Bendix

Aerospace Systems Division

Mr. I. R. Extra

| NO. | REV. NO. |
| --- | --- |
| ASTIR-TM-24-1 | A |
| PAGE 1 OF 52 | |
| DATE Jan. 1975 | |

# SYSTEM ENGINEERING APPROACHES FOR SPACE EXPERIMENT SYSTEM PROGRAMS

R. Wallace
ALSEP Project Engineer

B. Rusky
Manager, ALSEP

# PREFACE

The purpose of the discussion in this technical memorandum is to establish a perspective and motivate some thought on the program role of the system engineering function for those who are responsible for operational requirements and development of space flight scientific experiments. The objectives of a system engineering function, as stated in the academic literature and/or government agency policies and specifications, are, in the main, definitive, clear, and non-controversial. Nonetheless, effective organizational responsibilities and timely implementation of system engineering requirements to achieve cost-effective equipment performance goals are not so easily perceived nor planned for a particular program of unique complexity, as was exemplified by development of the Apollo Lunar Surface Experiments Package (ALSEP) for the Apollo program. The implementation of system engineering requirements, as was developed for ALSEP by NASA, Bendix, and Principal Investigators as the program evolved, are discussed in the report and are presented as a basis for planning future scientific experiment programs — programs consisting of a single experiment or which consider simultaneous development of "experiment clusters", as in the case of ALSEP "packages".

The roles of system engineering within typical program organization are discussed, but by no means should the reader regard organizational elements as presented within programs as "absolute" for the achievement of system engineering goals. Rather, one should view the various program organizations discussed in this report, in terms of whether or not a particular organization does, in fact, permit multiple inter-disciplinary plans to effectively focus for timely system engineering evaluation and decision-making to achieve equipment performance, schedule, and budget requirements. Too often, we bog down on "who" within an organization is responsible for "what" and "when" while the essential need for a "cohesive whole" escapes us. As such, the contractor's ALSEP program organization during a particular phase of the program may or may not be entirely suitable for other business organizations. Program organizations can vary but there is, it seems to us, no substitute for a strong, effective system engineering function, able to counsel management and plan the criteria for the efficient integration and implementation of total program requirements and goals.

CONTENTS

## ILLUSTRATIONS



## TABLES

## 1.0 INTRODUCTION

System Engineering is that part of a technical program's Management System which defines the system and performs integrated planning and control of the program efforts of design, system support, production engineering, test, and evaluation engineering. "It places together under a single command all of the technologies, skills, and resources required to realize the program".[1]

This technical memorandum discusses theoretical aspects of System Management, defines typical System Engineering Tasks, reviews the System Engineering approach used on the ALSEP program, and concludes with recommendations for future programs.

## 2.0 SYSTEM ENGINEERING MANAGEMENT

### 2.1 OBJECTIVES

The following objectives of System Management are summarized from AFSCM 375-4, Part 1.[2]

a. Ensure effective management of the definition, acquisition, and operation of the system.

b. Balance the factors of performance, time, cost, and other resources to obtain the required system.

c. Minimize technical, economical, and schedule risks during the development and production effort.

d. Control changes to system requirements during development and production.

e. Establish a high probability of success in obtaining a timely, economical, and suitable system.

f. Document decisions concerning the program.

---

* References are located in Section 4.4 at the end of this report.

g. Manage and control the efforts of subcontractors.

h. Identify the significant actions to be accomplished by all groups.

i. Establish requirements for flow of information between responsible groups.

j. Accomplish or manage the accomplishment of the actions identified for the definition, acquisition, and operational processes.

## 2.2 ORGANIZATION AND RESPONSIBILITIES

The operation of the "system engineering process" can be viewed as a multiple feedback loop control system which makes continuous trade-off studies of actual versus desired system parameters to assure that only the most effective modifications to the system baseline are implemented.

A program basically consists of four phases: (1) definition of customer needs, (2) analysis of the problem and formulation of a solution, including statement of resource requirements, (3) mechanization of the equipment to implement the solution, and (4) verification that the equipment functions within specification in the expected environments.

In a small program, one individual may provide the system engineering management, direction and coordination for the various groups. In a large program, a management team must perform the various system engineering management functions required to satisfy the requirements of the different phases. The transitions between phases must be anticipated and the subordinate management adjusted accordingly by the Program Manager.

A typical large program may have three organizational levels, from Program Manager, through System Engineering Manager, to the design level, as shown in Figure 2-1. The System Engineering interfaces are shown diagrammatically in Figure 2-2.

Here, system engineering is a line function. In some organizations, the function is a staff position and may advise over several programs or it may be at a project level with the design groups under an engineering manager.

