal; for smaller missions, less so. The study plan must consider the acquisition strategy for conducting the studies, the eventual procurement of the system(s) during Phase C/D (Execution), Phase E (Launch Operations), and activities conducted during Phase F (Mission Operations).

1.2 The New-Start Process for NASA Missions

Advocacy for new missions may originate in many organizations. These include Congress, NASA Headquarters (HQ), the field Centers, NASA Advisory Committees, the National Academy of Sciences, the National Space Council, and many other groups in the science and space communities. For science missions, the first formal stages are commonly proposals in response to Announcements of Opportunity (AOs) or NASA Research Announcements (NRAs). Concepts for new missions may also be presented as unsolicited proposals. In preparation for these proposals, a Pre-Phase A (Conceptual Design) study is done to establish a **strawman** set of mission objectives and requirements supported by a description of at least one way of accomplishing the proposed mission within a rough order magnitude (ROM) cost. These proposals are evaluated to determine which ideas have sufficient merit and an adequate prospect of success to warrant further examination. The decision-making process may include peer and advisory committees that make recommendations to the appropriate management level before proceeding into Phase A (Mission Analysis).

After a decision to proceed is made by a sponsoring organization, the Phase A process formally begins to refine the overall requirements and probable costs, along with the top-level definition of the best way to accomplish the mission. The programmatic guidelines (especially cost and funding profile) are a major factor used in determining the best way of accomplishing the mission. Following completion of Phase A, a formal decision to proceed into Phase B is made by NASA HQ. During Phase B, the system design is refined and optimized, lower-level specifications are developed, and the costs are finalized. At the completion of Phase B, a formal Non-Advocate Review (NAR) may be convened by HQ. The NAR panel reviews the realism of the technical approach, the schedule, and the cost. The NAR panel may then recommend approval for proceeding into Phase C/D.

1.3 The Phasing of the NASA Missions

NASA missions are developed and executed using a phased process, as illustrated in Figure 1-1. The full life cycle includes mission definition and system design; system, subsystem and component development; system and subsystem integration; design qualification; hardware/software acceptance testing; launch; deployment; mission operations; maintenance; data handling; and disposal if required. This document discusses the mission design process which occurs during Conceptual Design (Pre-Phase A), Mission Analysis (Phase A), and Definition (Phase B). It is the engineering and programmatic processes that occur in each of these phases that are important and not the names of the phases or lines of demarcation between the phases. In every case, the mission design process must put any proposed mission on firm technical, cost, and schedule grounds before committing to design, development, test, and evaluation.

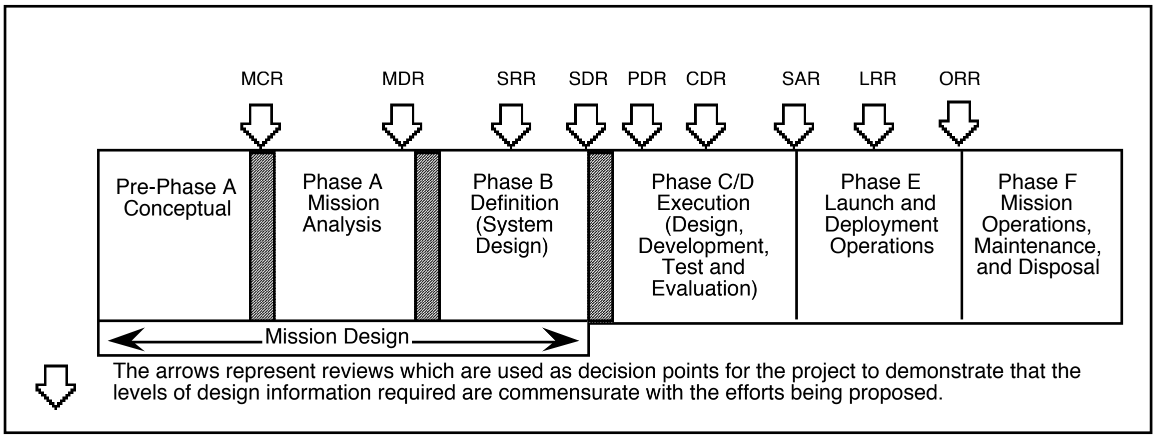


Figure 1-1. The Process of Mission Design, Execution, and Operations

1.4 Overview of the Mission Design Process

The mission design process generally begins with a statement of the mission objectives, mission classification, and programmatic constraints issued by NASA HQ. All NASA missions are categorized and given a classification from A through D in accordance with NMI 8010.1A, which establishes the level of risk acceptable in executing the mission and the minimum assurance requirements to be implemented. The mission classification guidelines allow room for interpretation of how the mission is to be implemented. Strict attention must be given to the mission classification when developing cost estimates. Higher classification levels typically require more hardware to provide robustness, redundancy, and operational flexibility to enhance the probability of mission success. Additional analyses, tests, and supporting documentation are also required. All of these contribute to higher cost. Table 1-1 lists the four classifications.

Table 1-1. Mission Classification

Class A	Minimum Risk
Class B	Risk/Cost Compromise
Class C	Single Purpose, Repeat Mission Possible, Some Risk Allowed
Class D	Routine, Rapid Mission, or Proof of Concept, More Risk Allowed

A Study Team is formed to define and refine requirements based on the mission objectives and classification. From these requirements the Team will engage in a process of developing and iterating system concepts, conducting trade studies, conducting analyses, and developing mission cost estimates. This process will generally follow a flow for the three study phases, as illustrated in Figure 1-2.

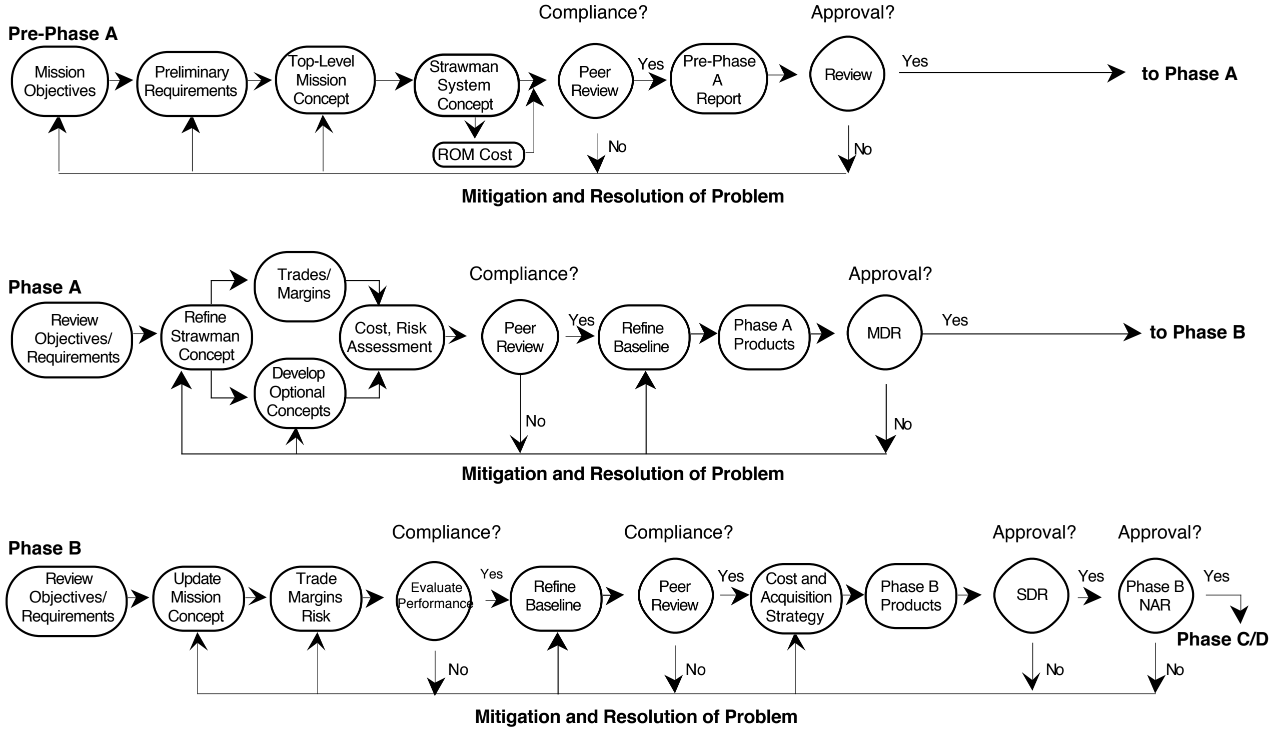


Figure 1-2. An Overview of the Mission Design Process

Pre-Phase A studies are generally done to develop concepts that sometimes culminate in a mission. The mission objectives and other constraints are analyzed to define mission requirements, from which a **strawman mission concept** is generated. Pre-Phase A studies **must** demonstrate one viable—but not necessarily optimized—concept for accomplishing the mission.

Phase A studies generally require NASA HQ approval, especially for a mission. Instrument studies may not, since they might be conducted in response to an AO. After a decision to proceed is made by the sponsoring organization, the Phase A process formally begins to refine the overall requirements and probable costs, along with the top-level definition of the best way to accomplish the mission. The programmatic guidelines (especially overall cost and funding profile) are a major factor used in determining this. Requirements are further defined and refined through trade studies and analyses. Various system concepts are examined by means of further trade studies and analyses. The overall mission and system architecture, the apportionment of functionality between the various systems, and candidate system designs are evaluated. A single mission architecture and system level design is selected. Following completion of Phase A, a formal decision to proceed into Phase B will be made by NASA HQ.

During Phase B, further analyses and trade studies are conducted to establish the lower hierarchical levels required to define the system(s) down to a level such that specifications/Statements of Work (SOWs) etc., are generated to permit entry into Phase C/D. At the completion of Phase B, a formal NAR may be initiated by HQ. The NAR panel reviews the realism of the technical approach, the schedule, and the cost. The NAR panel may then recommend approval for proceeding into Phase C/D.

Crucial to conducting a successful study is agreement on a set of realistic mission objectives. This is followed by establishing technical, functional, and performance requirements, which, when implemented, will satisfy the objectives. The next step in the process is to establish the weighted and prioritized mission evaluation criteria, which are used in assessing the merits of one mission/system design over another. Once the technical requirements are firm, cost and schedule can then be estimated. Any change to any requirement must be compared with the weighted evaluation criteria to ensure that the mission is not being over or under designed.

The mechanics for conducting a mission design effort will vary according to mission scope, complexity, and the organizations involved. Each mission will require unique or different kinds of hardware, software, facilities, operations, and human resources to meet the objectives. The technology used to develop these systems ranges from very simple to very complex and, in some cases, advances in the state-of-the-art. The more complex missions may require larger teams drawn from different jurisdictional, geographical, institutional, political, and culturally diverse organizations. It is for these reasons that every mission design study is different and, therefore, requires a tailored study approach.

The top-level activities occurring during the mission design process are summarized in Table 1-2. The listed products and reviews are representative of those generated for a typical science mission. The reviews do not include Center or HQ management reviews. While the listed activities, reviews, and products are generally required for most mission design studies, some may not be essential to a particular study. Therefore, the activities, products, and reviews should be tailored to each study.

Table 1-2. Summary of Mission Design Activities, Reviews, and Products

	Pre-Phase A	Phase A	Phase B
Input to Each Phase	Mission Needs and Objectives	Preliminary Mission Requirements Document Pre-Phase A Study Report Evaluation Criteria	Phase A Study Report Mission Requirements Document Operations Concept Document Project Initiation Agreement Evaluation Criteria Mission Requirements Request (preliminary)
Activities	Pre-Phase A Study Preliminary Mission Requirements Definition Top-Level Trade Studies ROM Costs and Schedule Feasibility Assessment	System and Subsystem Trade Studies Analysis of Performance Requirements Identification of Advanced Technology/Long Lead Items Risk Analysis End-to-End System Life-Cycle Cost as a Trade Parameter Cost and Schedule Development Top-Down Selection of Study Concepts Operational Concepts	Revalidation of Mission Requirements and System Operations Concept System Decomposition, Requirements Flow Down, and Verification Risk Analysis System and Subsystem Studies and Trades Development of the Work Breakdown Structure and Dictionary Updating Cost, Schedule, and Life-Cycle Cost System and Subsystem Concept Selection and Validation
Reviews	Peer Reviews Mission Concept Review	Peer Reviews Mission Design Review	Peer Reviews System Requirements Review System Design Review Non-Advocate Review
Products	Pre-Phase A Study Report Preliminary Mission Requirements Document Evaluation Criteria Science Definition Team Report ROM Cost Estimate	Phase A Study Report Mission Requirements Document (preliminary) Operations Concept Document Project Initiation Agreement Phase B Study Plan Technology Development Plan Top-Level System and Mission Architecture Preliminary Cost and Manpower Estimates	Non-Advocate Review Package Phase C/D Request for Proposal Package(s) Baseline Systems Description Technology Development/Risk Mitigation Design and Technical Documents Management and Control Plans Externally Required Documents and Agreements Mission Cost and Manpower Estimates Operations Plan

1.5 Definition of Terms

The following definitions are intended to provide the reader with an understanding of how each term is to be interpreted within the context of this guide. Hierarchy/hierarchical levels are used to briefly describe the relationship of a particular item with respect to items above and below in the relative order of things. The highest hierarchical level is at the mission level, and everything flows down from that point to the lowest level which is a nut, bolt, or electronic part.

Architecture - How functions are grouped together and interact with each other. Applies to the mission and to both inter- and intra-system, segment, element, and subsystem.

Assumption - A supposition that is made because information required to perform the study may not be complete or available from external sources. In order to obtain a full set of requirements, reasonable assumptions must be made and stated explicitly along with the rationale.

Constraint - A condition dictated by factors external to the study and which must be stated explicitly or may be implicit in the overall environment in which the mission is developed or operated. Examples are funding, schedule, and launch vehicle limitations.

Customer - The person or organization providing the final ratification of requirements, will use the products, and/or provides the funding.

Environmental and Design Requirements/Guidelines - The operating and survival environments that the system will encounter. These also include requirements peculiar to a design such as contamination, safety, maintainability, reliability, and any other applicable design guidelines and standard practices.

Hardware - The types of hardware uses for design evaluation and acceptance are as follows:

Prototype Unit - Hardware of a new design. It is subjected to a design **qualification** test program and is not intended for flight. It is also referred to as "qualification hardware."

Protoflight Unit - Hardware of a new design. It is subjected to a test program with design qualification levels and flight durations equivalent to a flight acceptance test program. It **is** intended for flight.

Flight Unit - Hardware built in accordance with a design that has been qualified either as a prototype or as a protoflight. This hardware is subjected to a flight acceptance test, i.e., flight levels and durations.

Brassboard - A high-fidelity replication of the flight design that is assembled using flight hardware workmanship standards. It is used solely for development and/or life testing.

Engineering Test Unit - Test hardware using nonflight parts and workmanship standards. It is used solely for proof of concept. It may also be referred to as a "breadboard" unit.

Hierarchy/Hierarchical Levels - The relationship of one item of hardware/software with respect to items above and below in the relative order of things. This is illustrated in Table 1-3.

Mission - An individual system or groups of systems operated to meet a specific set of mission objectives.

System - A composite of hardware, software, skills, personnel, and techniques capable of performing and/or supporting an operational role. A complete system includes related facilities, equipment, materials, services, software, technical data, and personnel required for its operation and support to the degree that it can be considered a self-sufficient unit in its intended operational and/or support environment. The system is what is employed operationally and supported logistically. (More than one system may be needed to conduct a mission.)

Segment - A grouping of elements that are closely related and which often physically interface. It may consist of elements produced by several organizations and integrated by one.

Element - A complete, integrated set of subsystems capable of accomplishing an operational role or function.

Subsystem - A functional grouping of components that combine to perform a major function within an element.

Component - A functional subdivision of a subsystem and generally a self-contained combination of items performing a function necessary for subsystem operation. A functional unit viewed as an entity for purpose of analysis, manufacturing, testing, or record keeping.

Part - A hardware element that is not normally subject to further subdivision or disassembly without destruction of designated use.

Table 1-3. Hierarchical Levels and Examples

Hierarchical Level Name	Examples
Mission	Needs + Objectives ‘ Operation of Everything Necessary to Meet the Objectives
System*	Total System = Spacecraft + Launch Vehicle + Ground Support Equipment + Communications Systems (TDRSS, etc.) + NASCOM + POCC + Science Data Center + ...+ Personnel
Segment	Flight = Spacecraft Bus + Instruments + Launch Vehicle +...
Element	Spacecraft = Structure + Power + C&DH + Thermal + ...
Subsystem	Power = Solar Arrays + Electronics + Battery + Fuses + ...
Component	Solar Arrays = Solar Cells + Interconnects + Cover Glass + ...
Part	Solar Cells

* Any given system can be organized into a hierarchy composed of segments and/or elements of succeedingly lower and less complex levels, which may in themselves be termed “systems” by their designers. In order to avoid misunderstandings, hierarchical levels for a given mission must be defined early.

Level I Requirements - Top-level performance requirements, which are few in number, approved by HQ, and are eventually used to assess the success of the mission.

Life-Cycle Cost - The sum total of the direct, indirect, recurring, nonrecurring, and other related costs incurred, or estimated to be incurred, in the design, development, test, evaluation, production, operation, maintenance, support, data handling, and disposal of a system over its anticipated life span.

Mission Objectives - Statements of the purpose of the mission, its output products, and the expected results of the mission which must be stated in the most descriptive and concise terms possible. The relative importance of achieving each objective must be clear.

Mission Operations - Any activity required to conduct and otherwise support the mission after launch and early orbit engineering checkout. This includes but is not limited to ground control of the mission, telemetry and command operations, maintenance of the mission systems, logistics support, data handling, and disposal.

Program - A related series of undertakings or collection of projects, which are funded for the most part from NASA's Research and Development (R&D) appropriation, which continue over a period of time (normally years), and which are designed to pursue a broad scientific or technical goal. (Programs are generally HQ-managed functions.)

Project - A defined time- and cost-controlled activity with clearly established objectives and boundary conditions executed to gain knowledge, create a capability, or provide a service. It typically encompasses definition; design; development; fabrication; integration; test; launch; mission operations; data acquisition, archiving, analysis, and distribution; and information extraction from ground, aeronautical, or space hardware. (Projects are generally Center-managed functions.)

Reviews - Generically, a review is defined as an in-depth assessment, by an **independent** team of discipline experts and managers, that the design (or concept) is **realistic** and attainable from a programmatic and technical sense. The reviews discussed herein are defined as follows:

> **Mission Concept Review** - A validation that the mission has clearly established needs, objectives, and top-level functional/performance requirements, and that at least **one** way of conducting the proposed mission is realistic and attainable within existing or projected technology and ROM cost.
>
> **Mission Design Review** - A validation that the mission objectives can be satisfied, the partitioning of the functionality to each of the systems is adequate, the top-level performance requirements for each system have been defined, and the technology required to develop the systems and implement the mission is attainable.
>
> **System Requirements Review** - A validation of the realism of the functional and performance requirements and their congruence with the system configurations selected to conduct the mission.
>
> **System Design Review** - A validation that an acceptable system configuration has been defined, the requirements allocations are valid and complete, and a system can be built—within cost—that will satisfy the mission objectives.
>
> **Peer Review** - A less formal evaluation by peer discipline persons who have been involved in similar efforts and can act as advisors or as a "sounding board" for new ideas.

Requirements:

> **Allocated** - Requirements which are quantitatively apportioned from a higher level to a lower level and for which the unit of measure remains the same. Examples include weight/kg, power/watts, pointing/degrees.

Derived - A self-identified or deduced requirement related to a higher-level requirement. The precise form and content of a derived requirement usually depends on the method selected for satisfying the higher-level requirement. (The unit of measure may change.)

Functional - Requirements which define **what an item must do** to accomplish the mission objectives.

Performance - Requirements which define and **quantify how well an item must accomplish** a particular function.

Reflected - Requirements placed on a higher hierarchical level that were uncovered during the allocated and derived requirements analysis that was conducted at a lower hierarchical level.

Risk Assessment - The identification and evaluation of the probable impact upon cost, technical performance, and schedule objectives of those items which, by analysis or test, appear to possess an inherent probability of failing in the design and development effort to meet some critical programmatic, performance or design requirement which is essential for the successful deployment of the system to accomplish its intended mission.

Strawman Concept - A mission and system approach used as a baseline for initiating the requirements definition and evolution process. This generalized approach is optimized through further studies and analyses.

Validation - The process used to ensure that the requirement is justifiable, applicable, traceable, and effective. This can be accomplished by tracing the requirement back to the objectives. The requirement must be proven to be linked to the objectives and make a contribution toward their successful accomplishment.

Verification - The process of evaluating the design—including hardware and software—to ensure the requirements have, in fact, been met. This is accomplished by analysis, test, inspection, and/or demonstration.

1.6 Topics To Be Covered

While this document does describe the process of conducting Pre-Phase A, Phase A, and Phase B studies, it does not describe detailed procedures to be followed except where deemed necessary for clarification. A brief discussion of the contents of each succeeding section follows:

- Section 2, "Implementing and Managing the Study Process," describes how the Study Team is formed and presents some guidelines for planning the study effort.
- Section 3, "Mission Design Activities," describes the activities, analyses, and other tools used during the mission design process.
- Section 4, "The Conceptual Design Process—Pre-Phase A," addresses the purpose of Pre-Phase A and describes its activities, reviews, and products.
- Section 5, "The Mission Analysis Process—Phase A," addresses the purpose of this phase and describes its activities, reviews, and products. This section also describes the preparations that must be completed before continuing to Phase B.
- Section 6, "The Definition Process—Phase B," addresses the purpose and activities of Phase B including the refinement and definition of requirements and system designs, cost, reviews, and products. This section also describes the preparation required for entering into Phase C/D.

- Section 7, "Conducting a Compressed Study," provides general guidelines for conducting a mission design study on a short time line.

Section 2. Implementing and Managing the Study Process

2.1 The Need for Conducting a Thorough Study

As budget constraints become tighter, it is more important than ever that NASA be on firm technical, cost, and schedule grounds before committing a mission to Phase C/D. One way of ensuring this happens is to conduct a thorough definition of the mission that results in a well-defined system design with realistic and consistent scope, cost, and schedule. NASA experience shows a positive correlation between a fully adequate mission design process (Pre-Phase A, Phase A, and Phase B) and a successful Phase C/D. Figure 2-1 presents some historical data illustrating the point. **It is generally accepted that Phase C/D cost overruns are usually created by a lack of understanding, inadequate definition of, and changing requirements.** Six to ten percent of the system development costs should be expended during the mission design process. This is likely to minimize cost problems during Phase C/D. If less is spent, then larger margins and contingencies must be maintained until the requirements and system are properly defined.

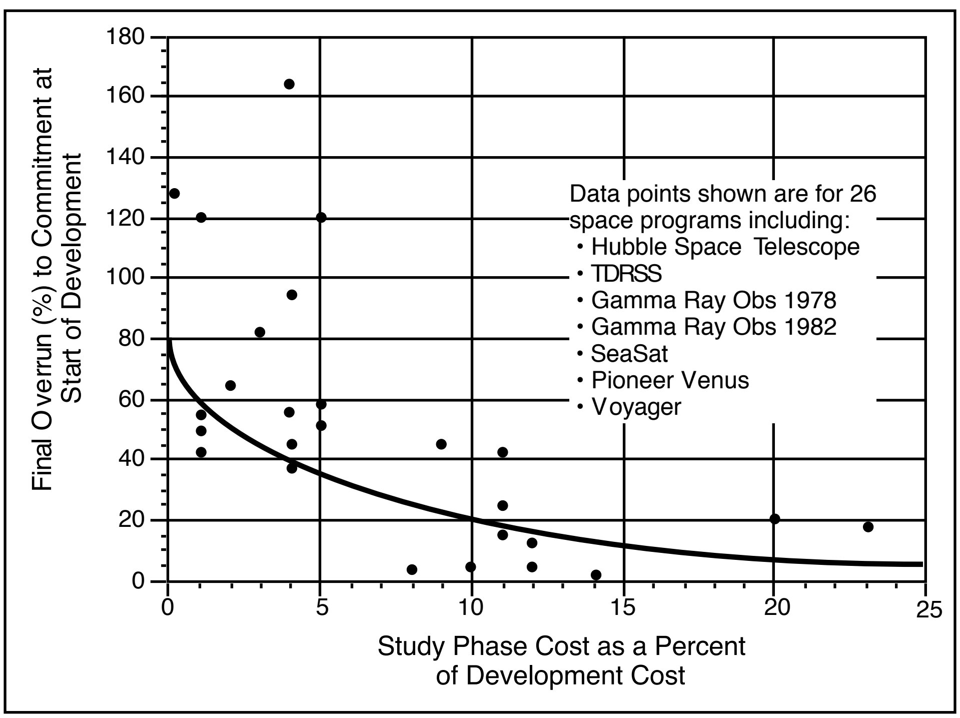


Figure 2-1. Benefit of Study Phase Investment

2.2 Forming the Study Team and Managing the Effort

Staffing the effort consists of assigning a Project/Study Manager to lead the effort, Systems Engineer(s), and a diverse complement of engineering, scientific, and resources personnel. Science missions may have a resident Study Scientist as well as support from a Principal Investigators/Science Team. For science missions, a key member of the Study Team is a Project Scientist, for it is this person who, along with the Science Team, gathers the support from the scientific community for advocating and justifying the mission. The Team must be tailored to the needs of the study and the particular phase of the study. An experienced engineering team is critical to accomplishing the phased development process. However, it remains a primary responsibility of the customer to advocate and justify the mission based on the overall prospect for sufficient return on the investment. A close working relationship between the customer and the Study Team is absolutely required to define requirements and perform an efficient and effective mission design process.

Study Managers are usually assigned to lead the Pre-Phase A and Phase A efforts. It is strongly urged that a Project Manager, who will carry the mission through Phase C/D, be assigned to lead the effort no later than the start of Phase B. The Study/Project Manager and Systems Engineer should have had prior experience in conducting studies as well as carrying a mission to the operations phase. Key Team members should have served at an equivalent level or the next immediate lower level during the conduct of a similar study or in the execution of a similar mission. In some cases, it may not be possible for the same personnel to remain with a project from the start of a study. In the earliest phases (Pre-Phase A and Phase A), the lead activities are heavily systems engineering in nature. Later (Phase B and Phase C/D), the engineering activities are more subsystem-oriented and require a strong management team to be in place. Significant portions of the "systems engineering-oriented" team should remain in place until the "managerial" team is firmly in control. This approach brings continuity to the entire process and ensures the definition of realistic technical and cost requirements during Phase B that will be subsequently verified and validated during Phase C/D.

Most science mission studies fall into particular ranges of duration, funding, and staffing levels. As an example, a typical science mission design study would normally fall into the ranges listed in Table 2-1. However, studies for very small or very large systems may fall outside these ranges. The types of technical experts required to support a typical science mission design study include: spacecraft discipline engineers (e.g., structural, thermal, and electrical), and experts in orbital mechanics, instrument development, mission operations, ground data systems, and launch vehicle interfaces. Resource specialists required during the study period consist primarily of those expert in cost estimating.

Table 2-1. Examples of Required Study Resources

	Duration	Funding	Staffing
Pre-Phase A	2 to 4 months	$0 to <$100 K	Study Manager/Systems Engineer Project Scientist Part-time help from others
Phase A	6 months to 1 year	1% to 2% of total system cost*	Study Manager Systems Engineer Project Scientist Resource Specialists Discipline Engineers and Specialists
Phase B	1 to 2 years	4% to 8% of total system cost*	Project Manager Systems Engineer Project Scientist Resource Specialists Discipline Engineers and Specialists

* Total system cost includes spacecraft, instruments, and ground segment (launch vehicle cost not included).

2.3 Developing the Study Plan

The Study Manager and the Study Team must develop tailored plans for each of the studies. The plan should address all elements of the process including but not limited to: objectives, methodology, evaluation criteria used in assessing the merits of one design over another, Center manpower requirements, analyses and other studies to be done, technology development plans, costs, schedule, and the strategy for conducting the study, i.e., in-house, contracted, or a combination of both. A recommended approach for the procurement of the system during Phase C/D must also be considered for this will affect how the study is accomplished and the resultant products. The Phase C/D implementation plan must be completed during Phase B.

A key parameter to consider in developing the overall study plan is the design maturity of the hardware that will be needed to satisfy the mission requirements. Quite often, some of this hardware may be in an early developmental stage and require advancing the "state-of-the-art." Typically, for science missions, spacecraft subsystems are of a mature design with the accommodation of the instruments being the most technically challenging aspect. It is permissible to start a mission design study that encompasses "advancing the state-of-the-art" for its instrument complement and/or portions of the spacecraft. However, the study plan must explicitly define the strategy for bringing the development to a sufficient level of maturity to permit establishing realistic schedule, cost, and performance parameters, including adequate margins. It is highly desirable that the study plan reflect an approach to ensure the convergence of equal levels of technology maturity by no later than the end of Phase B. If this is not possible, then appropriate margins and other contingency factors such as the use of existing technology must be reserved.

The general activities, relative levels of effort expended, and relative time phasing are shown in Figures 2-2, 2-3, and 2-4 as guidance to be used in formulating the overall study plan. **The indicated span times for the length of the study and each of the activities are only illustrative and may be shorter or longer depending on the specific study.**

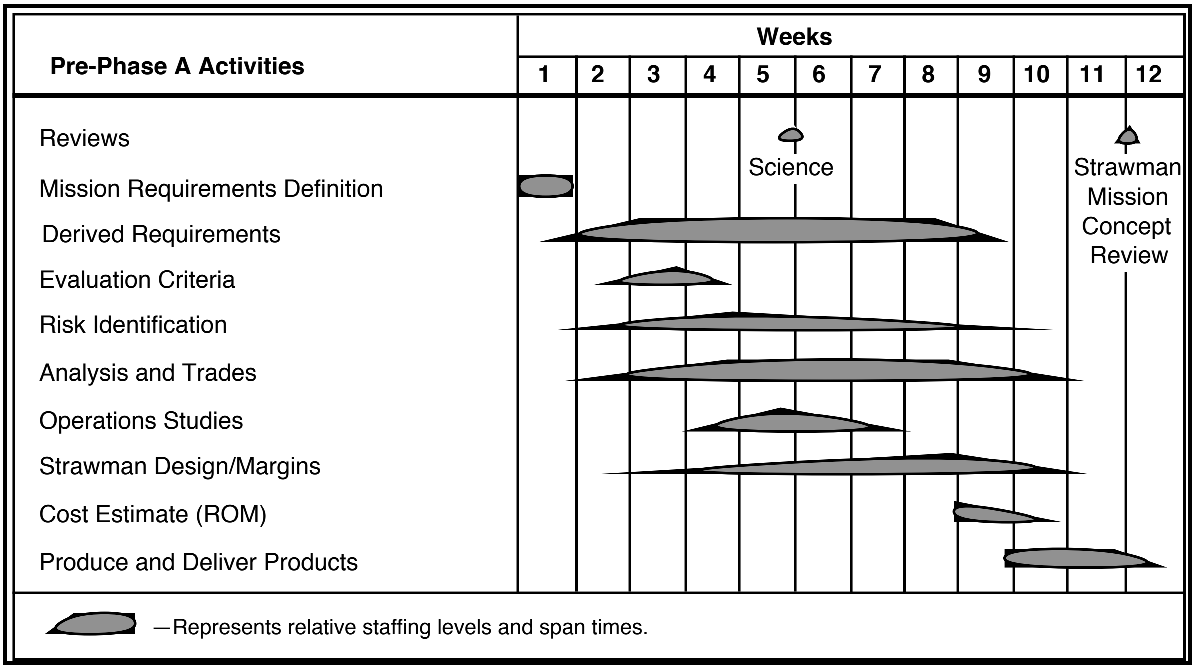


Figure 2-2. Typical Pre-Phase A Manpower Loading and Milestone Schedule (Durations Are Illustrative Only)