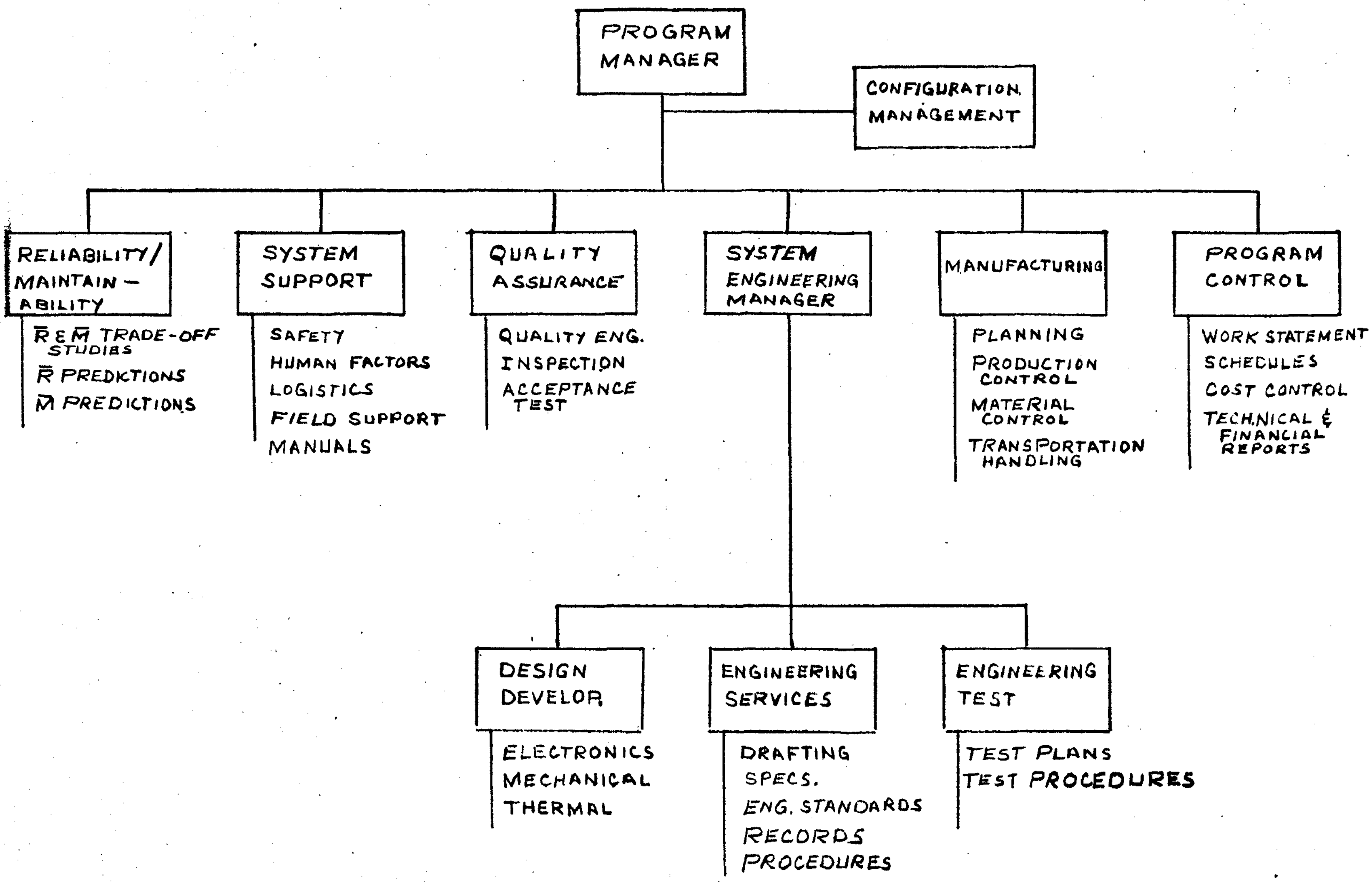



Figure 2-1 Typical Organization for a Large Program

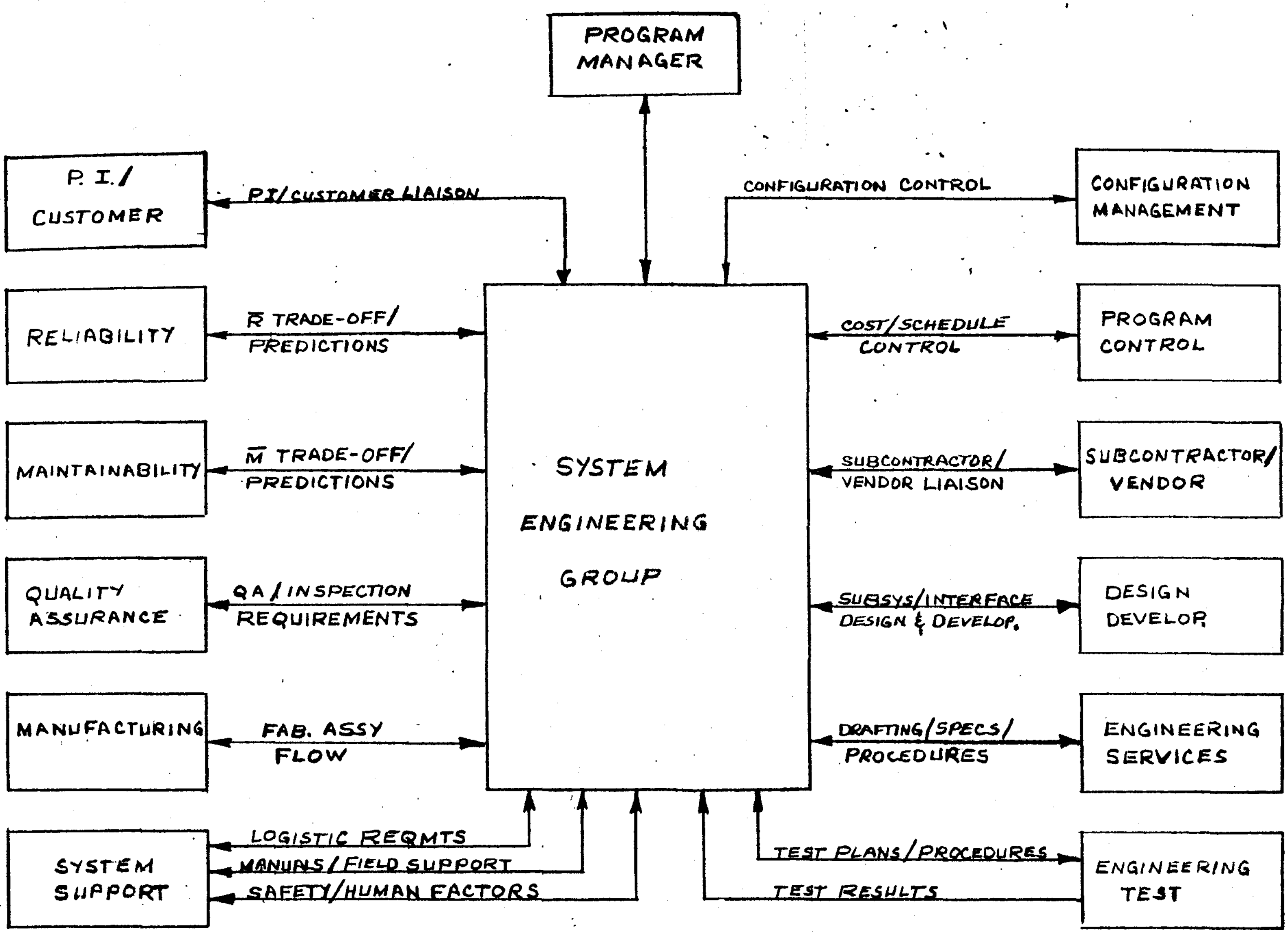



Figure 2-2 System Engineering Interfaces

## 2.3 SYSTEM ENGINEERING MANAGEMENT TASKS

"The contractor's system engineering process shall be a logical sequence of activities and decisions leading to the definition of the configuration, usage, and support of a system and the technical program for acquiring the system".[3]

The sequence of activities includes the following:

a. Concept formulation.

b. System definition.

c. Acquisition.

d. Deployment.

e. Phase out.

In accomplishing these activities, the following tasks are unique to systems engineering:[4]

a. Quantification.

b. Iteration.

c. Interdisciplinary approach.

d. Interface analysis.

e. Maintenance of communications feedback loops.

The extent to which particular system engineering tasks are applied to an individual program depends upon consideration of such items as objectives, program phase, detail of prior definition, program constraints, number and complexity of interfaces, and the functional uniqueness of the system. All of the requirements are not necessarily appropriate or sufficient for all program types. The prime tasks are to formulate the concepts of the solution to the problem, define the system, and integrate the efforts.

System engineering is a management technique; its main operational tasks are therefore an iterative process of analysis, monitoring, and control. This process is present, although perhaps not evident, in any technical design/development situation from the smallest of elements, such as the design of a circuit, to the largest as in the development of the Viking Spacecraft. In the former case, the circuit design engineer may perform the system engineering tasks and subsequent to the initial design will review the constraints originally placed on the circuit such as:

a. Power consumption.

b. Heat dissipation.

c. Volume.

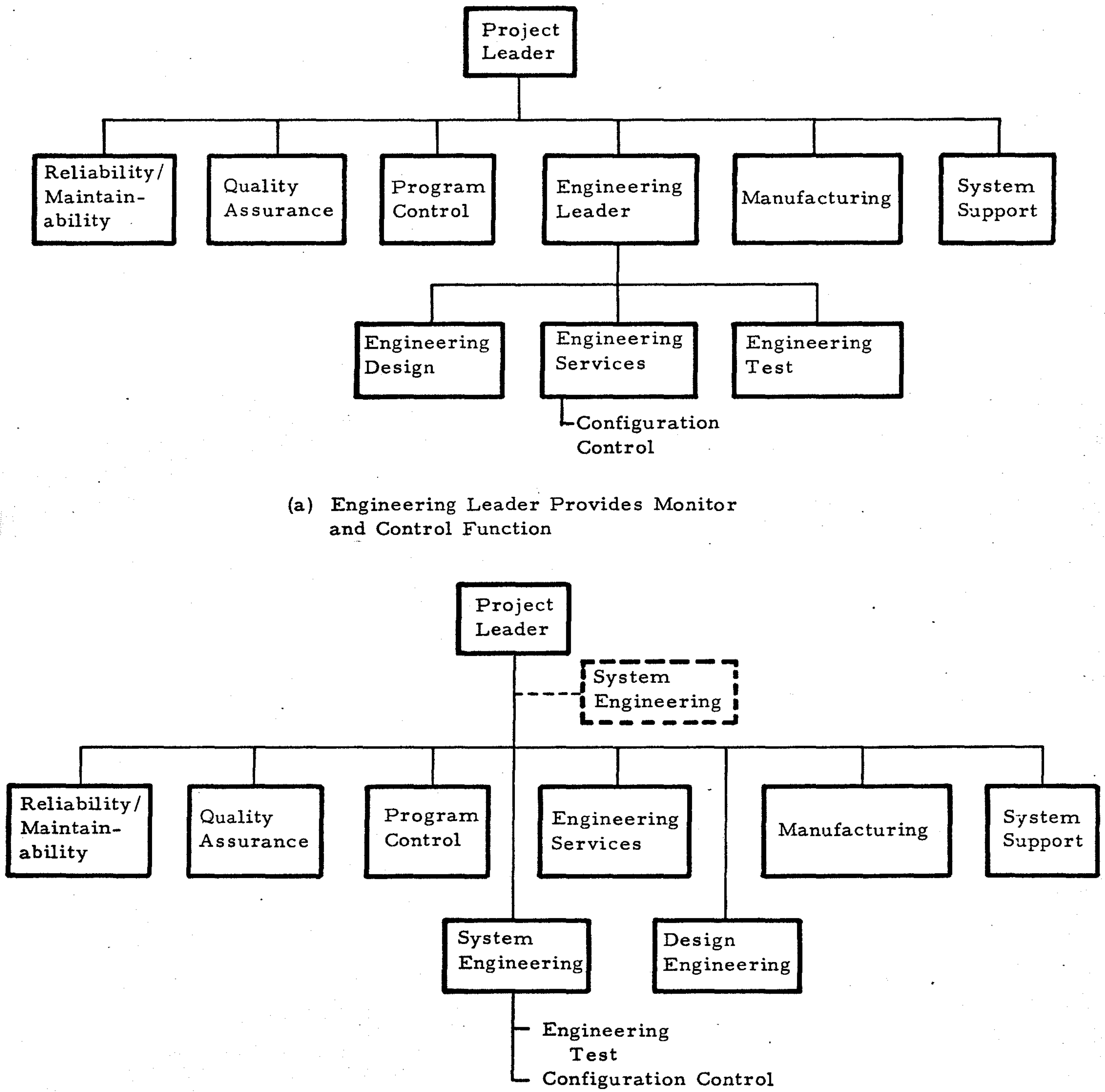
d. Weight.