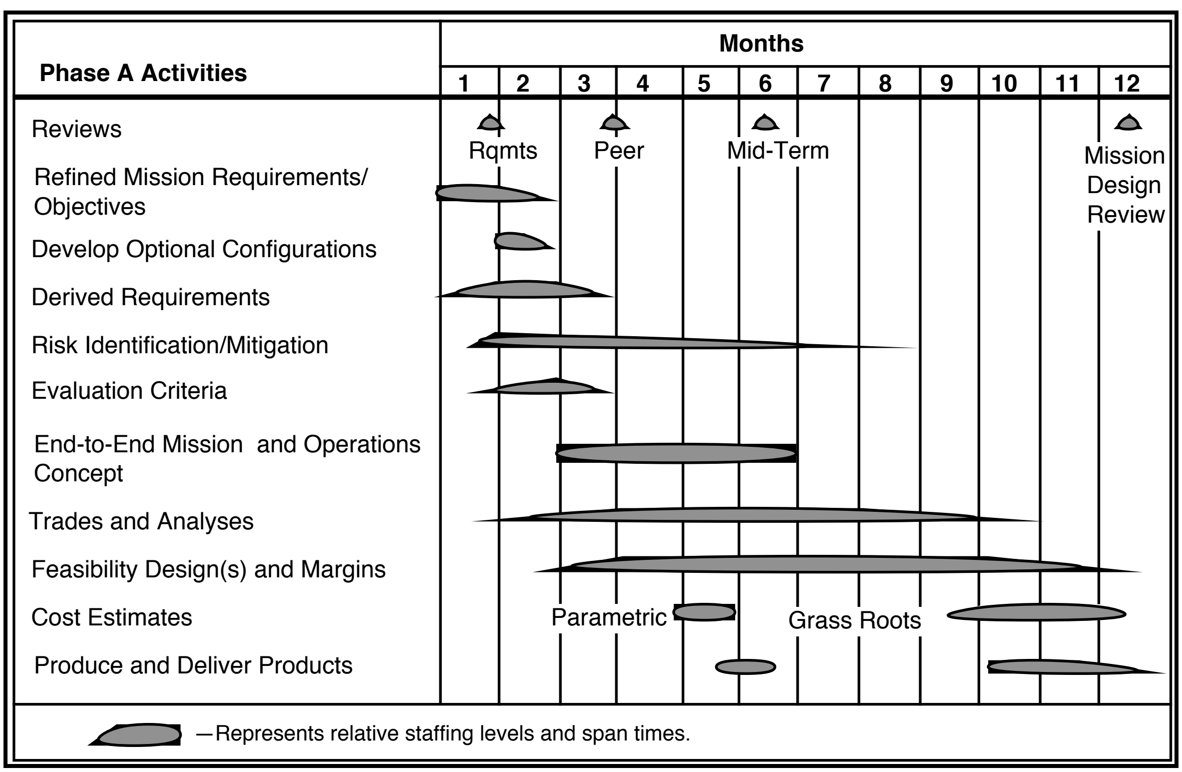


Figure 2-3. Typical Phase A Manpower Loading and Milestone Schedule (Durations Are Illustrative Only)

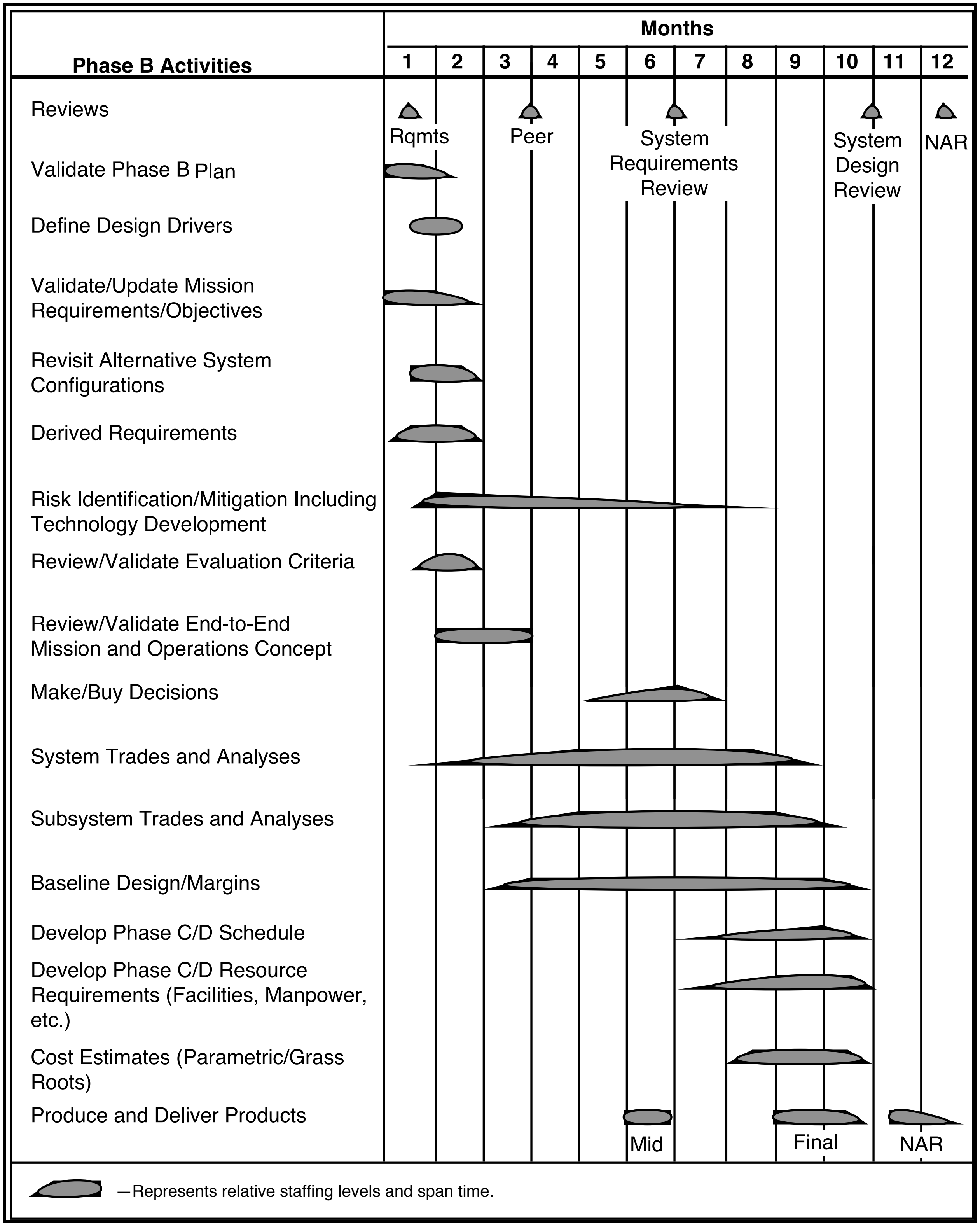


Figure 2-4. Typical Phase B Manpower Loading and Milestone Schedule (Durations Are Illustrative Only)

2.4 Selecting the Study Approach

Availability of in-house resources, funding, schedule, in-house expertise, training needs for the in-house work force, the availability of out-of-house expertise, and the overall scope of the project must be considered in selecting the study approach. For an **In-House** study, primary responsibility for product delivery, cost, schedule, and quality lies within a designated government organization and is done primarily with civil service manpower with or without contractor task support. For a **Contracted** study, primary responsibility for product delivery lies within a contractor organization and is done with contractor manpower; overview of the contractor effort is accomplished by a civil servant.

Various combinations may be selected ranging from a totally in-house to a totally contracted study effort. Regardless of the strategy chosen, completeness and continuity of information and personnel are key to the successful completion of each study phase. Comprehensive and accurate technical documentation is critical to efficient and informed decision making. It should be recognized that, if the executing study organization changes at any point in the cycle, the potential for deviation from the objectives increases.

As an absolute minimum, it is recommended that Pre-Phase A studies be done in-house. Whenever possible, the Phase A study should also be done in-house. An advantage for doing the studies in-house is that the study process can frequently be expedited, resulting in lower overall study costs. In addition, when the requirements need extensive iteration and evolution, the process is likely to be more effectively executed by an in-house team. If the main study effort is to be contracted, especially for Phase A but also for Phase B, some in-house studies **must** be conducted in parallel to permit the government to better understand and evaluate the approach proposed by a contractor.

Section 3. Mission Design Activities

3.1 Scope

This section provides a general description of the activities and “tools” that are used during the mission design process. These activities and tools must be tailored to the study and applied to the appropriate levels of the mission and system hierarchy as the mission design effort progresses.

Efficient engineering depends on the use of a disciplined and structured thought process. A flow diagram of such a process is given in Figure 3-1. This process can and should be applied at all stages, at all hierarchical levels, and by all disciplines during the development of a mission or system. It is equally applicable to the earliest stages of mission analysis and system design and to the later stages such as the development of a design concept for an electronics package during Phase C/D. This engineering process provides the core for the discussions in the following sections. The activities and tools discussed in this section are to be selected and used as appropriate in executing each of the functions in the logical cycle iteratively until the goals of a given activity have been achieved and documented.

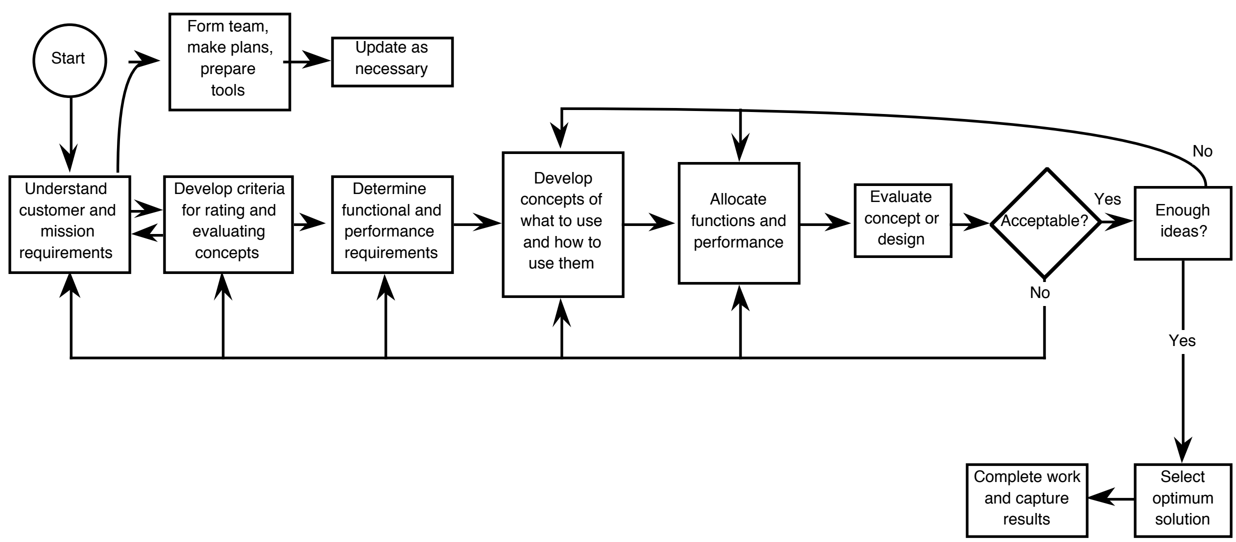


Figure 3-1. The Engineering Process – A Systematic Approach

3.2 Requirements

3.2.1 Introduction

The definition and tracking of requirements are among the most important aspects of the mission definition and system design process. The definition of requirements begins with an analysis of the customer‘s needs and constraints starting in Pre-Phase A. Requirements definition and tracking to the original requirements continue throughout the entire study process to yield functional, performance, operational, and interface requirements that will be implemented and verified during Phase C/D. This flow down is illustrated in Figure 3-2.

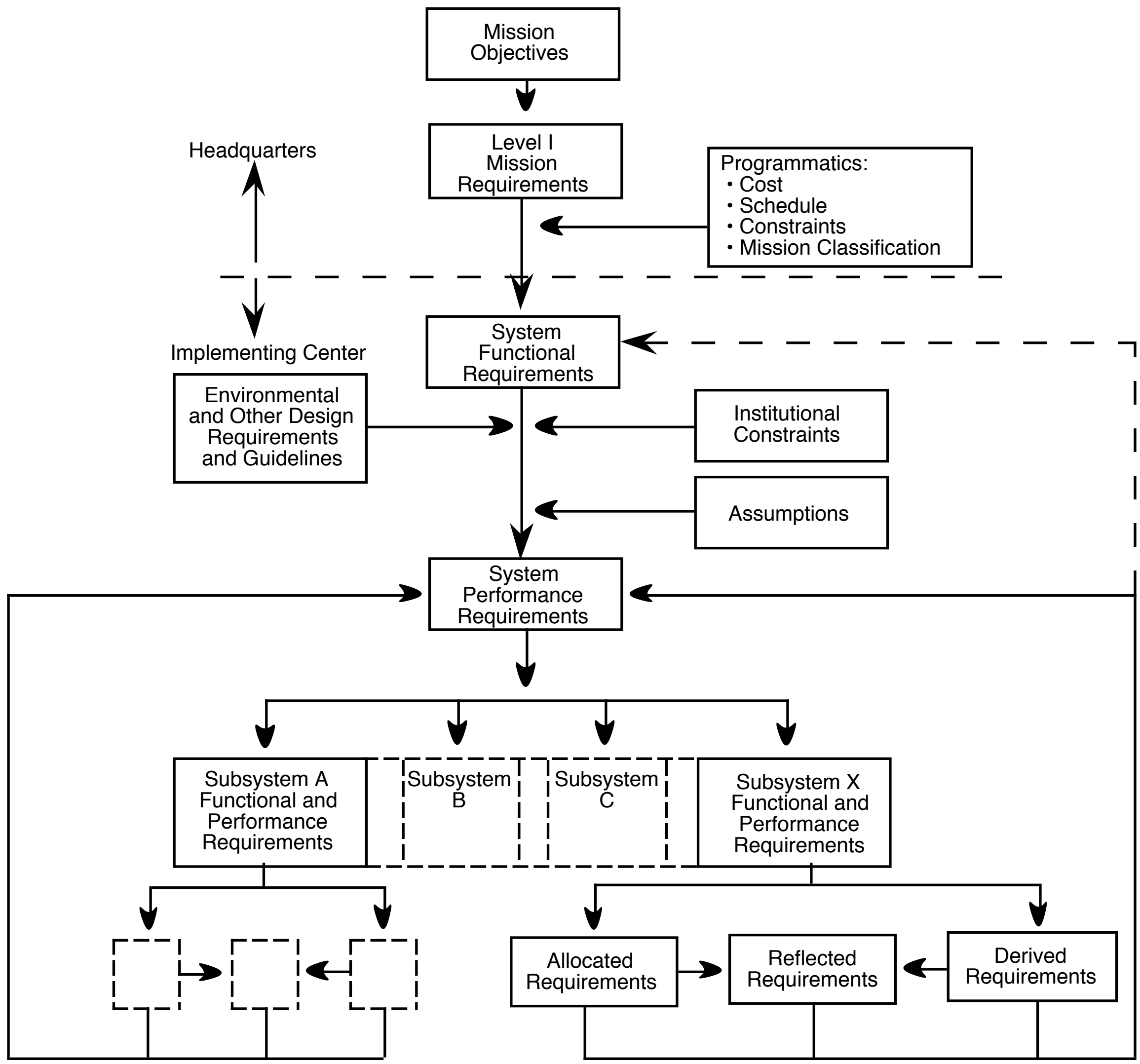


Figure 3-2. The Flow Down of Requirements

Arriving at a set of agreed-to requirements—of any kind and at any level within the hierarchy—can and usually does become a long and arduous task. Because of the long times between mission analysis (Phase A) and the operation of a mission (Phase F), it may be difficult to predict what functions and overall level of performance will be necessary to meet the mission objectives and provide a reasonable return on the resources invested. The process can be made more difficult by lack of specific knowledge of—or relevant experience with—the problem at hand. The proactive iteration with the customer on the definition of requirements, concepts, and the resulting performance and cost is the **only** way that all parties can come to a true understanding of what should be done and what it takes to do the job. The traceability of requirements to the lowest level is necessary to ensure that requirements are valid, can be met, and can be verified.

Requirements that are not allocated to lower levels or are not implemented at a lower level result in a design that does not meet objectives and is, therefore, not valid. Conversely, lower-level requirements that are not traceable to higher-level requirements result in an over-design that is not justified. In either case, the end result is a greater risk of failure in meeting performance, cost, and schedule. It is important to develop requirements from a view that is both broad and long—broad in covering both the objectives and the agenda of the customers, long in considering all phases of the mission life cycle.

3.2.2 Requirements Iteration, Traceability, Verification, and Validation

Figure 3-3 is an example of how science pointing requirements are successively distributed and allocated from the top-down for a typical science mission. It is important to understand and document the relationship between requirements. This will reduce the possibility of misinterpretation and the possibility of an unsatisfactory design and associated cost increases.

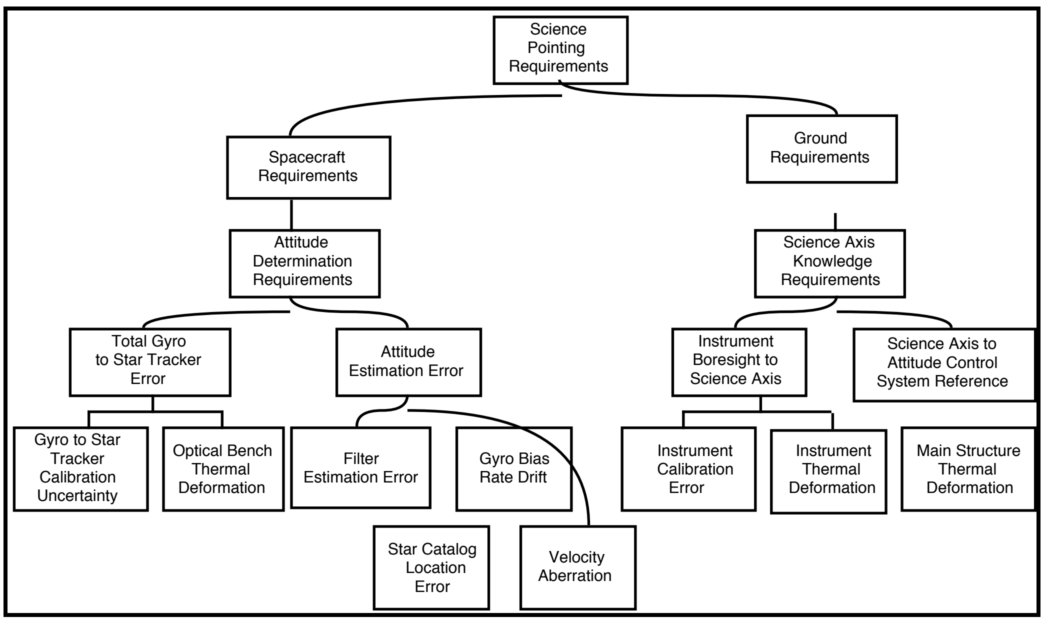


Figure 3-3. An Example of Pointing Requirements Allocation for a Science Mission

Throughout Phases A and B, changes in requirements and constraints will occur. It is imperative that all changes be thoroughly evaluated to determine the impacts on both higher and lower hierarchical levels. All changes must be subjected to a review and approval cycle to maintain traceability and to assure the impacts of any changes are fully assessed for all parts of the system. A more formal change control process may be required if the mission is very large and involves more than one Center or crosses other jurisdictional or organizational boundaries.

Requirements must be iterated through the conduct of functional and sensitivity analyses to ensure that the requirements are realistic and evenly allocated. Rigorous requirements verification and validation ensure that the requirements can be satisfied and conform to mission objectives.

The design of a mission and the system(s) must consider the methods needed to demonstrate that performance has, in fact, been satisfied. A system is defined by a set of objectives and functional/performance requirements, the environment in which it is to operate, its useful life, and its constraints. A system cannot be verified until the objectives are defined by a set of measurable and quantifiable requirements. A system is verified and validated when it is shown to meet all of its requirements. The mission design process must establish the methods required to verify performance and to identify when and where the verification process is to occur. The verification approach applicable to a particular design has cost and schedule implications which must be part of the evaluation criteria. To select a design which is difficult to verify may cause cost and schedule impacts, and have serious implications in meeting mission objectives.

3.3 Decision Making and Evaluation Criteria

In order to effectively evaluate a mission or a system design, it is necessary to have a defined and weighted set of prioritized evaluation criteria which can be used to separate "acceptable" from "unacceptable," "better" from "good," and to assess the merits of one design over another. The criteria must be derived from and reflect all of the technical and programmatic requirements and constraints. Care should be taken to ensure that the evaluation criteria include and apply to all portions of the mission throughout the full life cycle. The techniques used to develop sets of evaluation criteria vary widely. Poorly defined sets will almost certainly result in an inadequate study. Examples of parameters used to develop evaluation criteria are: development costs, operations costs, total life-cycle costs, power, risks, weight, size, and any mission- or system-peculiar or critical functional or performance parameters. Although the criteria may change with increased insight later in the study, it is important that the criteria be defined before a concept has been established. If done afterward, the criteria may be developed to justify the selected concept and might result in the selection of a less-than-optimum design. Decisions should be made using the explicit criteria associated with each of the technical and programmatic requirements and constraints.

3.4 Optimization and De-Scope Options

Obtaining the best possible compromise between cost, performance, risk, schedule and other constraints within a fixed envelope is the goal of the optimization process. De-scoping is the process of explicitly reducing the envelope in one area to allow for improvement in another. The most common use of de-scope options is to reduce cost or schedule in return for reduced performance or increased risk. A properly defined mission and the system designed to implement that mission should not have significant de-scope options that can be exercised to reduce cost or schedule without impacting its ability to satisfy other requirements. If such options exist, they should have been used during the normal course of the study process. It is necessary, however, for the design of a mission or system to allow for reasonable trades between cost, performance, risk, schedule, and other constraints without completely negating the work already done. For example, if a reduced or constrained budget or funding profile is imposed, it is desirable to be able to accommodate this with a reasonable increase in risk or decrease in performance rather than having to cancel the mission or completely rework the design. Such robustness is usually obtained at the cost of perfect optimization. Some robustness is good but more is not necessarily better.

Planning de-scope options early will allow the best compromise to be made between optimization and robustness. De-scope options should be considered during all phases of the study. In every instance, care must be taken to ensure that the trade to be made is well understood, explicitly stated, and agreed to by all parties. Typically, the type of de-scope option that can be reasonably carried will change as the design matures, and the return that can be expected for a specific de-scope item will decrease. Well into Phase A, de-scope options may include any element or attribute of the mission or system and the operation of that system. At that stage, it is likely that a reduction in one area can at least be partially compensated by improvements in another. Later on, de-scopes are more likely to entail discrete eliminations of functions and/or decreases in performance.

It is essential that each de-scope option include an explicit definition of when the option must be exercised or equivalently, what return can be expected if the option is exercised at different times. In general, the later in the program the option is exercised, the lower the return. De-scopes exercised at the wrong time can result in a negative return. For example, a de-scope option exercised after contract award in Phase C/D could lead to excessive cost increases, especially for a fixed-price contract. Following the start of Phase C/D, the de-scope options should primarily address the reduction of functionality or performance in such a way that there are no gross perturbations to the overall design that would jeopardize meeting mission objectives.

3.5 Robustness and Flexibility

In addition to the normally explicit inclusion of functional, performance, cost, and schedule requirements, robustness and flexibility should be considered and be part of the mission design process. **Robustness** is a measure of the ability of a system to absorb changes in requirements, constraints, and/or failure while minimizing the impacts on the performance, functionality, or composition of the mission or system. **Flexibility** consists of features incorporated into the design that enhance the capability of conducting operational workarounds should problems be experienced in orbit.

Robustness and flexibility can be achieved in many ways. Any viable mission and system design must be robust enough to accept reasonable changes to requirements without resulting in cancellation. A good design should have some degree of operational flexibility to minimize the effect of on-orbit failures in meeting mission objectives. The degree of robustness and flexibility must be demonstrated explicitly through the conduct of appropriate analyses and trade studies and verified through appropriate tests. A major benefit is the ability to overcome unanticipated problems. The allocation of available margins in a way to reduce programmatic and technical risk is an extremely important tool to enhance robustness and flexibility. The mission classification guidelines provide explicit top-level guidance and have cost implications but leave significant room for interpretation. It is important that the final result be consistent with mission classification. **Excessive and unnecessary addition** of robustness or flexibility may increase cost and/or schedule as well as result in decreased reliability.

Early identification of critical functions and failure modes is crucial to increasing robustness and flexibility without resorting to a "brute force" solution at a later time. A thorough and disciplined Failure Mode Effects Analysis (FMEA) at the appropriate level can be used as a design tool in identifying problem areas and making quantitative comparisons between different design options. Such an analysis might be used to determine whether the best overall expectation of performance or functionality could be obtained by adding a parallel functional path (redundancy), fault isolation (cross-strapping), or by improving reliability of specific parts or components. Component and part reliability is typically enhanced by some combination of derating the design for the application, testing, screening, "burn-in," and/or manufacturing process controls. The analysis might show that improvements in other areas would have little effect on the overall expectation and would therefore be a waste of resources. Other factors that may be worthy of consideration include "failsoft" designs, reconfigurable systems, and the provision for adequate engineering data to allow fault identification during mission operations.

Maintainability, reparability, logistics support, and disposal requirements must also be factored into the overall mission design process since these factors are closely coupled with and have a direct impact on robustness and flexibility, **and** the meeting of mission objectives.

3.6 Cost and Schedule as a Trade Parameter

Analyses and trade studies that are conducted to select the best way of technically accomplishing the mission and implementing the system design must also include cost and schedule as trade parameters to ensure that the mission objectives are attained for the lowest possible cost. Schedule must also be factored into the analysis since cost and schedule are closely coupled, and any schedule extensions will **always** result in a cost increase. Cost/performance trades generally fall into the following categories:

- Designing for performance in which the goal is to obtain the lowest cost for a given level of performance.
- Designing for cost in which the goal is to obtain the highest possible performance for a specified maximum cost.
- Designing against a fixed schedule.

Designing for minimum life-cycle cost is sometimes easier said than done. Nevertheless, total life-cycle costs are important, and decisions based on less comprehensive considerations should be made explicitly and with the liens identified. Sometimes design decisions that determine the apportionment of a function are made to minimize system development cost, which may result in increased system maintenance, logistics, operations, data handling, and disposal costs. Phases A through E are generally funded by one budget line item while Phase F is funded by another. Therefore, the design and subsequent cost estimates for the entire life cycle must be agreed to by all organizations involved over the life cycle.

A valid cost estimate cannot be generated without an associated funding profile that covers the entire duration of the proposed mission life cycle from the start of Phase C/D through the end of Phase F. Any change in the funding profile, at any time, may affect the run-out cost. The cost estimate used in the trade-off study must also consider technology development risk as well as including a reasonable cost margin to account for unforeseen problems or other uncertainties.

3.7 Developing the Cost Plan and Schedule

3.7.1 Developing the Cost Plan

Early in the mission design process, the cost and schedule estimates are used primarily to compare system concepts with one another and against programmatic constraints. During Pre-Phase A, costs are normally ROM estimates. During Phase A and Phase B, the estimates are refined to a greater level of detail by means of the grass-roots estimates. Parametric and comparative estimates are used as a crosscheck. At the close of Phase B, the cost estimate must be realistic and firm in order to allow commitment to Phase C/D. The cost estimate must include a reasonable cost margin to account for technology maturity, unforeseen problems, or include equivalent de-scope options to create the margin. The cost plan must also include the funding profile needed to execute, operate, handle the data, and otherwise maintain and support the mission. When cost analyses are done using different methods, any differences must be reconciled and explained.

Three basic techniques are used to develop cost estimates: grassroots, parametric, and comparative. The advantages and disadvantages of each of the methods are presented in Table 3-1. **Grass-roots** (bottom-up) estimating starts with estimating the cost of materials and labor to develop and produce the lowest hierarchical level and continues up through each level to the highest hierarchical level. This method requires the development of an implementation/ development plan that includes a detailed schedule and Work Breakdown Structure (WBS). **Parametric** (cost modeling) estimating uses a Cost-Estimating Ratio (CER) to express cost as a function of design and performance parameters. CERs are derived from historical data from actual programs. Complexity factors can be added to account for technology differences. **Comparative** estimating adjusts the cost of a similar item for differences in size and complexity.

Table 3-1. Cost-Estimating Techniques

Estimating Technique	Advantages	Disadvantages
Grass-Roots Estimates (Bottom-Up)	• Most detailed technique • Best inherent accuracy • Capable of establishing a funding profile • Provides best estimating base for future program change estimates • Commits responsible organization to the stated cost	• Requires detailed program and product definition • Time-consuming • Subject to engineering bias • May underestimate system integration costs • Requires experienced personnel
Parametric Estimates (Cost Modeling)	• Application is simple, quick, and low cost • Statistical database can provide expected values and prediction intervals • Can be used for equipment or systems prior to defining detail design or project planning • Effective for trade studies	• Requires parametric cost relationships to be established • Limited frequently to specific subsystems or functional hardware of systems • Requires extrapolation for new technology or approaches. • Depends on quantity and quality of the database • Limited by the available data and the number of independent variables
Comparative Estimates (Analogy)	• Relatively simple • Low cost • Emphasizes incremental program and product changes • Good accuracy for similarly configured item level	• Requires analogous product and program data • Limited to stable technology • Narrow range of applications • Difficult to extrapolate with confidence • May be limited to systems and equipment built by the same firm

It is essential that financial reserves be established early to mitigate the effect of both uncertainties and the lack of mature technology. Increased dollar margins may be used to offset lower margins in other areas, e.g., technical performance or unknown development schedules. Extreme care must be exercised to prevent "double budgeting," i.e., hidden and overstated financial margins. Different contingency cost factors must be applied to portions of the system based on differences in design maturity and/or risk. A cost sanity check can be made by comparison with a similarly developed system. Generally, the following contingency cost factors should be applied in establishing realistic and adequate financial reserves:

Design Maturity	Contingency Cost Factor
Proven design/low to moderate risk	~ 15% to 20%
Moderate to high risk	~ 40% to 50%
New technology/high risk	~ 100%

Agreement on the life-cycle cost is extremely important because a total mission generally is funded by different HQ organizations. All levels of management at both HQ and the responsible Centers must assure that the study phase costs are realistic and not a "buy-in." As design details evolve and are better understood, the costs may change. **"Center sign-up" to a cost ceiling** should not occur until well into Phase B, after a proper study has been done to provide an in-depth understanding of the mission and its appropriate implementation.

3.7.2 Developing the Schedule

Initially, a master schedule is developed to identify task and major activity dependencies that tie the entire mission together from the lowest to the highest hierarchical levels. Work flow diagrams or Program Evaluation and Review Technique (PERT) charts are then developed to establish the time phasing and dependencies between interfacing portions of the mission and system(s). The master schedule should cover major reviews, significant events such as integration, test, and launch, and all inputs/outputs to and from external interfaces. Each schedule line item should further be defined in terms of major events such as design, Request for Proposal (RFP) release, contract award, fabrication/assembly, and delivery for integration and test into the next higher hierarchical level. As the design evolves and is refined, lower level and more detailed schedules and flowcharts are developed down to the lowest level necessary to develop realistic cost estimates. As a minimum, it is recommended that a 15 percent schedule margin be carried through Phase A and a 10 percent schedule margin through Phase B. Extreme care must be used in assigning a schedule contingency and the associated costs to ensure the absence of "double budgeting," since any schedule extension automatically results in increased costs.

3.8 Risk Assessment and Mitigation

In planning the study effort and continuing on throughout the effort, an important factor to consider is the assessment and mitigation of risks and uncertainties. These perturbations may come from a number of sources, some within the control of the Team (and eventually the project) and others outside the immediate sphere of influence. They can be both programmatic as well as technology driven. In either case, all potential risks and uncertainties must be identified and plans put in place to mitigate the potential effects during Phase C/D.

Some commonly encountered problems and strategies to mitigate these uncertainties are listed in Table 3-2. Other factors that should be considered in assessing risk include, but are not necessarily limited to, complexity of management and technical interfaces; design and test margins; mission criticality; availability and allocation of resources such as weight, power, volume, data volume, data rates, and computing resources; scheduling and manpower limitations; ability to adjust to cost and funding profile constraints; mission operations; data handling, i.e., acquisition, archiving, distribution and analysis; launch system characteristics; and available facilities.

Table 3-2. Uncertainties That Plague Projects

	Uncertainties	Offsets
Mission Objectives	• Will the baseline system satisfy the needs and objectives? • Are they the best ones?	• Thorough study • Analyses • Cost and schedule credibility
Technical Factors	• Can baseline technology achieve the objectives? • Can the specified technology be attained? • Are all the requirements known?	• Technology development plan • Paper studies • Design reviews • Establish performance margins • Engineering model test and prototyping • Test and evaluation
Internal Factors	• Can the plan and strategy meet the objectives?	• Resources - Manpower skills - Time - Facilities • Program strategy • Budget allocations • Contingency planning
External Factors	• Will outside influences jeopardize the project?	• Contingency • Robust design

Risk assessments are also required to ensure that a technical approach is valid, the maturity of design is understood, and that realistic cost and schedule estimates can be developed. The Study Team should explicitly list and categorize the technical risks and apply specific contingency factors, i.e., design margins, cost, and/or schedule, as appropriate to mitigate those risks. The design maturity of any portion of a system is an important factor in assessing the merits of one design over another. The data in Table 3-3 presents some guidelines on how to assess the maturity of a particular design and the probability of a redesign. For those cases where the technology advances the state-of-the-art, the use of engineering breadboard and other development tests should be done to a sufficient level to validate the approach before cost and schedule are agreed to. If this is not possible, then appropriate cost and schedule margins must be applied. The amount of contingency applied to a specific factor may be varied according to the stated constraints, as well as trading off one contingency factor against another.

It is common for major portions of a proposed mission or system to be at different levels of design maturity at any given time. For example, the AO for scientific instruments may be issued after completion of Phase A. Instruments are always pushing the state-of-the-art, whereas, for the most part, spacecraft designs have had the benefit of prior usage in similar applications. Generally, the most challenging aspect of a spacecraft design is the accommodation of the instruments. A technology development and risk mitigation plan should be developed early to identify the potential “tall poles” and the associated methodology to be employed to minimize the potential impacts. Examples of risk assessment and mitigation activities include analyses, development tests, and other engineering model/breadboard tests. It is preferable that all technology demonstration and development activities for the flight segment(s) be completed by the end of Phase B. If this is not possible, then appropriate schedule, cost, and design margins must be reserved for Phase C/D, or preplanned backup/alternative approaches be available for implementation.