e. Input/output.

f. EMI.

If the design does not meet its interface or performance criteria, the designer then seeks relief either by modification of the original constraints or by redesign. As the size and complexity of the design/development tasks grow, so the magnitude of the management task increases to the point where an individual project leader cannot cope with maintaining a close surveillance of all technical phases while meeting the demands of cost and schedule. At this point, a single individual may be appointed "system engineer", "assistant project leader", or "engineering leader" with the delegated responsibility for monitoring the technical developments and providing control, or for providing an input to control. The organizational difference between "providing control" or providing an "input to control" is shown in Figure 2-3, where the system engineering "input for control" may be provided as a line function or staff function. The relative merits of either organization depend on the circumstance and the strengths and weaknesses of the individuals involved at the time of the forming of the organization.

As the magnitude of the design/development task becomes larger, the role of system engineering management increases to the point where an identifiable system engineering organization is required. This organization or group would play the same role, as discussed above, and the total organization would take the form shown in Figure 2-4.

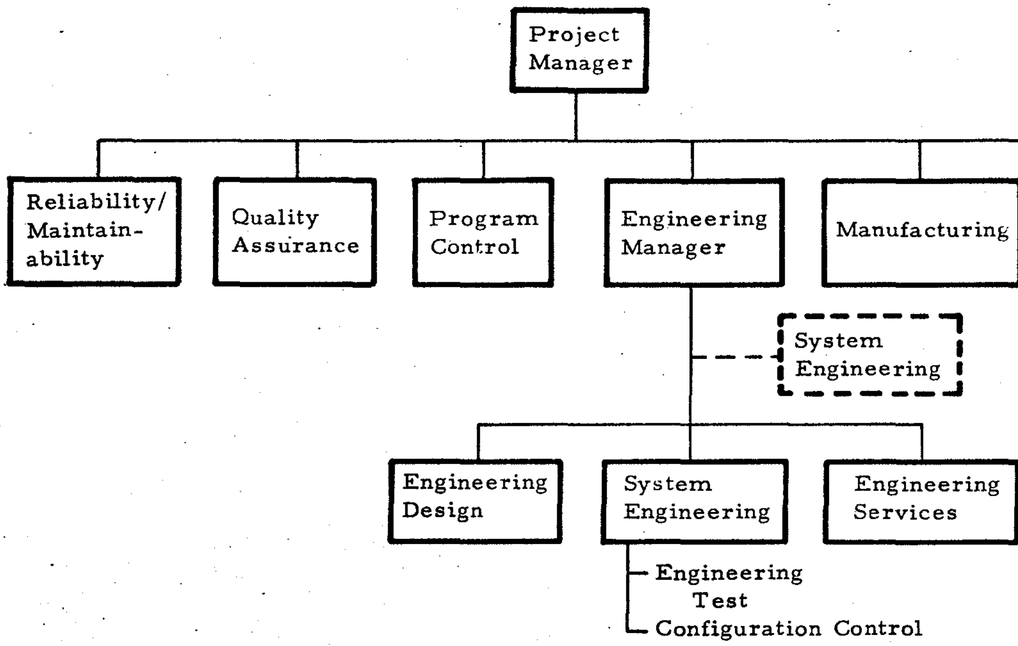



(a) Engineering Leader Provides Monitor and Control Function

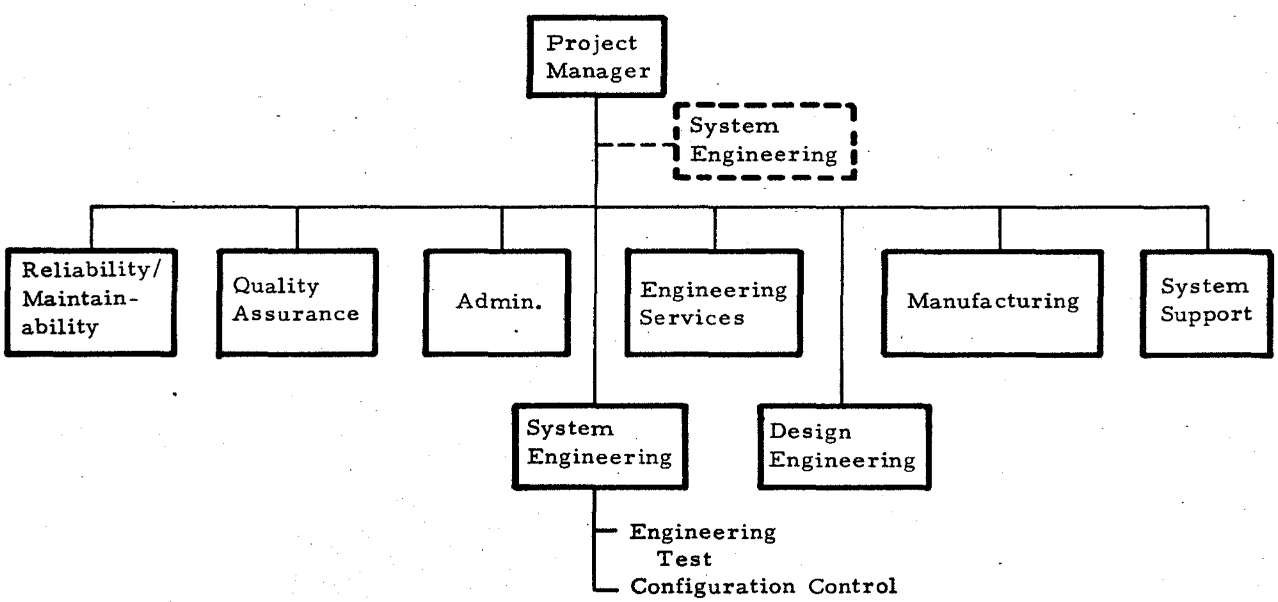


(b) System Engineering Provides Input for Control; Project Leader Provides Control

Figure 2-3 Project Inputs and Control




(a) Engineering Manager Provides Control; System Engineering Provides Input for Control




(b) Project Manager Provides Control; System Engineering Provides Input for Control

Figure 2-4 System Engineering Organization Options

From the above discussion, it is seen that system engineering is a management tool which provides a means to monitor the technical progress of development and to provide an output for control of technical development. The system engineer/group therefore works with the mechanical, thermal, and electrical design engineers/groups and provides the technical overview as development progresses, providing the necessary feedback to the project or engineering manager as required to control development within the requirements, cost, and constraints dictated by the program.

## 2.4 TYPICAL SYSTEM ENGINEERING RESPONSIBILITIES

Space and military systems generally employ a logical step-by-step developmental sequence which may be divided into four phases:

Phase A - Conceptual
Phase B - Definition
Phase C - Development and Qualification
Phase D - Mission Support

System engineering processes apply to all phases; the iterative process of developing requirements and constraints, alternative solutions, and then comparing solutions to requirements for additional modification may be seen from the flow charts for Phases A and B provided in Figures 2-5 and 2-6. By completion of Phase B, sufficient analysis and definition has been accomplished to commit funds to the relatively more expensive tasks of developing hardware. Section 2.4.1 describes typical Phase C/D System Engineering tasks.