Table 3-3. Design Maturity vs. Risk

Design Maturity	Uncertainty Criteria	Development Status	Confidence	Probability of Redesign
Normal, i.e., existing or similar designs used in a similar application	Negligible	• Fully demonstrated	Total	Negligible
	Low	• Partially demonstrated - few unknowns remaining	High	Remote
	Low to Moderate	• Well-established baseline • Substantial tests • Design criteria proven	Good	Low
Possible extension of state-of-the-art	Moderate	• Principles verified • Some data available • Some unknowns	Adequate	Possible
	Moderate to High	• Principles and technology established • Data not conclusive	Marginal	Likely
	High	• Principle established • Configuration not valid • Missing technology base • Limited test	Lower	High
	Very High	• Some elements of concept • Very limited or ambiguous data	Very Low	Very High
	Extremely High	• Principles unproved • Required state-of-the-art needs invention	Extremely Low	Almost Certain

3.9 Establishing Design Margins

The assignment and allocation of margins are an important risk mitigation technique. Proper handling of margins can greatly reduce the impact of unexpected changes in requirements, interfaces, and constraints. It can minimize the ripple effect of a concept or design change from one portion of the mission or system to other portions. Margins must be assigned carefully and take into account the maturity of the design, any development risks, risks associated with uncertainties in interfaces, other ill-defined factors, and cost.

For each performance parameter, there must be an associated margin. Development of margins starts during Pre-Phase A, is central to Phase A, and continues into Phase B. A fair and equitable distribution of margins to lower hierarchical levels must be implemented. Tracking the allocation of these margins is important, especially when requirements changes occur. Table 3-4 lists some margins and safety factors that are generally used for a typical scientific spacecraft. It is to be noted that margins are lowered as the design matures and is refined through continuing analyses and tests. As this occurs, it is acceptable to redistribute the allocations.

Table 3-4. Summary of Typical Design Margins and Safety Factors by Project Phase for an Unmanned Free-Flyer Scientific Spacecraft

	Project Phase / Parameter	Pre-Phase A	Phase A	Phase B	Phase C Pre-PDR
Technical	Weight	25-35%	25-35%	20-30%	15-25%
	Power EOL	25-35%	25-35%	15-20%	15-20%
	Pointing Accuracy	X2	X2	X1.5	X1.5
	Pointing Knowledge	X2	X2	X1.5	X1.5
	Pointing Jitter	X3	X3	X2	X2
	Propellant	30-35%	30-35%	20-25%	10-15%
	Data Throughput	30-40%	30-40%	20-30%	15-25%
	Data Storage	40-50%	40-50%	40-50%	30-40%
	RF Link Margin	6 dB	6 dB	6 dB	4 dB
	Torque Factor	X6	X6	X4	X4
	Strength Factor (Ultimate)	2.1	2.1	2.1	1.75
Programmatic	Cost (Including De-Scope Options)	25-35%	25-35%	20-30%	15-20%
	Schedule	15%	15%	10%	10%

All values given assume an average level of uncertainty or risk. They should be adjusted upward for items with higher than average risk or greater than average uncertainty. They should be adjusted downward for items with lower risk or uncertainty.

In order not to over-budget, factors and margins may be applied individually to portions of the system and then summed to define the system margin.

Certain design margins may be traded off against each other, e.g., weight vs. strength margins.

Increased dollar margins may be used to offset lower margins in other areas, e.g., technical performance or unknown development schedules.

Each project should generate a list of design margins and highlight critical parameters that must be tracked.

In order not to over- or under-allocate design margins and safety factors, the mission and system should be broken down into successively lower hierarchical levels until each portion has distinct levels of maturity and risk. For example, a scientific spacecraft might have relatively low margins assigned to portions of the spacecraft that are similar to ones previously designed and flown. A higher margin would be assigned to an instrument with small extensions to an existing design. A much higher margin would be assigned to an instrument design that advances the state-of-the-art. Each project should develop a list of critical margins and parameters to be tracked. Explicitly relating the status of these items as a function of time and keyed to significant milestones, de-scope options and back-up options can be a critical risk reduction activity.

3.10 Analyses and Trade Studies

Functional analyses, sensitivity analyses, and trade studies are performed by all disciplines during all phases to promote an optimized mission and system architecture, design, and configuration. These analyses provide a rigorous quantitative basis for the development of performance, functional, operational, interface, and design requirements. This includes intrafunction trade-offs of item designs to provide the balanced capability for fulfilling a given requirement that considers both technical feasibility and cost-effectiveness. The analyses also assess the effectiveness of alternative designs with respect to variations in environments and performance. It is important to consider all factors that affect the function, performance, or design requirement. Analytical models are generally constructed to enhance the analytical process. The parameters used in the analytical model must correlate to parameters expressed in the performance characteristics allocated to each associated function.

3.10.1 Functional Analysis

Functional analysis takes a functional or performance requirement at a given hierarchical level and determines the optimum distribution and implementation of the requirement at succeedingly lower hierarchical levels. This results in a hierarchical architecture that progressively divides and allocates how a function is to be accomplished down to the lowest common denominator. It is extremely useful in deciding where to cut the interface, especially when viewed in light of verification and accountability. By its nature, it is a highly iterative process.

3.10.2 Sensitivity Analysis

Sensitivity analysis is used to verify the capability of design solutions to satisfy higher-level requirements and to allocate, evaluate, and provide traceability of functional, performance, operational, and interface requirements to lower hierarchical levels. It is also used to assess the effect on higher-level performance caused by a variation in a lower-level performance parameter. This is accomplished by varying a particular performance parameter between its established worst case limits and as perturbed by worst case environmental stresses to determine the resultant effect on the next level performance parameter. Sensitivity analysis is a continuing process that updates and refines performance based on more mature performance data. The depth of detail depends upon the maturity of the design. Test data is used to confirm the validity of the analytical models constructed for the analysis.

3.10.3 Trade Studies

Trade studies are done to evaluate different ways of implementing a particular function or requirement to assist in the selection of the best way. Functional and sensitivity analyses are used in the conduct of these studies. Trade studies are done at the mission and system levels during Pre-Phase A and Phase A and at the subsystem level and for some components during Phase B. Different degrees of rigor are applied depending upon the study phase, i.e., less during Pre-Phase A and with increasing intensity and level of detail during subsequent phases. Before a trade study is started, weighted and prioritized evaluation criteria must be defined. The flow down of trade studies follows a plan that should minimize in-line decisions to other studies.

Trade studies are highly iterative and are used to ensure that all factors which might impact the function or requirement are considered, e.g., performance, reliability, safety, cost, risk, schedule, complexity, mission operations, data handling, and maintainability. The mission operations and disposal phase (Phase F) is often overlooked, or given minimal consideration, when trade studies are performed. The life cycle must be explicit in defining the operations concept and the benefits, or impacts, of the operations approach. A major consideration in the conduct of trade studies is the capability of the proposed design to accommodate de-scoping of requirements should this be necessary due to programmatic or technical performance perturbations. It must be noted that trade studies are used as a means-to-an-end objective, i.e., arriving at the best way of conducting a mission or implementing a design. Excessive and unnecessary trade studies may only result in an overly narrow design and the over-expenditure of usually constrained manpower and dollar resources.

3.11 Technical Performance Measurement

The tracking of the technical performance parameter is done to ensure that the convergence of predicted versus required performance is occurring as expected and to allow a judicious reallocation of the resource if required. Therefore, managing the risks and uncertainties associated with the development of new systems and technologies is critical to the orderly progress of the design effort. There are two different principal sources for the uncertainty: 1) inadequate definition of a new combination of familiar technologies and designs, and 2) the uncertainty of the results that will be obtained in the development and application of a new and unfamiliar technology. The problems associated with both kinds of uncertainties can be minimized by: 1) defining allocations and margins so that changes in one discipline area or hierarchical level have little effect on other areas or hierarchical levels and 2) rigorous tracking of predicted versus measured technical performance against a predetermined plan or criterion as a function of time.

For systems utilizing familiar technologies and designs combined in new ways, the margins and allocations can be firmly founded on past experience. These will typically depend both on the maturity of the definition, i.e., design, and on the maturity of the verification method (estimate, analysis including analytical model, test, etc.) used to determine the value of the parameter of interest. The definition and verification methods should span a range for the expected parameter, as shown in Figure 3-4. For example, weight allocations to be used in the design should be based on the lower limit of the available resource while strength analyses should be based on the upper limit. Predictions of structural frequencies might have to be done for both cases if both the lower and higher frequency cases were of concern. Since the design may be driven by either or both ends of the range, care should be taken not to assign excessive and unrealistic margins or to budget margins in such a way that they are not easily identifiable or trackable. As the degree of definition and verification progresses, the range of uncertainty decreases.

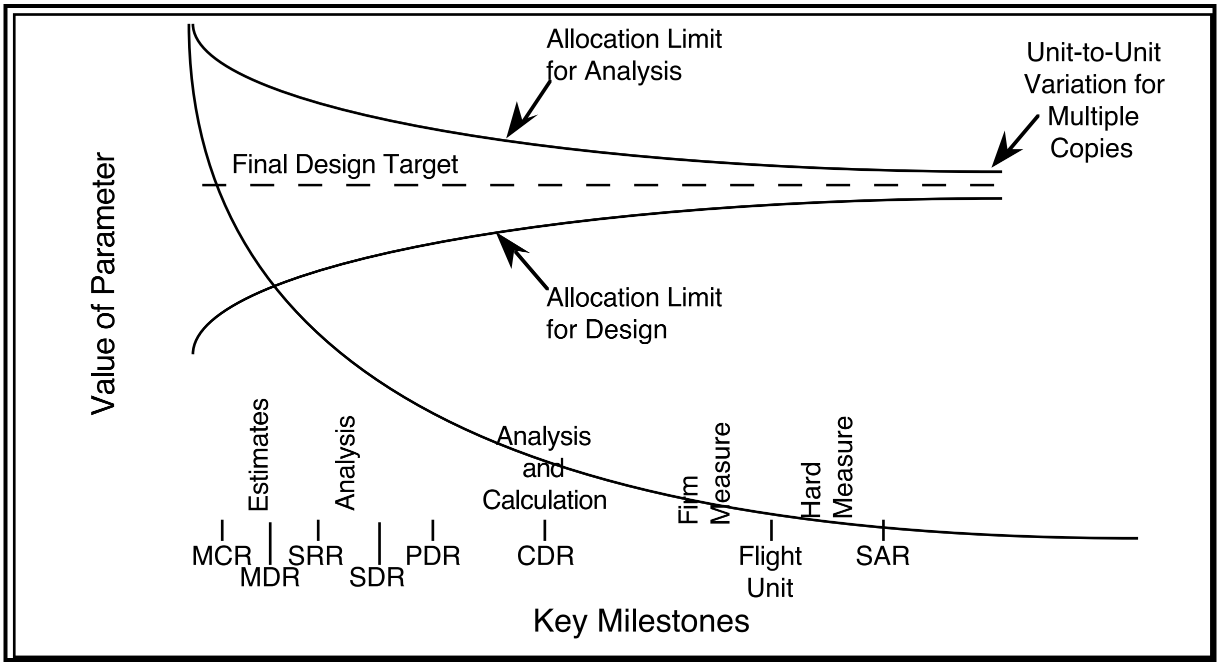
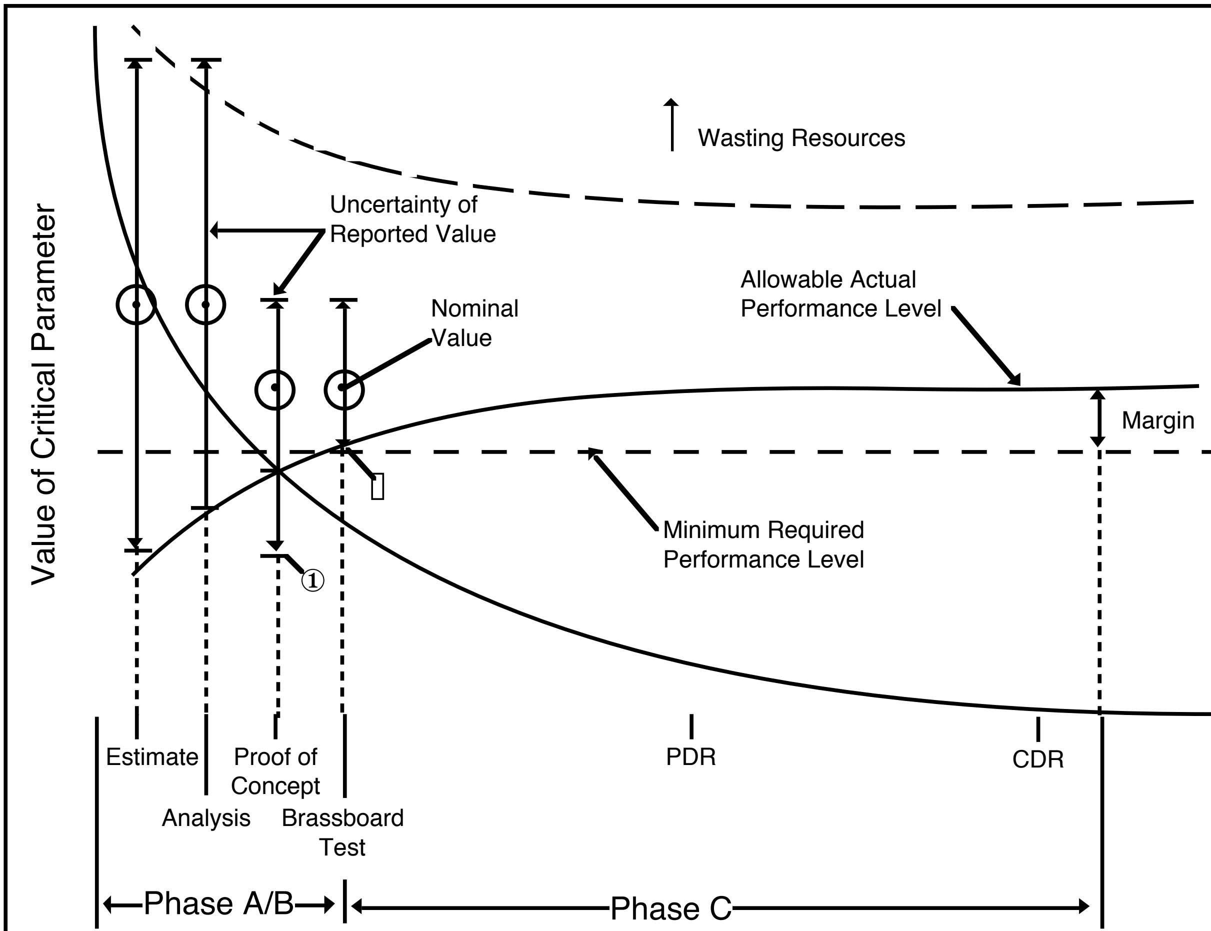


Figure 3-4. Technical Performance Measurement as a Function of Design Maturity for Familiar Technologies

In the development of new technologies, it may be difficult to predict within a narrow range what performance will be obtained. The general principles of allocations of margins and tracking should also be used but the expectation of orderly progress may be lower and the range of possible responses to problems larger. In general, the definition and verification process must begin earlier and be pursued more vigorously. For example, a succession of analyses, proof of concept, breadboard, brassboard, and engineering models may be required to bring the uncertainties to the required maturity level. The span between the "best" and "worst" performance that may be obtained will be large and must be taken into consideration in the design and definition of related hardware. An approach for dealing with situations such as this is presented in Figure 3-5. An overall plan describing both the required level of performance to be demonstrated and the uncertainty in that parameter as a function of time must be made. This plan should consider both the reasonable expectation of the development of the new technology and the level of uncertainty as a function of time that can be tolerated if the definition of related hardware is to progress appropriately. The tracking of the technical performance parameter should be done against this plan. If either the actual value of the critical parameter or the predicted value with the uncertainty factored in falls below the minimum requirement, i.e., "worst" case value, specific preplanned actions should be initiated. These may range from a reallocation of resources, to a redesign, to the implementation of a backup development, or to a de-scoping of requirements.



Notes: ① The approach must be reexamined if the lower limit of uncertainty falls below the minimum required performance level.

□ **Positive action** is required if the lower limit of uncertainty falls below the minimum required performance level.

Figure 3-5. Technical Performance Measurement for New Technologies

Section 4. The Conceptual Design Process—Pre-Phase A

4.1 Purpose of Pre-Phase A

Pre-Phase A is a basic mission study of limited scope which results in a single **strawman mission concept**. It is devoted to identifying and providing a justification for the mission, mission objectives, and mission requirements, and a technical description of how the mission will be accomplished. During Pre-Phase A, the customer is developing advocacy for the mission, while the engineering group is assisting to determine if the mission is technically feasible. Sometimes, firm constraints are **not** imposed on the study. When this happens, it is extremely important that the constraints—imposed or assumed—along with any other assumptions be explicitly identified and the impacts addressed. Both groups must ensure the technical approach, costs, and schedule are reasonable and realistic in order for the study to proceed into Phase A. Pre-Phase A studies are occasionally started without a formal approval to begin, without a schedule, and with nonexistent or insufficient funding. This may dictate a process less formal and structured than that described below. In this case, the study process must be compressed in proportion to the resources available. It is imperative that a well-thought-out plan be developed that especially concentrates on the most significant issues. In either case, the output products must be of a sufficient maturity to describe the following:

- One possible **strawman mission design and system(s) concept** supported by a feasibility estimate.
- A ROM estimate of resources.
- A validated and refined set of mission objectives and requirements.
- A set of prioritized and weighted concept evaluation criteria.
- Technical tall poles and risks.

4.2 Checklist for Beginning the Pre-Phase A Study

- Have the customer and engineering teams been formed?
- Have funding and manpower resources been identified?
- Have all the participants, internal and external, been identified?
- Have constraints and assumptions been identified?

4.3 A Generic Conceptual Design Study Process

Trade studies and analyses are performed to evaluate performance and cost factors for both the mission and the system(s) as a function of the mission requirements. As an example, for a spacecraft design the mission life duration will likely be a defined requirement. Trade studies for the life-dependent parameters, such as orbit selection, are influenced by the launch vehicle lift capability, orbital drag due to spacecraft projected area, spacecraft weight, orbit altitude, orbit inclination, ground coverage, and instrument performance. Alternative orbit selections will have different effects on system and subsystem designs and performance. Mission-level analyses are done to optimize the distribution of functional and performance requirements to the next lower level, i.e., system, and to succeedingly lower hierarchical levels. These analyses identify "tall poles" and provide inputs to develop more refined mission requirements to be carried into Phase A. Several top-level approaches should be identified so that a **strawman mission and system** architecture can be selected. It is important to consider alternative approaches so that a "reasonable" design can be selected and to minimize risk at the next hierarchical level. The intent should be to identify one good **strawman mission and concept** rather than the "best" or an "optimized" concept.

A generic conceptual design study process is shown in Figure 4-1. A summary of each of the activities within the flow follows.

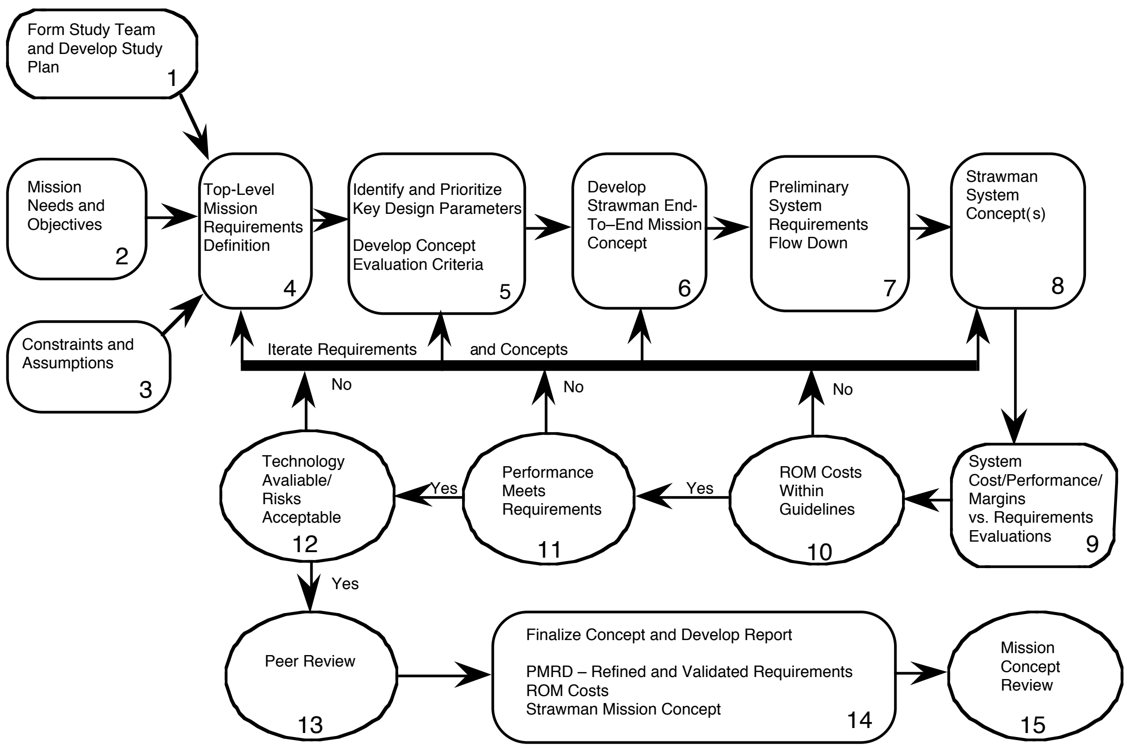


Figure 4-1. Representative Top-Level Flow for a Conceptual Design Study — Pre-Phase A

1. A multi-disciplined Study Team is selected and sized to conform to the mission to be studied. A Study Manager develops an overall study plan that defines key milestones to guide the Team.
2. The design process is initiated with a set of mission requirements that detail the mission objectives, top-level performance, and top-level programmatic guidelines.
3. A set of constraints in addition to the programmatic guidelines may be imposed, e.g., the selection of the launch vehicle and the use of existing hardware or technology. The Team may identify information that is needed to proceed with the study that has been unavailable or it may determine that the scope of the options to be considered must be limited. If this information is unavailable, the Team must then make reason-

able assumptions to obtain a complete, closed set of working requirements. The assumptions must be stated explicitly and tracked like any other input data.

4. The Team uses the mission objectives, programmatic constraints, and assumptions necessary to generate a preliminary set of top-level mission requirements. These are normally grouped into functional and performance requirements.

5. The Team, in conjunction with the customer, develops a set of evaluation criteria describing the relative importance of the various requirements and the priorities that are used in allocating margins and available resources above the minimum acceptable levels. Normal criteria include the programmatic guidelines such as cost and schedule, performance requirements, and risks. The Team may determine that additional categories are appropriate. In particular, robustness and flexibility should be considered whether it is done implicitly within other categories or explicitly as a stand-alone criterion. The Team identifies the design drivers, the key trade studies that are needed, and the desired output products. A flow down of trade studies is important so that individual designs are not impacted by an uncoordinated trade study effort that evolves without regard to other interfacing designs.

6. The Team develops an initial end-to-end mission concept to provide a working framework for requirements flow down. The initial strawman serves as a top-level configuration that indicates how well the design fits within the overall mission requirements and study guidelines.

7. Using the initial strawman end-to-end mission concept, the Team develops lower-level derived requirements to be used in the development of possible configurations.

8. A preliminary strawman design is configured to make an initial assessment of the mutual compatibility in terms of accommodations, top-level interfaces, performance criteria, margins, and the ability to stay within the programmatic guidelines.

9. From this configuration, the major design drivers are iterated, and more detailed or additional trade studies are identified. This process is repeated until an acceptable strawman concept is developed and reviewed by a peer review committee.

10, 11, 12. The strawman mission and system concept is typically evaluated against the criteria developed in Activity 5 described above. The Team may determine that additional categories are appropriate, and the criteria may need to be iterated and revised.

13. The peer review process should be ongoing and not limited to a single effort. The quality of the study is largely determined by the number and complexity of the options and issues that are identified and addressed. The review process is an invaluable aid in validating plans, trade studies, and conclusions, and in suggesting other profitable areas for exploration.

14. The conceptual design is documented in a report that clearly states the assumptions, conclusions, and recommendations for activities that should be done during Phase A. A major product of the Pre-Phase A study is the set of refined and validated requirements. Depending on the mission, these may be documented for internal use or given formally in a Preliminary Mission Requirements Document (PMRD). The report should describe the **concept/strawman** mission and system and correlate their characteristics to the requirements and programmatic inputs.

15. The concept is reviewed by appropriate senior personnel who will make the necessary judgments and decisions to carry the project into the next phase.

4.4 Pre-Phase A Reviews

4.4.1 Peer Reviews

The peer group is composed of individuals selected from outside the project according to their expertise in the applicable disciplines. Throughout Pre-Phase A, peer reviews should informally check the evolving mission concept against objectives, requirements, and constraints.

4.4.2 Mission Concept Review

An internal Center review(s) of all Pre-Phase A activities and products should be conducted prior to forwarding the Pre-Phase A report to HQ. Technical, management, resources, and scientific personnel should conduct the review.

4.5 Pre-Phase A Study Products

4.5.1 Pre-Phase A Study Report

The Pre-Phase A study report is usually a single document containing the elements described below. A PMRD may be generated as a separate item or incorporated into this report.

4.5.1.1 Mission Objectives Statement

The mission objectives statement identifies all mission objectives that are to be accomplished as defined by customer requirements. It states primary and secondary objectives that are important to the mission.

4.5.1.2 Mission and System Concept

The end-to-end mission and system concept describes each segment of the mission (e.g., ground, flight, and launch segments), the operations concept, mission flexibility/robustness considerations, internal or external constraints that are imposed, and any assumptions that are made. Care should be taken to ensure the concept describes the full end-to-end mission, especially the handling of data, i.e., acquisition, transmission, capture, archiving, analysis, and distribution. A brief description of alternative concepts that were studied may also be included.

4.5.1.3 Technology Maturity, Risk Assessment, and Risk Mitigation

The potential technologies that have been chosen, the technology readiness level, and the projected confidence and risk mitigation techniques needed to offset new technology items must be addressed. Alternative concepts and technologies that could be used to satisfy the mission requirements in lieu of the "new" technology should also be addressed .

4.5.1.4 Cost/Schedule

This study product states ROM cost and schedule estimates along with the method that was used to arrive at the cost and schedule estimates. Typically, the Pre-Phase A ROM cost and schedule estimates are performed using parametric modeling or are determined by comparison with a similar mission. Cost growth/contingency is applied as a function of the technical complexity. These estimates should include options for later consideration and explicitly state any assumptions that were made. A ROM-type funding profile should also be included.

4.5.2 Preliminary Mission Requirements Document

The PMRD contains the results of the requirements identification and derivation activities and a listing of the precedence and weighting of different requirements, constraints, and assumptions.

4.5.3 Institutional Capabilities Assessment

This document must be of a sufficient depth of detail to identify any requirements that may result in exceeding existing institutional capabilities, e.g., facilities and human resources.

Section 5. The Mission Analysis Process—Phase A

5.1 Purpose of Phase A

The purpose of the Phase A study is to **refine** the mission and system(s) requirements, determine a **baseline mission configuration and system architecture**, identify risks and risk mitigation strategies, identify the "best" candidates, and select one.

Early identification of mission design drivers is important, with the emphasis placed on resolving associated issues before the detailed effort begins. The most important aspect of Phase A is to identify alternative ways of accomplishing the mission and trading off the Pre-Phase A **strawman mission concept** and all other options to ensure the best way is selected. This is done by exploring alternatives, performing trade studies, and evaluating alternative concepts. Using classical systems engineering techniques, Phase A also aims to translate mission needs and objectives into a validated set of functional, performance and operational requirements.

A key aspect of Phase A is the establishment of the overall system architecture. For example, the improper allocation of functionality between the ground and flight segments may have serious impacts on development costs during Phase C/D as well as potentially greater cost impacts during Phase F. Arriving at a point design that is relatively inexpensive to develop and launch could very well complicate the operational phase and grossly inflate operational costs because of an extended mission life that may require excessive amounts of human intervention by the mission operations, data handling, maintenance, repair, or logistics teams.

Occasionally at the end of Phase A, it may not be possible to select a firm design before proceeding into Phase B. For example, this may be caused by a lack of firm requirements (e.g., instrument complement, fluid programmatics, etc.) or an ill-defined implementation/development approach. For those cases, the proposed Phase A design must reflect some options and the possibility of de-scoping some requirements, subject to further analysis.

5.2 Checklist for Beginning the Phase A Study

- Has HQ reviewed the PMRD?
- Has the Phase A Project/Study Manager been identified and appointed?
- Will the study be performed in-house, out-of-house, or a combination of both? For a contracted study, prepare the RFP. For an in-house study, identify key study participants and determine each participant's availability and the products to be delivered.
- Has funding been provided?
- Has a study plan been prepared?
- Has concurrence with the plan been obtained?

5.3 A Generic Mission Analysis Study Process

The Phase A flow is similar to the Pre-Phase A flow except that more detailed analyses and trade studies are conducted at the mission and system levels as well as at lower hierarchical levels. Pre-Phase A was a quick study to establish a **strawman mission concept** that appears technically feasible and can be developed within the directed (or defined) constraints. Phase A is a more thorough investigation of other options so that an optimized mission and system architecture and/or operations concept is developed. This is also supported by a more complete cost analysis.

The Pre-Phase A **strawman mission concept** is examined in detail to assess robustness with respect to functional and performance requirements. Alternative strawman concepts are also established and examined. Trade studies and other analyses are conducted in order to optimize the mission and system architecture and the functionality of each of the segments and elements. Risk assessment and mission classification factors are an important consideration in conducting these analyses. Each strawman design is further analyzed to establish functional, performance, operational, and interface requirements. Each design is iterated as necessary, considering all factors needed to optimize performance, validate and refine performance requirements, and to assess risk and cost. Each design should be decomposed into successively lower hierarchical levels as necessary to meet the study objectives. Different portions may require different levels of decomposition. The attributes of the decomposed design must then be recombined back up to the mission and system levels in order to effectively evaluate the overall concept using the predetermined evaluation criteria.

Evaluation and Selection of a Mission/System—A **mission** and **system architecture** should be baselined by the end of Phase A using appropriate and predetermined weighted and prioritized evaluation criteria to select the "best" of the candidate designs that were evaluated. It is important that the concept development and evaluation criteria be iterated appropriately to ensure that the best approach results. The optimum technical design may not be the best approach when evaluated against cost and schedule.

A generic mission analysis study process is shown in Figure 5-1, with each of the steps in the flow described below:

1. The study begins by forming a Study Team. The selection of the Study or Project Manager and makeup of the Team may be influenced by the activities that were done during Pre-Phase A. The Study Manager needs to develop a study plan with a milestone schedule that defines the optional concepts to be studied as well as top-level trade studies to be done. Generally, a list is requested from the discipline engineers for candidate studies that need to be incorporated into the overall plan.
2. The mission objectives are revisited and redefined as necessary.
3. The Pre-Phase A concept was based on some constraints and assumptions. Identification of other options may require that the directed (or defined) constraints not be violated. Additionally, it may be determined that the original as well as the newly derived constraints or assumptions may not be drivers applicable to the alternative approaches.

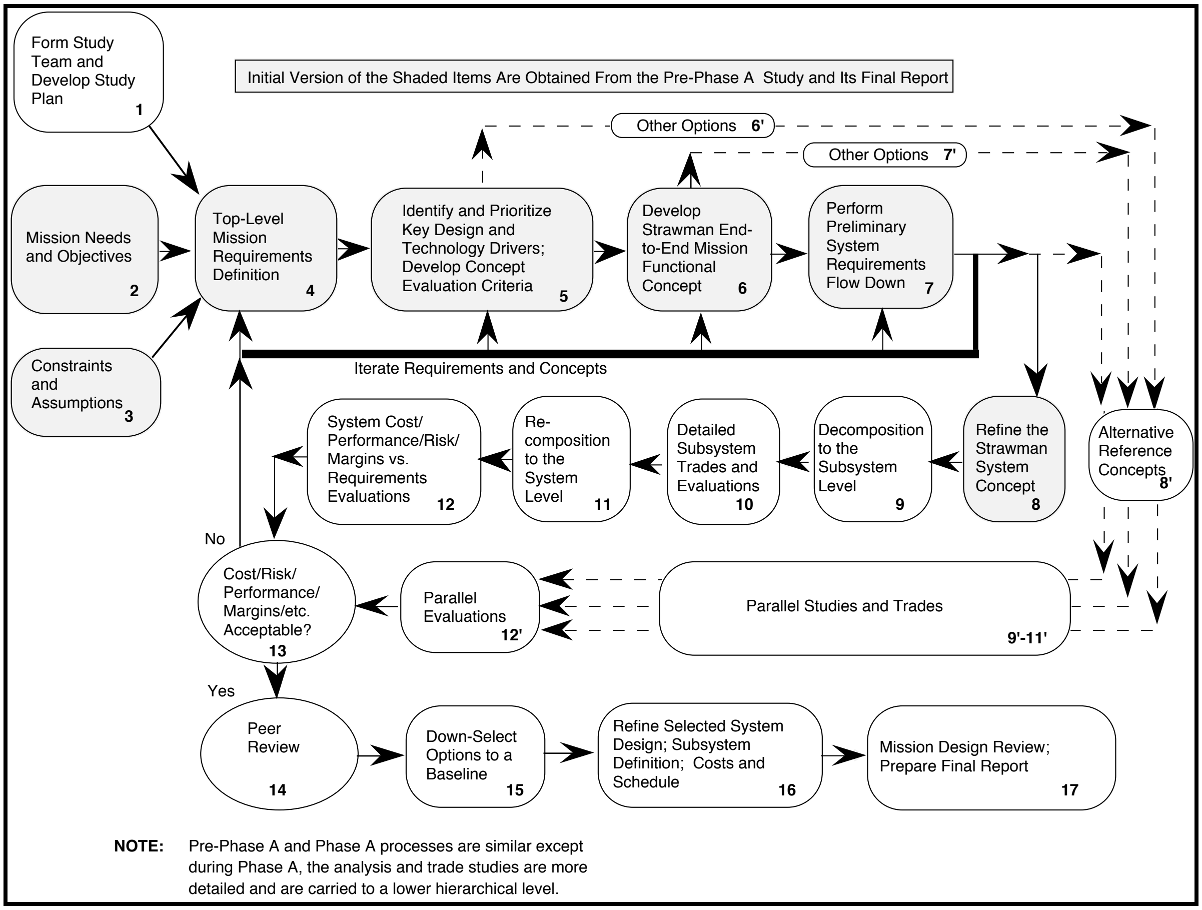


Figure 5-1. Representative Top-Level Flow for a Mission Analysis Study—Phase A

4. A Mission Requirements Document (MRD) is generated which provides the basis for the system design. This includes the stated mission classification and how the design will reflect this.