### 2.4.1 Phase C/D System Engineering Process

A typical system engineering process is shown diagramatically in Figure 2-7. The inputs provided at the start of this phase are those developed from Phase B studies:

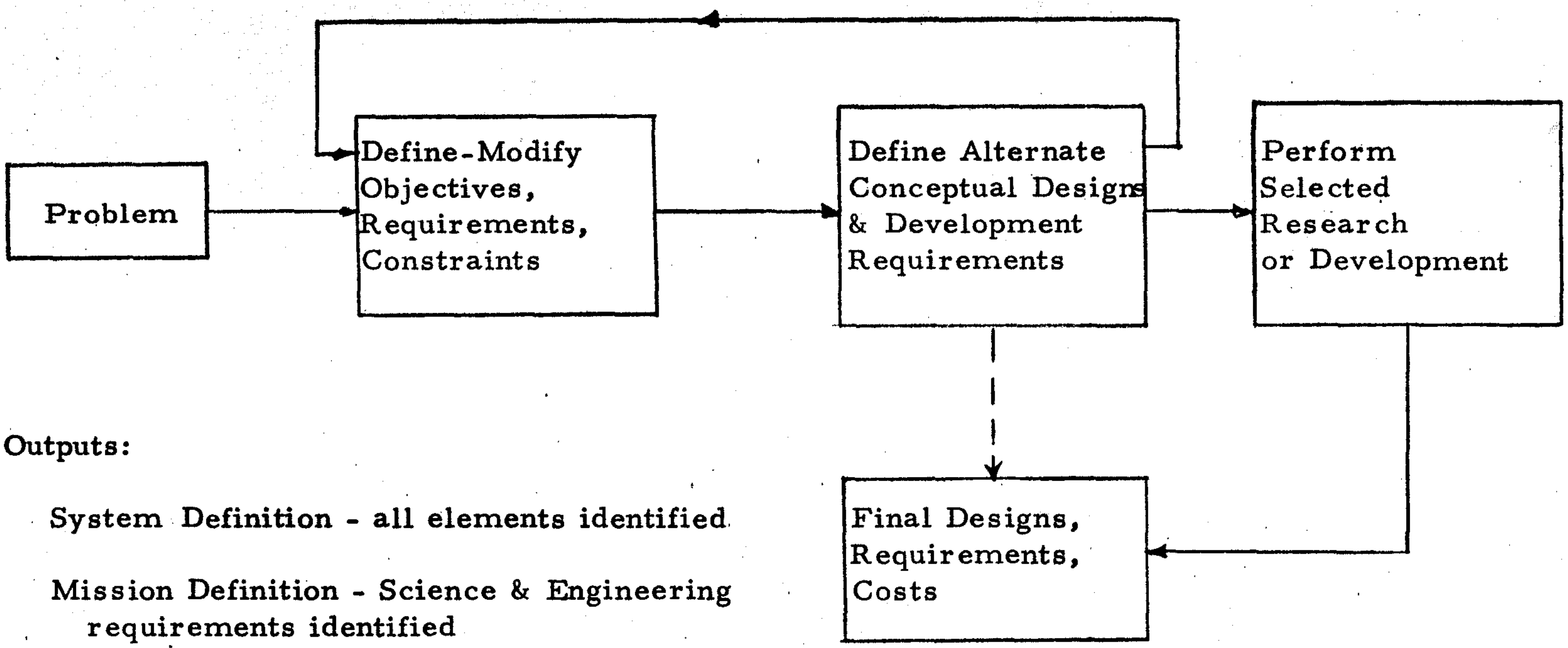
a. System Specification.

b. Interface Definitions.

c. System Support Requirements.

d. Program Plan with Schedule and Cost.

e. Hardware Design Concepts with High Confidence in Feasibility.




**Outputs:**

System Definition - all elements identified

Mission Definition - Science & Engineering requirements identified

Payload Hardware Concept - feasible alternatives defined

Interface Requirements - preliminary definition

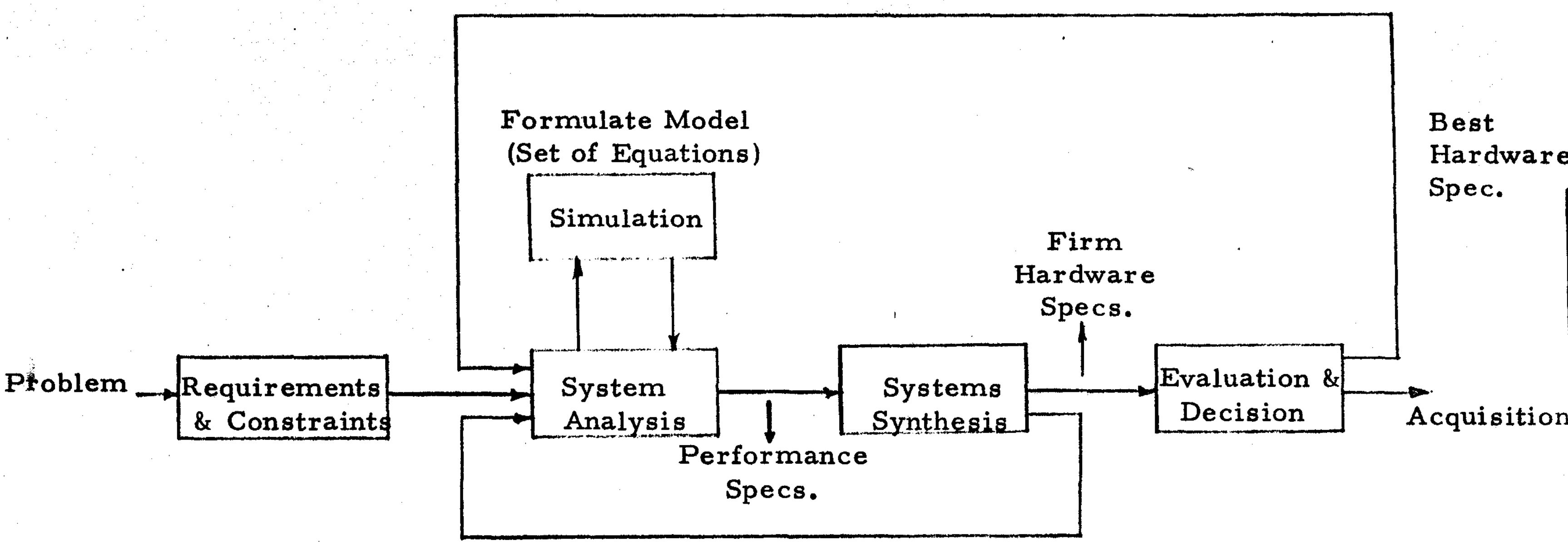
Program Requirements - cost, schedule resources identified

Reliability Goals - system

Maintainability Goals - system

Logistic Planning - system

Figure 2-5 Concept Formulation - Phase A




<u>Solve in Broad Terms</u>

- Identify Major Elements
- Identify assemblies and subassemblies
- Evaluate interfaces
- Cost effectiveness
- Identify parameters
- Optimize
- Equipment, personnel facilities, support
- Reliability Allocations - Subsystem
- Maintainability Allocations - Subsystem
- Logistic Planning - Subsystem

<u>Implement the Means</u>

- Contact suppliers
- Prepare catalog of systems candidates

Figure 2-6 System Definition - Phase B

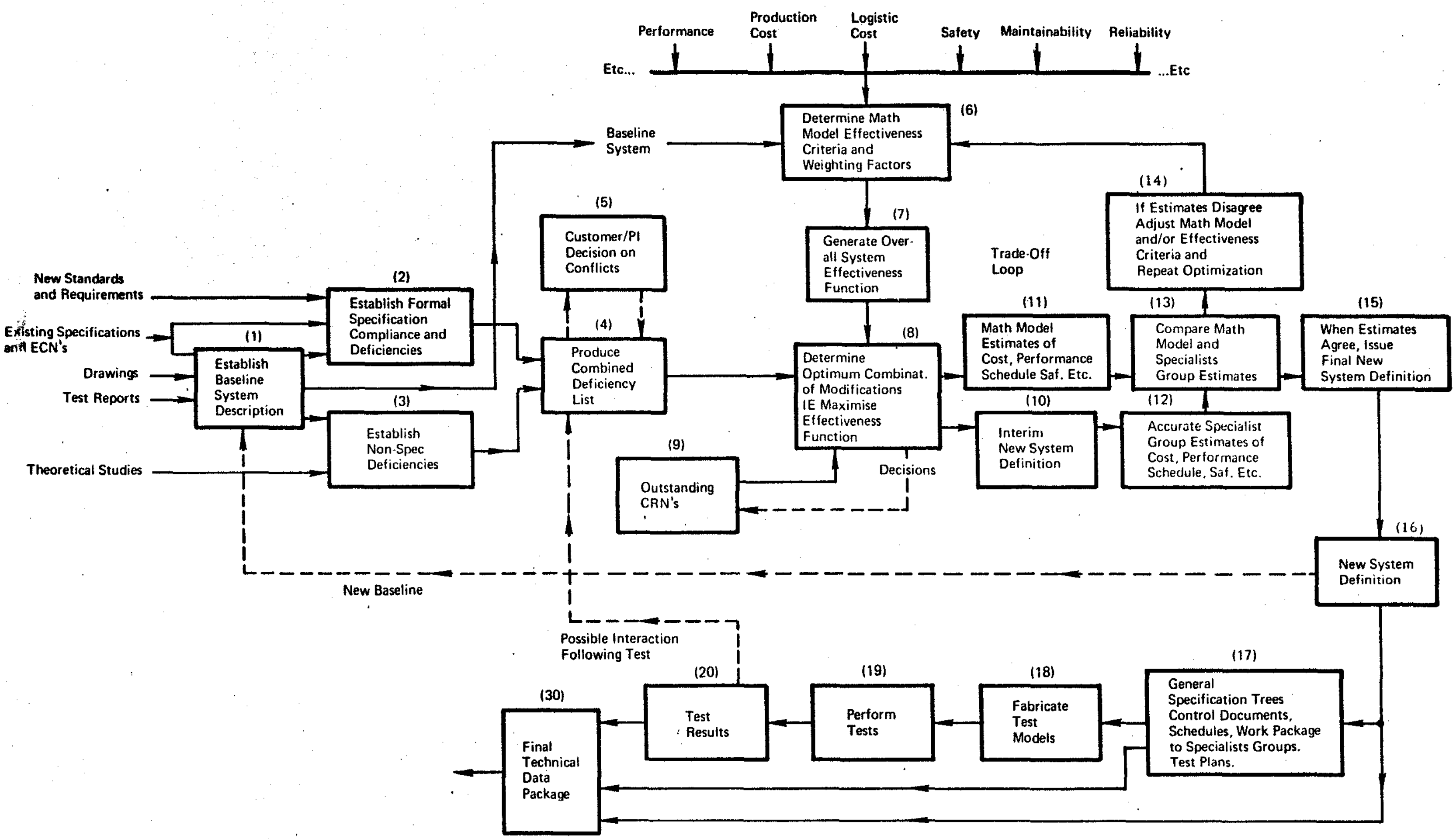



Figure 2-7 Flow Diagram of the System Engineering Process

2.4.1.1 System Engineering

The system engineering process is utilized within the System Engineering Group. The three main stages of the system engineering process may be summarized as follows:

a. Establish the deficiencies of the existing baseline system relative to specifications as determined during Phases C and D of the program.

b. Perform tradeoff studies using appropriately weighted parameters to determine the most effective set of modifications which can be implemented.

c. Generate the necessary specifications, schedules, test requirements, manpower requirements, etc., to define, fabricate, and qualify the system.

The decision-making logic to achieve these aims is defined in detail below. The numbers after the titles of the section headings that follow correspond to the numbers of the boxes in Figure 2-7.

2.4.1.2 Establish Baseline System Description (1)

Before the deficiencies can be determined, it is first necessary to define the existing baseline system and its performance. This will involve a detailed study of all available documentation, including specifications, drawings, test data, etc., generated during Phases A and B.

From this study, an overall system description and several subsystem descriptions, or data packages, will result. The major subsystems of a typical system are shown in the hardware tree of Figure 2-8.

2.4.1.3 Establish Baseline System Compliance with Existing Specifications (2)

Comparison of the data in Section 2.4.1.2 with the proposed system and subsystem specifications will show the areas where deficiencies exist. It will also show the areas in which the specification requirements are considerably exceeded, a possible useful margin for future tradeoff studies.

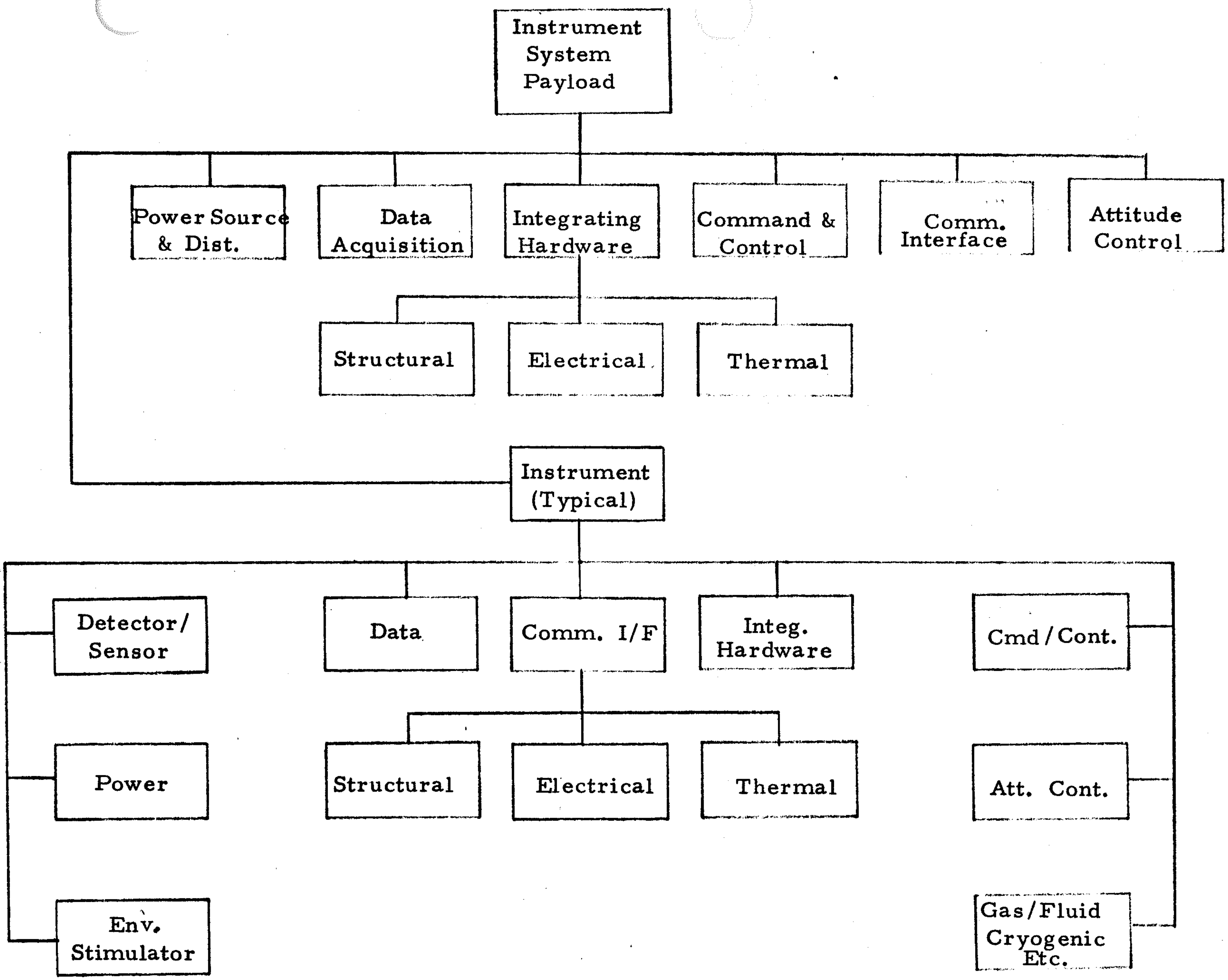



Figure 2-8 Typical Phase C/D Instrument Hardware Tree

2.4.1.4 Identify Design and Operational Deficiencies of Baseline System (3)

This will be mainly the result of breadboard and engineering tests. However, some design improvements may be suggested by an independent theoretical assessment of features not previously covered by specification or operations to date. Reference will also be made to new standards.