5. The preliminary study plan is reviewed by the Team members. Key mission drivers, design parameters, technology drivers, and trade studies are prioritized, and more realistic milestones may be generated. Some form of evaluation parameters or criteria are developed in order to assess the study results.

6. The end-to-end mission concept is iterated based on any redefinition or refinement of the mission objectives. This may result in a modified strawman design or just a fresh look at what had been passed on from Pre-Phase A. Alternative solutions may be possible that would have less risk, cost, and/or schedule impact. A mechanism is necessary to allow parallel concepts to be developed and evaluated against the selected design rather than using a single study approach.

7. Allocation of resources (such as weight and power) is made by a flow down of requirements. The solution to subsystem designs has to be developed within the context of the overall system requirements. Requirements allocation could be system configuration dependent. Therefore, it is necessary to maintain a traceability matrix

as to how the allocated requirements were distributed and the derived requirements were generated.

8. The system concept is iterated and refined based on outputs of analyses from the requirements flow down and resources allocations. The results of trade studies, cost analysis, risk assessment, and performance analysis all provide inputs into selecting the design. Selection of an alternative reference concept based on parallel trade studies has the greatest impact on the initial concept design process. The requirements flow down and the subsequent trade study, cost, risk, and performance assessment follow the same flow as the process used in the refinement of the initial strawman.

9. The system is decomposed into its subsystems and components. Resources (such as power and weight) initially allocated among the subsystems are further suballocated to the components.

10. Detailed trade studies are performed at the subsystem level. These trade studies are based on the defined and derived requirements and are accomplished using analytical models and related analyses to determine performance and margins. Often the requirements may not be totally defined and, therefore, some assumptions have to be made. These assumptions must be clearly stated so that the requirements can be traced through the requirements matrix. The selection of components may need to be made using an analytical model to represent other system components. Candidate components are placed into a subsystem model and evaluated against the original flow down of the system requirements but at the subsystem level. The choices at the subsystem level are made by assessing the availability of components; development risk and risk offsets; cost; and schedule.

11. The subsystems are re-composed into an overall system configuration.

12, 13. An end-to-end system performance evaluation is then made to verify that the mission requirements, programmatic constraints, and assumptions are satisfied. System margins and risk assessments are evaluated to ensure the evolving design remains within the acceptable boundaries. Physical and performance margins are evaluated against the mission requirements. Risk factors that flow upward are assessed relative to the overall system. At this point, the resulting risks are traded with the risk offset plans to determine if they are acceptable.

A cost assessment for the mission life cycle is made using both a grass-roots process and a parametric analysis. A preliminary implementation plan is generated to establish the basis for the cost estimate. The character of the costing exercise is very dependent on the type of mission being studied.

It is still possible to carry system options through the evaluation process and then select the most appropriate design as a baseline concept to carry into the review and selection process. The presumption in all cases is that the mission requirements and programmatic guidelines are met.

At this point, the system design is either passed onto the review process or the design is iterated until an acceptable design emerges. If a feasible design cannot be developed that falls within the mission requirements or budgetary guidelines, then the results are thoroughly documented and a briefing made to the appropriate managers. The study is either terminated or the top-level requirements are modified. This sometimes results in de-scoping the mission or breaking the mission up into different segments.

14. The review process includes a formal peer review of the selected design, although less formal peer reviews are generally conducted at intermediate decision points during the study. The peer review is a coordinated review that is designed to flush out any questionable issues that might exist. This review will assist in the down selection of a baseline configuration to be carried into Phase B.

15. Based on the recommendations and/or actions resulting from the peer review, an end-to-end mission and system baseline configuration is selected.

16, 17. The selected design is refined, and a Phase A study report and other supporting documentation are developed. A Mission Design Review (MDR) is conducted, which serves as the final buy-off of the Phase A baseline configuration. The design is then ready for proceeding into Phase B.

5.4 Risk Assessment and Mitigation

Risk assessment and developing plans to mitigate these risks are an important aspect of Phase A. The process must assess technical performance, design and technology maturity, cost, and schedule risks inherent in the approach being contemplated. Analyses are required to ensure the technical approach is valid and that any advanced technology and associated risks have been identified. The potential impact of uncertainties must be identified to ensure the best design emerges and adequate funding and schedule offsets have been allocated. Certain critical functional or performance requirements may require further assessment through the conduct of engineering/laboratory testing. System-level FMEAs may be required to identify mission and system-level critical single-point failures which may negate meeting the mission success criteria and violate the requirements of the mission classification as defined in NMI 8010.1A. Care must be taken to ensure the appropriate balance has been achieved between robustness, flexibility, cost, risk, mission classification, and mission objectives.

5.5 Mission Operations Considerations

One of the key Phase A trade parameters is the methodology selected for the conduct of post-launch mission operations. This includes operations, maintenance, logistics, data handling, and disposal. Data handling is intended to include data acquisition and capture, archiving, analysis, and distribution. All of these factors have serious life-cycle cost implications. The operational scenario must be defined and agreed to during Phase A because it has numerous implications throughout the remainder of the study as well as in design and development (Phase C/D).

In conducting the trade studies, proper emphasis must be brought to bear on all portions of the mission. Care must be exercised in the apportionment of operational functionality between the ground and flight segments. Minimizing flight segment development costs may result in excessive postlaunch operational costs, especially for those missions with extended orbital lifetimes. The reverse is also true. Another key input to these trade studies is the projected availability of institutional facilities and other resources needed to conduct the mission operations and the resultant data acquisition, archiving, analysis, and distribution. Once an operations concept and system architecture have been selected, only minimum changes should be permitted because of the potential for increasing cost.

5.6 Cost as a Trade Parameter

Meeting mission objectives and technical performance requirements should be the prime trade parameters in assessing the merits of one design over another. Life-cycle costs are an equally important trade parameter and should be addressed early so that cost-effective solutions can be found. The life-cycle cost must include full development (Phase C/D), deployment (Phase E), operations and maintenance (Phase F), and, if necessary, disposal. All organizations funding the life cycle must be involved in the review and approval process. Performance, life-cycle cost, and adherence to fiscal or funding profile limits cannot be optimized independently. Improvements in one area will necessitate compromises in the others. This approach, when properly applied, provides data necessary to evaluate each candidate design and then arrive at the best overall solution.

5.7 Cost and Schedule Development

The Phase A design and a preliminary implementation/development plan are used to establish a detailed WBS and schedule. A mission and system(s) cost estimate and funding profile are developed from the WBS and schedule using the grass-roots approach. Costs must also be estimated by a parametric analysis done by a group independent of the main study team. It is important that the grass-roots cost estimate be reconciled with the parametric analysis and any differences explained. Care should be taken to ensure that sufficient detail of the concept and an implementation plan have been generated to enable the development of realistic cost estimates. De-scoping of requirements must be considered in the estimate should funding levels be changed or should the refined and updated costs exceed the initial estimates to a significant degree.

5.8 Acquisition Strategy

The strategy intended for conducting Phase B, as well as the acquisition of the system(s) needed to implement the mission and to conduct the mission operations, must be defined early. If the Phase B effort is contracted out, then the activities and products (form, contents, and types) to be generated during Phase A may change accordingly.

5.9 Phase A Reviews

5.9.1 Peer Reviews

Peer reviews should be conducted periodically throughout Phase A. The group should be composed of individuals chosen from outside the project. Review of analyses, drawings, and other design documentation versus viewgraphs is recommended.

5.9.2 Mission Design Review

This review is keyed to the end of Phase A and evaluates the mission definition, system design, operational concepts, schedule, and cost estimates.

5.10 Phase A Study Products

The contents of some documents are not defined in detail because they may be driven by the type of mission under study. In other cases, the contents may be prescribed by an existing regulation, e.g., an NMI. Some of the document topics listed below may be combined and covered in a single Phase A study report. This report must have sufficient data and address the applicable topics listed in Table 5-1 so that the following questions can be answered:

- Does the conceptual design(s) meet the overall mission objectives?
- Is the design technically feasible?
- Is the level of risk acceptable?
- Are the schedule and costs within the specified limits?
- Do the study results show this option to be better than all others?

Table 5-1. Phase A Study Document Topics

❑ *Technology needs and development plan	❑ Data handling requirements
❑ *Refined and validated mission requirements	❑ Launch vehicle requirements
❑ Final feasibility assessment	❑ Mission operations
❑ Disposal requirements	❑ Preliminary Work Breakdown Structure
❑ Functional/operational description	❑ Refined cost estimates and schedules
❑ Hardware/software distribution	❑ Establishment of accountability for delivery of an end item and its performance
❑ Design requirements	❑ Apportionment of technical resources, the distribution of margins, and allocation error budgets
❑ Definition of top-level interfaces and responsibilities	❑ System-level block diagram, flight and ground
❑ System/subsystem description	❑ Maintenance and logistics requirements
❑ Mission description	
❑ *Top-level system architecture	

*Baseline configured products

5.10.1 Mission Requirements Document

The MRD describes each mission segment, identifies the objectives of each segment, and describes the operations concepts. It identifies significant design constraints and assumptions that are mission drivers. Major interface requirements that cross institutional, hardware, or jurisdictional boundaries are also identified.

5.10.2 Memoranda of Understanding (MOU)

MOUs are required when a formal contract is not applicable or required or when authorities or procedures are unavailable to execute a contract.

5.10.3 Technology Development Plan

A Technology Development Plan must be prepared when new or state-of-the-art technology is needed to satisfy the mission requirements. Proven and tried (flown before) "off-the-shelf" designs are the most desirable to use, but the nature of NASA missions generally pushes the requirements to the edge or beyond the capabilities of existing designs. Developing technology usually will not have flight history or test data to show that the design can withstand the expected operating environments. The plan, therefore, must state the status of the designs to be used and what is required to bring these designs to a flight readiness status. The plan must have a cost and risk offset discussion and what fallback or optional designs will be used in the event the technology cannot be developed to satisfy the mission requirements. The plan must have specific functional and/or qualitative performance demonstrations to be met as a function of time which can then be used as a basis for determining the realism of performance margins. The goal should be to develop and demonstrate technology readiness by no later than the end of Phase B.

5.11 Preparing for Phase B

Long periods of relative inactivity, changes to instrument complements and/or changes to requirements can occur between the end of Phase A and the beginning of Phase B. When this happens, a comprehensive review and revalidation of both the Phase A results and the Phase B study plan is necessary. At some point prior to beginning Phase B, a decision must be made on how the Phase B process will be conducted, i.e., done in-house, contracted out to one or more contractors, or a combination of the two. In any case, a Phase B study plan detailing the approach is required and should cover the following topics:

- Center work force requirements.
- In-house contractor support manpower.
- Schedule.
- Extent of in-house studies.
- Technology development/demonstration activities.
- Dollars required to complete the study.
- Acquisition strategy(ies).
- Evaluation criteria.

Toward the end of Phase A, preparation of a preliminary Project Initiation Agreement (PIA) should be undertaken. The PIA is an agreement between NASA HQ and the implementing Center. It defines project objectives and describes the end-to-end mission concept, technical/management interfaces, acquisition/development strategy, schedule/cost, resource plans, uncertainties (technical, cost, and schedule risks), contingency reserves, assumptions, and constraints. The PIA is eventually superseded by the Project Plan (PP).

Section 6. The Definition Process — Phase B

6.1 Purpose of Phase B

Entry into this phase occurs as a result of an approved Project Initiation Agreement (PIA). In some cases, an informal Pre-Phase B may take place if there is a delay in the beginning of the formal Phase B process. This may be needed for those missions where advanced instrument designs are under way and preliminary interface definition is needed. It is also appropriate if there have been changes in requirements or constraints since the completion of Phase A. If the changes from Phase A are too large, a Phase A recap may be needed to ensure that the top-level mission and system architecture, design, and conclusions still apply.

It must be accepted that the Phase B process should be only a refinement of the mission and system architecture and design established during Phase A. Once the mission and system architecture has been defined, subsystem and component trade studies are conducted to ensure the selection that best meets the functional requirements of the system architecture. Phase B converts the Phase A preliminary design into a more mature and final design that becomes the baseline for the generation of all data required for entering Phase C/D. Functional, operational, and performance requirements are refined. Interface requirements and specifications allocated to the subsystem or major component level are established. Firm costs and schedules are prepared for the transition from study to execution. RFP packages are prepared as appropriate. Once a detailed baseline configuration that satisfies all the mission and programmatic requirements has been established, the Phase B design, cost, and schedule are submitted to a NAR committee.

6.2 Checklist for Beginning the Phase B Study

- Has the Project Manager been assigned?
- Has there been a long hiatus between Phase A and Phase B and/or significant changes to requirements? If so, it is important that the results of the Phase A study be reviewed and updated as necessary to reflect the current guidelines and technology base.
- Does an appropriate and complete Phase A study report exist? If not, an equivalent product must be developed prior to the initiation of major Phase B activities.
- Have the Project Office, funding, and organization to support the effort been established?
- Has the acquisition strategy been determined?
- Has the Phase B study plan been approved?