2.4.1.5 Combine and Reconcile Deficiency Lists (4)

The deficiencies resulting from Sections 2.4.1.3 and 2.4.1.4 may cover the same item to different levels or may be in conflict. It will be necessary to compare the two lists and produce one combined list. The resolution of any conflicts may require reference back to the customer. (5)

2.4.1.6 Establish System Effectiveness Criteria (SEC) (6, 7)

The system must ideally be satisfactory in several, possibly conflicting areas. These include:

a. Safety.

b. Mission availability (maintainability and reliability).

c. Operational capability.

d. Product cost.

e. Logistic support cost.

Obviously, a, b, and c are ideally to be maximized and d and e are ideally to be minimized. With regard to safety, there are precise standards to be satisfied, but in the other areas the final requirements will be the result of a tradeoff, taking into account the relative importance of each feature and the practical possibilities.

A significant part of this stage of the study is the method of establishing numerical values to such items as safety, availability, and capability. As a result of the tradeoff calculations, it may be necessary to revise the initially allocated weightings and maximum/minimum values for realistic solutions.

2.4.1.7 Evaluate Outstanding Change Request/Notices (CRN's) Against System Effectiveness Criteria and the Deficiency List (8, 9)

This evaluation will establish which of the CRN's are really important, which are of no real benefit, and which, if any, may actually be detrimental on an overall, weighted assessment basis.

When the worthwhile CRN's have been selected, they will be incorporated into the baseline system description to give an alternative starting point. The deficiency list will be modified similarly to reflect the (theoretical) incorporation of the CRN's.

2.4.1.8 Establish New System and Subsystem Requirements (8)

This step results in a modified set of requirements which allow for the correction of the earlier deficiencies through formal tradeoff studies.

2.4.1.9 Generate a System Effectiveness Tradeoff Matrix (complete tradeoff loop)

The tradeoff matrix shows the interaction of the System Effectiveness Criteria. For example, the required reliability and maintainability standards may be achieved with probably little or no effect upon safety, but with noticeable effect upon production cost, and significant effects upon performance and logistic cost. Increasing operational capability may not affect mission availability, but it could have a noticeable effect upon life expectancy.

A mathematical model of the system is set up, (6), defining the effect of system parameters upon each of the System Effectiveness Criteria. The mathematical models may be developed from first principles or derived empirically.

To provide a means of assessing how closely any configuration approaches the theoretical optimum, the parameter values that give the maximum weighted sum of the numerical SEC will be determined by linear programming, or Monte Carlo methods, whichever appears appropriate. (8)

It may be found that the optimum system on the basis of the weighted SEC effectively removes a previously accepted, outstanding CRN. If this is noticed, then an allowance may be made in the cost estimate. However, it will probably be less confusing to run two optimizations, one starting from the original baseline and the other starting from the original baseline plus outstanding ECP's.

2.4.1.10 Generate New System and Subsystem Specifications for Performance and Interfaces (10)

As a result of the parametric studies in Section 2.4.1.9, the modified system requirements can be defined, (15, 16), with a high probability that they will be achievable in practice. The new series of system and subsystem specifications can be written and given to the specialist groups for detailed designing, planning, and costing. At this point, it will be possible to define the areas that can be improved by substitution of alternative parts and those which require a separate development program. It may happen that the accurate estimates of cost, etc., from the specialist groups will not agree with the math model solutions. In that case, the math model will be modified and the process will be repeated. (11, 12, 13, 14)

2.4.1.11 Establish Program Requirements and Schedules (17)

After the above actions have been conducted, the total task will be broken down into a series of precise work statements, each being related to the overall schedule. The schedule will also define dates for milestone events in the program, including formal documentation, tests, and review. The purpose and extent of each of these will be defined.

2.4.1.12 Establish Hardware Requirements (17)

From the detailed design of the new system, the part selection process is initiated to define those which are to be bought outside and those which are to be fabricated as new items, either in or out of house. Source control specifications and drawings will be prepared for each part. Total quantities of each part and need dates will be defined.

2.4.1.13 Establish Documentation Requirements (17)

The system engineering process will be defined, controlled, and reported by a series of agreed-upon documents. These may include:

Specification Trees and Specifications

Work Statements

Schedules

Engineering Work Directive (EWD)

Change Requests/Notices (CRN)

Contract Change Proposals (CCP)

Test Plans

Test Procedures

Test Reports

Discrepancy Reports (DR)

Requests for Action/Change

Technical Memos/Reports

Progress Reports

Training and Servicing Manuals

The extent to which each of these will apply, their contents, level of approval, due dates, number of copies, and method of processing will be defined.

2.4.1.14 Establish Test Requirements (17)

The purpose of testing is to provide assurance that the system satisfies the new specification requirements. Since the starting point was a new baseline design, it is necessary to provide the rationale for qualifying some areas by similarity with the previous system design, and others by a completely new series of tests.

When the necessary test areas have been defined, a "test plan" optimizing the combination of individual test and facilities will be devised to provide the maximum information for a given effort.

The test plan will describe the overall test program in terms of hardware, schedules, objectives, and requirements. A detailed "test procedure" will be written for each test described in this plan. Each test procedure will define precisely the facilities required, the actions to be taken, the quantities to be measured, and the criteria for success or failure. The need for on-the-spot engineering judgment will be confined to decisions on whether to proceed or to abandon the test following a partial failure or a discrepancy.

Test results are to be fed back to the mathematical modeling stage in order to refine the model and to suggest possible further improvements. (20)

2.4.1.15 Establish Manpower Requirements (17)

When the total tasks and schedule have been defined, the manpower at any time and the total man-months for the project can be determined.

Although the above actions have been listed sequentially, they will interact to a considerable extent. In practice, there will be much iteration and feedback before a completely consistent and reliable set of outputs are available.

2.4.1.16 Assemble Final Technical Data Package (30)

The end product of the program will be a complete definition of the design, operation, and performance of the improved system, sufficient for any manufacturer to cost accurately and to go into immediate production.

2.4.2 Typical Phase C/D System Engineering Tasks

The flow diagram of Figure 2-9 presents typical Phase C/D System Engineering tasks and interactions with program elements for a space instrument as described by the hardware tree of Figure 2-8. This hardware tree, which describes an instrument that is a member of a large instrument system such as ALSEP or Viking, is included to indicate the general types of hardware involved and the multidisciplines which must be considered.

The flow diagram of Figure 2-10 illustrates the relationship of system performance, schedule, cost, reliability, maintainability, and logistics. Desired system performance is compared to the anticipated system performance in the performance feedback loop. Important elements of this loop are system requirements, subsystem parameters, system performance equations, and resulting system performance. System requirements and subsystem parameters are also common to the schedule and cost feedback loops. Logic elements are used in these closed-loop systems to vary the system requirements and subsystem parameters, and to determine

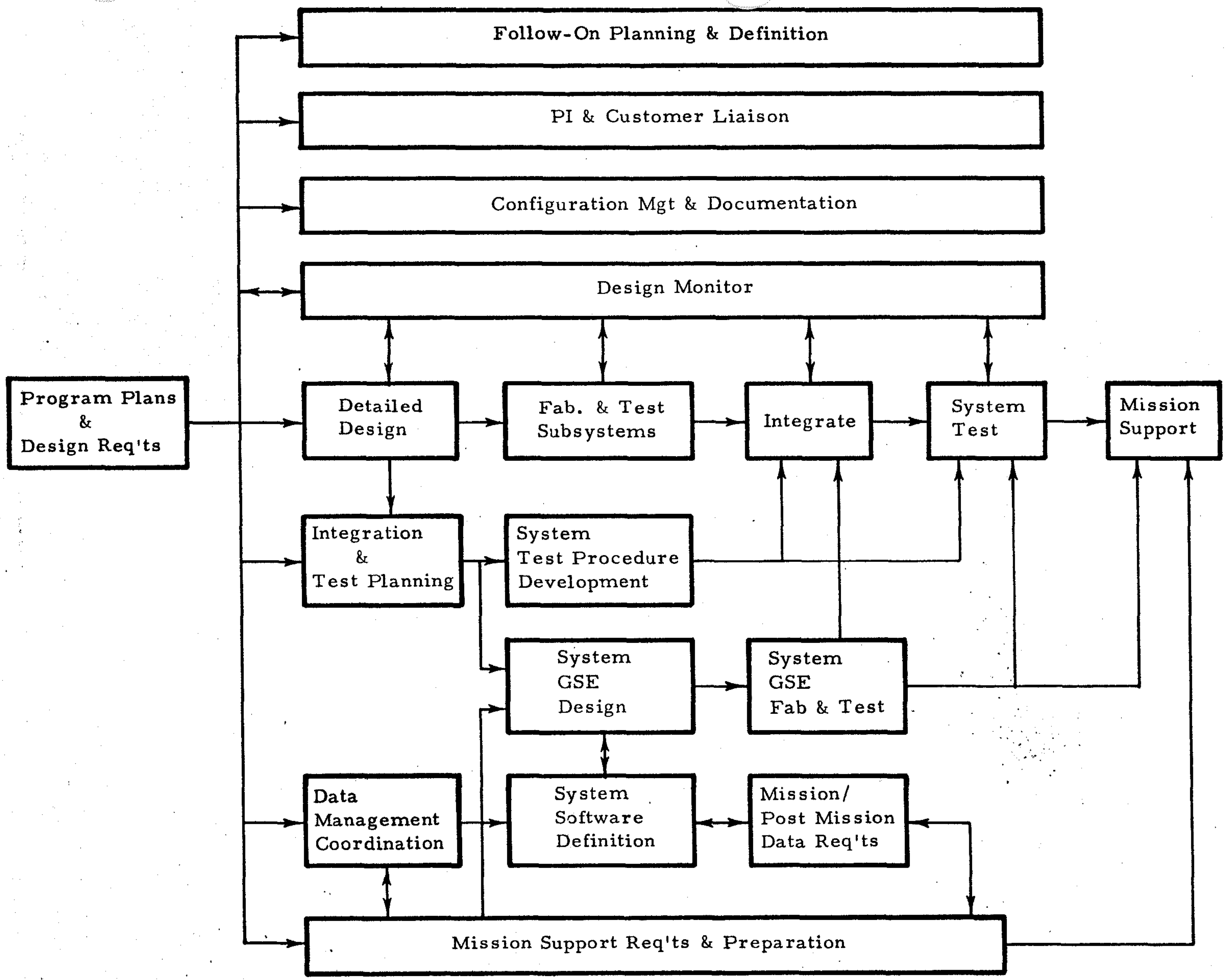



Figure 2-9 Phase C/D Flow Diagram

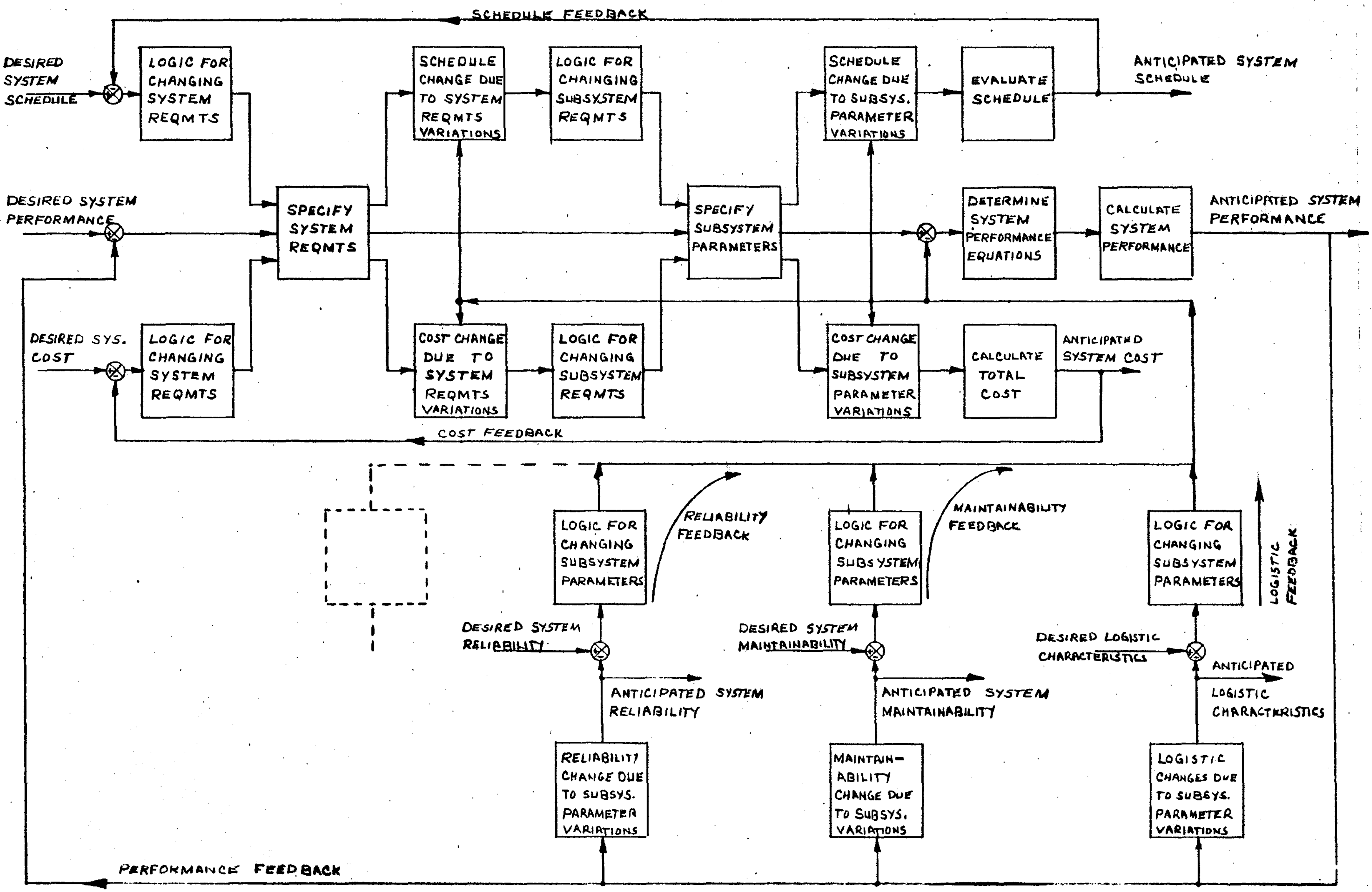



Figure 2-10 Multiple Feedback Flow Diagram

their effect on cost and schedule. Elements of the performance feedback loop concerned with determining system performance equations and calculated system performance are also common to the reliability, maintainability, and logistic feedback loops. In these loops, the desired reliability, maintainability, and logistic characteristics are compared to those anticipated. This simplified flow diagram demonstrates that several elements are common to more than one loop; therefore, changes in performance, cost, schedule, reliability, maintainability, and logistics are interrelated. This feedback concept can be extended to include weight budgets, power budgets, volume constraints, EMI constraints, safety, human factors, quality assurance, or other factors deemed important for a particular effort.

2.4.2.1 Program Plans and Design Requirements

To provide orderly and cost-effective progress at the initiation of the Phase C/D program, it is essential that System Engineering establish program plans and a firm basis for the design. In this context, the system engineering technical tasks involve the following:

a. Preparation of System Drawings/Specs for Interface Definition/Approval.

b. Analyze Preliminary Design Concepts for System and Subsystems - Final System Iteration to Result in:

- Subsystem performance specification.
- Subsystem interface drawings and specifications.
- System layout.
- Weight budgets.
- Power budgets.
- Volume constraints.
- Parts and materials requirements (including common or standardized usage).
- EMI design constraints.
- Safety and maintainability design constraints.
- GSE design requirements.
- Human Engineering requirements.