6.3 A Generic Definition Study Process

A generic system design study process is shown in Figure 6-1. Activities conducted in each of the steps in the flow are summarized below:

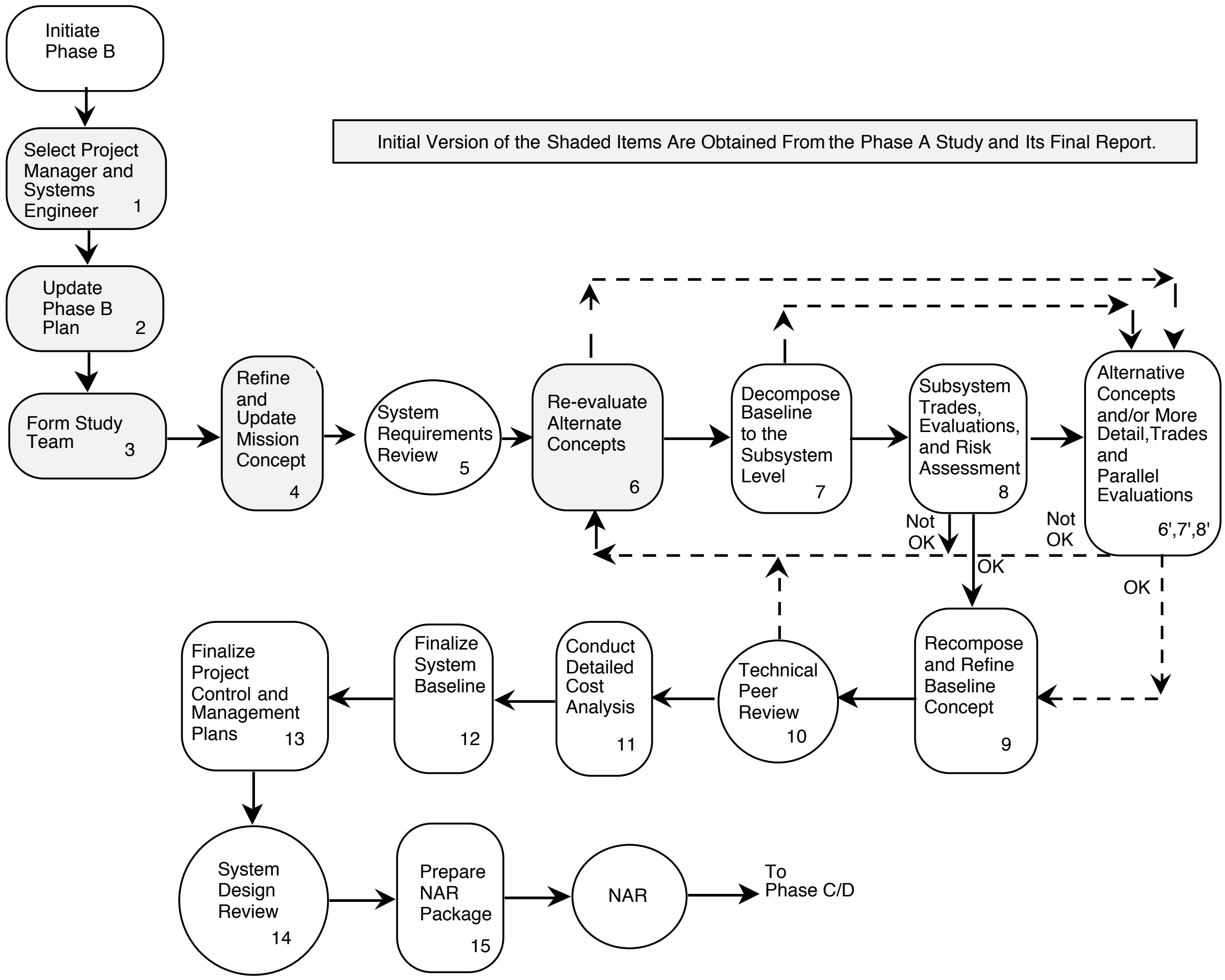


Figure 6-1. Representative Top-Level Flow for a Definition Study—Phase B

1. Phase B is initiated with the selection of the **Project Manager**, Systems Engineer, and other key participants.
2. The preliminary Phase B study plan that was developed during Phase A is reviewed, updated, and expanded to reflect any changes.
3. A Project Team is appointed. The Team is made up of discipline engineers that are or will consult with experts in the appropriate component areas. Generally, the Team meets on a routine (weekly) basis to review the status of the study efforts and to facilitate communications.
4. The Team reviews and refines the mission requirements where necessary. Based on this review, the mission concept is updated and all end-to-end external interfaces are refined and formalized. For a science mission, the ground/flight communications and tracking Mission Requirements Request (MRR) and Detailed Mission Requirements (DMR) documents are developed. The major subsystem interface requirements are developed, and the resource allocations are reviewed for completeness.

5. A peer review team of technical experts, including some who are not participating in the study effort, should review the mission and system **requirements** and architecture.

6. Viable alternative system options (concepts) that should be carried while selecting a point design are reviewed at both system and subsystem levels.

7. Once the baseline and options are defined, the concepts are decomposed into system and subsystem elements. The subsystems are further decomposed into their component parts, and the grass-roots technical designs and cost are formulated. The parametric cost estimate is also updated to reflect any changes. Several activities occur in parallel but are phased somewhat in order to ensure compatibility between subsystems. Some activities may depend on a satisfactory completion of a prior activity. Primary activities to be performed include:

   - Validate the allocated resources at the subsystem level.
   - Refine subsystem performance specifications.
   - Provide a more detailed WBS.
   - Expand the implementation plan to the subsystem level (PERTs).
   - Generate subsystem designs.
   - Perform trade studies.
   - Conduct subsystem performance and margins analysis.
   - Establish the redundancy scheme.
   - Expand the intra- and inter-subsystem (component) interfaces.
   - Risk assessment.

8. Within each subsystem, the component designs, technology, and availability are assessed for cost, schedule, and performance risk. The assessment may result in some alternative approaches in order to minimize or eliminate risks. If the preferred approach is the higher risk option, then it may be necessary to carry a fall-back approach that will offset the risk. These options are evaluated as to their effects on other subsystems. Use of new technology must be supported by implementing the technology development plan.

6′, 7′, 8′. It is possible that, during the detailed analysis of subsystem designs, the candidate components or configurations may not be acceptable and the designated margins or performance capabilities could not be met. Alternative concepts or more detail may then be required that would result in additional subsystem trade studies or the selection of an alternative configuration.

9. The results of the subsystem trade studies and performance analyses are recombined into a refinement of the overall baseline system design. The system margins are reviewed and reallocated as necessary within the constraints of the requirements. The trade studies and resulting design must address the mission operations concept. If the resulting system design falls within the requirements, then it is baselined as a candidate point design.

10. A technical peer review is conducted. The system design is reviewed against the mission requirements, performance goals, and the development/implementation risks.

11. A detailed grass-roots cost estimate is performed. This must be backed up with an independent parametric cost modeling estimate. Differences between the two estimating techniques must be reconciled and explained. If the cost and schedule assessments have uncovered an unforeseen risk in meeting the mission objectives, then it may be necessary to return to an alternative approach.
12. The baseline system concept is finalized as the point design, and the design, analysis, and margins are summarized in a Phase B Study Report. Detailed subsystem functional and performance requirements and specifications are prepared, and interfaces defined in IRDs. The IRDs and specifications are maintained under configuration control.
13. Project management and control plans are developed. System, subsystem, and component specifications, and SOWs are developed.
14. A System Design Review (SDR) is conducted by senior-level management, technical, and resources personnel.
15. If required, the design may then be presented to a NAR committee.

6.4 Risk Assessment and Mitigation

The risk assessment started during Phase A must be updated to account for any changes. It should be carried to a greater level of detail to identify mission, system, and subsystem-critical single points of failure. The risk assessment may be refined by conducting engineering breadboard-level tests in those areas where the technology risk may be high. **By the end of Phase B, all significant new technologies and/or new uses of old technologies should have been demonstrated.** If this cannot be done, explicit backups and/or parallel developments should be executed.

6.5 Cost and Schedule Refinement

The Phase B design refinement provides the final data used to develop a detailed WBS and schedule. This data is then used to update the grass-roots cost estimate and funding profile over the life of the mission. This estimate is performed by starting at the lowest hierarchical level and accumulating task-by-task and hardware/software costs up to the highest level, with identified heritage and vendor estimates included where available. The parametric (cost modeling) estimate developed during Phase A is updated to reflect any changes and is used as an independent check on the grass-roots cost estimate. All differences must be reconciled and explained.

System development costs will have become firm because the details of implementing the requirements are well understood. Additionally, the full operational and ground data handling scenarios will have been refined to permit a complete assessment of the life-cycle cost. The final output must contain a detailed cost breakdown including Center and contractor support manpower estimates; hardware/software design, development, test, and evaluation costs; launch and support service costs; flight operations costs; maintenance and logistics costs; disposal; data handling, i.e., acquisition, archiving, processing, and distribution costs; facilities; and associated contingency allowances. The cost estimates must be iterated against the funding profile constraints. Because of these factors, it is at this point that a Center sign-up to a “not-to-exceed-mission-cost” should be exercised.

6.6 Phase B Reviews

6.6.1 Peer Reviews

The peer review process started during Phase A should continue throughout Phase B. The technical part of the review should also examine associated cost and schedule data.

6.6.2 System Requirements Review

The primary focus of the SRR is to verify the realism of the functional and performance requirements, ensure their congruence with the mission and system configuration, and ensure the mission objectives can be satisfied.

6.6.3 System(s) Design Review

The objective of the SDR is to demonstrate that an acceptable system configuration has been defined and the requirement allocations are complete for all portions of the mission. The primary focus of the SDR is to show that a system can be built which will satisfy the mission objectives. More than one review may be necessary if more than one system is required to conduct the mission. If necessary, the system(s) design reviews are summarized and then evaluated from a total mission standpoint.

6.6.4 Non-Advocate Review

NASA HQ will appoint a NAR team of experienced management, technical, and fiscal personnel from outside organizations to: review the project; assess technical risks, schedules, and costs; and assess readiness for proceeding into Phase C/D. The NAR should occur well into Phase B when the mission definition and systems design and attendant costs are well defined. An ongoing liaison between the Project Manager, HQ Program Manager, and NAR Chairperson will contribute significantly to the effectiveness of the NAR. It must be demonstrated to the review team and upper management that:

- The proposed mission is adequately defined scientifically, technically, and programmatically.
- The objectives of the mission are sound and properly support NASA’s objectives.
- The program and project offices have properly coordinated with other program and staff offices, with the Centers, and with appropriate organizations outside of NASA to assure that the technical, operational, managerial, and procurement aspects of the proposed effort have been adequately defined and assessed.
- Programmatic risks have been assessed, acceptable offsets or alternatives have been identified, and necessary resources have been allocated.

The NAR package in general will address the management structure, technical approach, and resources required to implement and conduct the project.

6.7 Phase B Products

The study products listed in Table 6-1 have been identified as those generally required to proceed from Phase B into Phase C/D. Not every product is required for every mission or system, but most are required in some form. Some of the products may exist as a named independent document, whereas others may be incorporated into common documents. In general, larger and more complex missions and those crossing more organizational or jurisdictional boundaries require more formal, separate and detailed documentation. The key issue is to make the information accessible to all who require it and, at the same time, maintain control of the documentation to protect the integrity of the data.

Data requirements descriptions should be as high level as possible and focus on the minimum required information content. Excess documentation and extraneous information content can be damaging since they are costly to produce as well as extremely cumbersome and time consuming to sort through. On the other hand, documentation that includes insufficient data will cause inaction or require assumptions to be made which, if made incorrectly, will lead to wasted efforts. In general, it is more productive to begin with the minimum perceived complete set of data and add to it as circumstances dictate. When working across organizational boundaries, careful consideration should be given to using existing and/or proven documents and processes both within the government as well as with contractors.

Table 6-1. Typical Phase B Products

- ❑ Baseline systems description
- ❑ Configuration management plan
- ❑ Contamination control plan
- ❑ Data handling plans
- ❑ Data management plan
- ❑ Detailed Mission Requirements Document
- ❑ Disposal plans
- ❑ Documentation management plan
- ❑ Firm life-cycle cost and schedule
- ❑ Interface Requirements Document
- ❑ Preliminary Interface Control Document
- ❑ Logistics plan
- ❑ Maintainability plan
- ❑ Manufacturing, integration, and test plan
- ❑ Materials, processes, and parts plans
- ❑ Mission Interface Requirements Document
- ❑ Mission Requirements Request
- ❑ Non-Advocate Review package
- ❑ Operations plan
- ❑ Performance measurement plan
- ❑ Preliminary system and subsystem specifications
- ❑ Project Management Plan
- ❑ Project Plan
- ❑ Proof of concept results/technology demonstration results
- ❑ Reliability and quality assurance plan
- ❑ Request for Proposal package(s)
- ❑ Risk assessment
- ❑ Software management plan
- ❑ Project-level Work Breakdown Structure
- ❑ Staffing Plan
- ❑ Statements of Work
- ❑ Support equipment requirements
- ❑ System engineering management plan
- ❑ System Implementation or Acquisition Plan
- ❑ System safety plan
- ❑ Training plan
- ❑ Verification matrix/plan/specification

6.8 Preparing for Phase C/D

A properly conducted Phase B study must be an exhaustive and complete system design and planning effort that has been scrutinized, reviewed, and thoroughly documented to the satisfaction of advocates and non-advocates At the end of Phase B, system performance specifications, subsystem specifications, acquisition plans, and implementation plans are completed. Preparation of the procurement packages (RFPs) allows for the transition into Phase C/D. However, because of budgetary considerations, there may be an interim period following Phase B. The interim period from the end of Phase B until the start of Phase C/D can be used to complete the assignment of individual project team members and to set up the Project Office. The personnel that conducted the Phase B study should be assigned to Phase C/D to ensure continuity of experience. Additionally, during the interim period, review, refinement, and/or completion or addition of documentation necessary to produce and verify all elements of the design and manage programmatic commitments can be accomplished. The RFP package(s) should be reviewed and amended as necessary, and the appointment of Source Evaluation Boards (SEBs) for the evaluation of proposals should be made. Procurement of long lead items (for in-house projects) can be initiated to improve schedule considerations.

Section 7. Conducting a Compressed Study

Occasionally, situations arise where a mission must be developed and launched on an extremely tight schedule without the benefit of an ideally structured Phase A/B process that would address numerous options and determine the best fit for the mission. When faced with a scenario such as this, the Study Manager must be very cautious in devising a solution to the problem. It should be recognized that all portions of the study process must still be executed although the scope may be limited and the assumptions simplified to reduce the time and resources expended. It should also be recognized that a compressed study presents the risk of an inadequate design in some areas, and hence a potential for a later overrun. A top-level flow is shown in Figure 7-1.

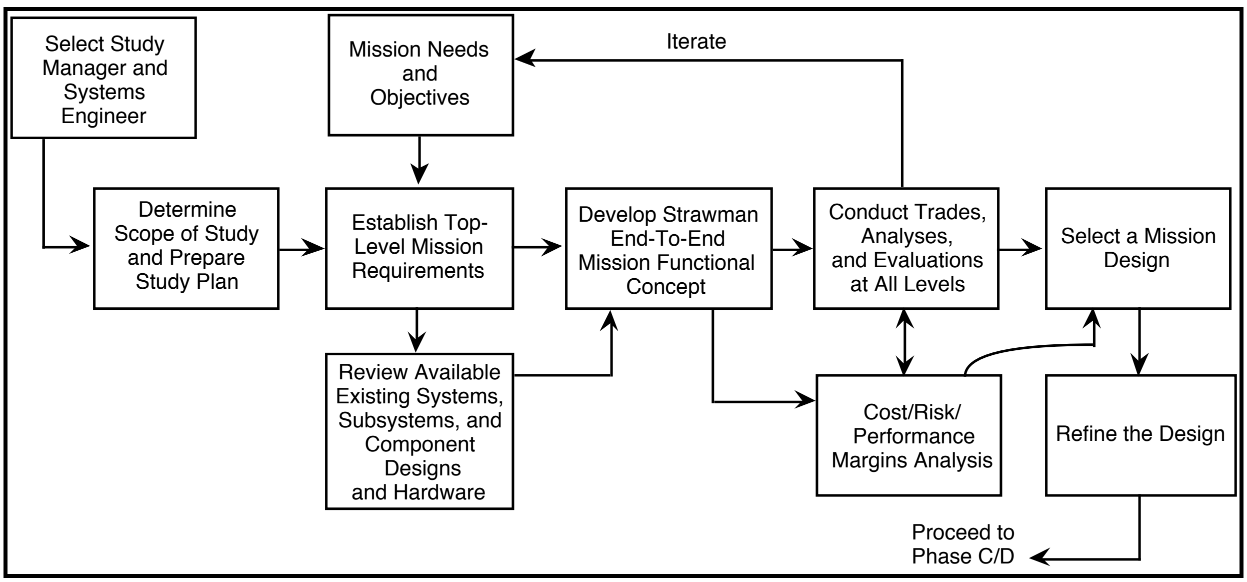


Figure 7-1. Representative Top-Level Flow for a Compressed Mission Design Study

It is imperative that the Study Manager identify what may be missing or inadequate. Some examples are: improperly identified and validated top-level requirements, risk identification and offset strategies, valid ROM costs and schedules, and systems concepts trades and down selection. Furthermore, it is most critical to compensate for what is missing. For example, evaluate what information is missing, identify what requirements or constraints have changed, determine if faulty assumptions were made, and evaluate the risks and risk management plans to be sure they are still complete and appropriate.

Compressing the study timeline necessitates shortening the communication lines and streamlining the decision-making process to enhance the concurrent engineering process. The psychological impact on personnel must also be considered since the people involved may tend to subconsciously implement the mission in the structured manner with which they are accustomed.

The compressed timeline also requires the maximum utilization of existing designs and hardware. Changes to these existing designs or hardware should only be made to ensure that the design/hardware can operate as intended and not to make them better or overly optimize the approach to accomplishing the mission.

In conducting the compressed study process, it is imperative that the entire Team take instruction only from the Study Manager. Daily design meetings are required with participation by all lead discipline engineers. A prioritized list of activities **must** be developed. Each activity should be characterized in terms of the depth of knowledge and definitions and its impact on the study as well as the mission. The majority of the effort should be expended on those items that are deemed critical or are not well-defined. The list should also identify those activities that are only looked at in a cursory manner and the associated rationale. Problem areas must be identified and resolved in near real-time, with trade-offs done on-the-spot or action items assigned for short turnaround and resolution. Technical and managerial risks must be identified and analyzed, and risk offsets immediately implemented. Finally, because the Study Team may be too involved in the technical details and could possibly lose its objectivity, peer review groups composed of unbiased technical experts must conduct detailed in-depth reviews of the mission, system, and subsystem designs.