In addition, the overall planning aspects of the program will be reviewed, traded off, and updated to correspond with the technical definition of the system. This involves:

a. Design plans and schedules.

b. Organization and responsibility definition.

c. Manpower planning - skills, number, loading.

d. Manufacturing plans, make/buy, schedule.

e. Safety, reliability, Quality Assurance Planning.

f. Test plans including facility definition and scheduling.

g. GSE design plans.

h. Training and Logistic Support Plans.

This phase involves the skeleton organization structure with each planning discipline represented and a system engineering staff. The output includes the following typical information:

Program directives
Organization and responsibility and MCP's
Subsystem design specifications
Interface drawings, specifications
System layout
Power, weight, volume budgets
Basic test plan
Design plans
PWO's, manning plan, schedules
Make/buy plan.

2.4.2.2 Design Monitor

Following this initial phase of detailed planning and definition of design requirements, the system engineering effort proceeds in a design monitor role. In this context, it is the responsibility of the system engineer to continue to assess the development progress in terms of the system requirements and to control the design as it evolves. In complex systems, tradeoffs of performance, reliability, weight, power, cost, and schedule may continue during the detailed design phases; monitor and control to maintain the optimum balance of these parameters is the system engineering challenge. The detailed tasks typically required are as follows:

a. Maintain subsystem specification updates current with progress in detailed design phase.

b. Maintain weight, power, volume, interface control.

c. Analyze performance characteristics of subsystems.

d. Maintain current system design configuration.

e. Conduct design reviews and assure communication of interface information between subsystem design groups.

f. Review changes in subsystem design for compatibility with system requirements.

g. Plan, direct, and enforce required design analysis prior to hardware commitment.

h. Generate work-around solutions to design problems.

i. Review breadboard test results for compatibility with analysis and system requirements.

j. Approve completed subsystem assembly designs prior to manufacturing release.

k. Provide analytical support, such as safety, stress, thermal, human factors, energy, EMI, etc., for individual design groups.

l. Perform or coordinate analyses for single-point failure and other reliability aspects.

m. Review subsystem design requirements and concepts for standardization/commonality aspects.

n. Review subsystem test set requirements and designs for simulation of interfaces and functional test capability.

o. Review and approve subsystem test methods and procedures for adequacy of proving specification compliance.

p. Provide direction to detailed design groups for application of parts and materials. (This task may be assigned to R&QA group, depending on contract size.)

q. Perform maintainability analyses and input to design specifications.

2.4.2.3 Design Integration

In addition to the design monitor tasks, the System Engineering Group may be assigned specific design and development activities which are necessary for the integration of the subsystem into a composite operational system. These activities can be grouped under the general heading of design integration and will include the following subtasks:

2.4.2.4 System Integration, Design, and Planning

a. Perform integration design (mechanical and electrical) as required to integrate subsystems into composite system.

b. Provide direction and engineering support required for integration and test.

c. Perform integration and test planning.

d. Develop system test set and mechanical GSE requirements.

e. Design mechanical layout and harness.

f. Develop integration sequences and procedures.

g. Fabricate and assemble integration hardware.

h. Integrate and test subsystems as composite system.

i. Test or verify mechanical thermal and electrical interfaces.

j. Update subsystem interface specification.

2.4.2.5 System Test Procedure Development

a. Define pre/post environments test parameters.

b. Define unique test conditions and equipment requirements.

c. Determine test equipment and software functional capability.

d. Develop integration procedures.

e. Develop system functional procedures.

f. Develop system environmental procedures.

2.4.2.6 System Test

a. Integrate qualification system and verify interfaces.

b. Perform qualification functional testing.

c. Perform qualification environmental testing.

d. Calibrate qualification system.

e. Analyze qualification data and verify performance.

f. Integrate flight system and perform functional, environmental, and calibration tests.

g. Analyze flight data and verify performance.

2.4.2.7 Data Management

The data management task is also one that is delegated to an activity with a wide range of responsibility such as system engineering. For this purpose, the following system tasks are included:

2.4.2.8 Data Management Coordination

a. Perform total system design for data management.

b. Specify requirements for flight hardware, communication, GSE, and ground stations.

c. Define system software and coordinate commonality and standardization thereof.

d. Provide inputs, perform tradeoffs, define requirements, and coordinate with customer and PI to determine most cost-effective data management system.

e. Plan and coordinate data utilization throughout development program and mission.

2.4.2.9 System Software Definition

a. Define real-time display requirements.

b. Define data analysis requirements.

c. Determine data retrieval options.

d. Define engineering/science data conversion factors and assess program storage requirements.

e. Define fault isolation requirements.

f. Define data limit testing and error testing.

2.4.2.10 Mission/Post Mission Data Requirements

a. Define real-time engineering/science data requirements.

b. Define long-term data recovery and processing requirements.

c. Determine bulk processing methods and data distribution requirements.

d. Determine Principal Investigator data requirements for science, engineering, status, and event information.

e. Define PI interfaces for data processing.

2.4.2.11 Mission Operations Requirements and Preparation

Coordination of the system hardware and its integration and operation into the mission are ongoing tasks that must receive appropriate attention during the development phase. This is also considered as a system engineering task and includes the following activities:

a. Perform mission planning in conjunction with user.

b. Generate mission operations documents such as handbooks, data books, operational sequences, calibration data, contingency procedures, training manuals, etc.

c. Interface with user, customer, etc., for requirements.

d. Generate plans, procedures, work requirements, etc., for all mission tasks: post-delivery testing, integration, prelaunch assembly and checkout, environmental control, shipping, repair and overhaul, flight testing, post-mission data analysis, and viewing.

e. Mission planning includes coordination with PI in determining how the instrument is applied to accomplishing the experiment.

2.4.2.12 Mission Support

This activity includes the following tasks:

a. Provide real-time deployment support.

b. Provide support for engineering and science data analysis.

c. Provide anomaly and investigation support.

d. Provide post-mission data analysis.

2.4.2.13 Configuration Management and Documentation

Configuration management is a systematic approach with specific operating techniques and procedural disciplines to ensure that: (1) product configurations are defined and identified, (2) changes to defined and identified products are evaluated for impact upon design, manufacturing, procurement, test, operation, maintenance, and support in terms of cost and schedule, and (3) product configurations will reflect the configurations as initially defined, identified, and subsequently modified by approved changes at any point in their life cycles. Configuration management is normally a staff discipline reporting to the program manager on large programs; however, because of its application to all elements within a hardware program, configuration management can be conveniently considered a system engineering responsibility on small programs.

The need for configuration status and accountability within a program cannot be over-emphasized, handled either within a typical system engineering function or as an important interface with a system engineering function. This is obviously true, not only in establishing achievement of performance and operational support requirements, but also in cost effective evaluations and tradeoff decisions by program management of both the contractor and the customer relative to contractual cost and delivery requirements.

Configuration management is valuable to a program because it can speedily provide accurate information needed for management decisions, both in the normal operation of a program to ensure positive uniform control and in emergencies when a change in plans must be evaluated quickly. It must provide firm requirements for all programs, yet be flexible enough to meet contractual obligations of a specific program.

The objective of configuration management is to provide cost-effective configuration management for phases of a given program as well as for small to large programs. This can best be achieved by disciplines which will:

a. Use existing contractor configuration management practices and procedures to the maximum extent practicable, including periodic product configuration audits.

b. Provide a single point of contact for configuration management activities to assure uniform interpretation of requirements and continuity of action.

c. Provide, at each phase, only that formal configuration identification needed for that phase and required for the initiation of the next phase.

d. Provide guidance and direction to participating functional departments who in turn will exercise the same guidance and direction with their subcontractor and vendor organizations.

e. Provide an internally operated change control board to review, analyze, and process for approval/disapproval all engineering changes commensurate with the program phases and resource.

f. Provide interface and specification control capability and engineering release function to assign drawing and change numbers in accordance with approved format limitations.

Configuration management involves all activity which directly or indirectly contributes to a product and the contractual definition of a product. It is essential that uniform procedures be maintained, understood, and adhered to. Figure 2-11 defines a typical engineering change flow. Figure 2-12 defines the interrelationships of configuration management functional activities. All activities shown are considered members of the contractor change control board.

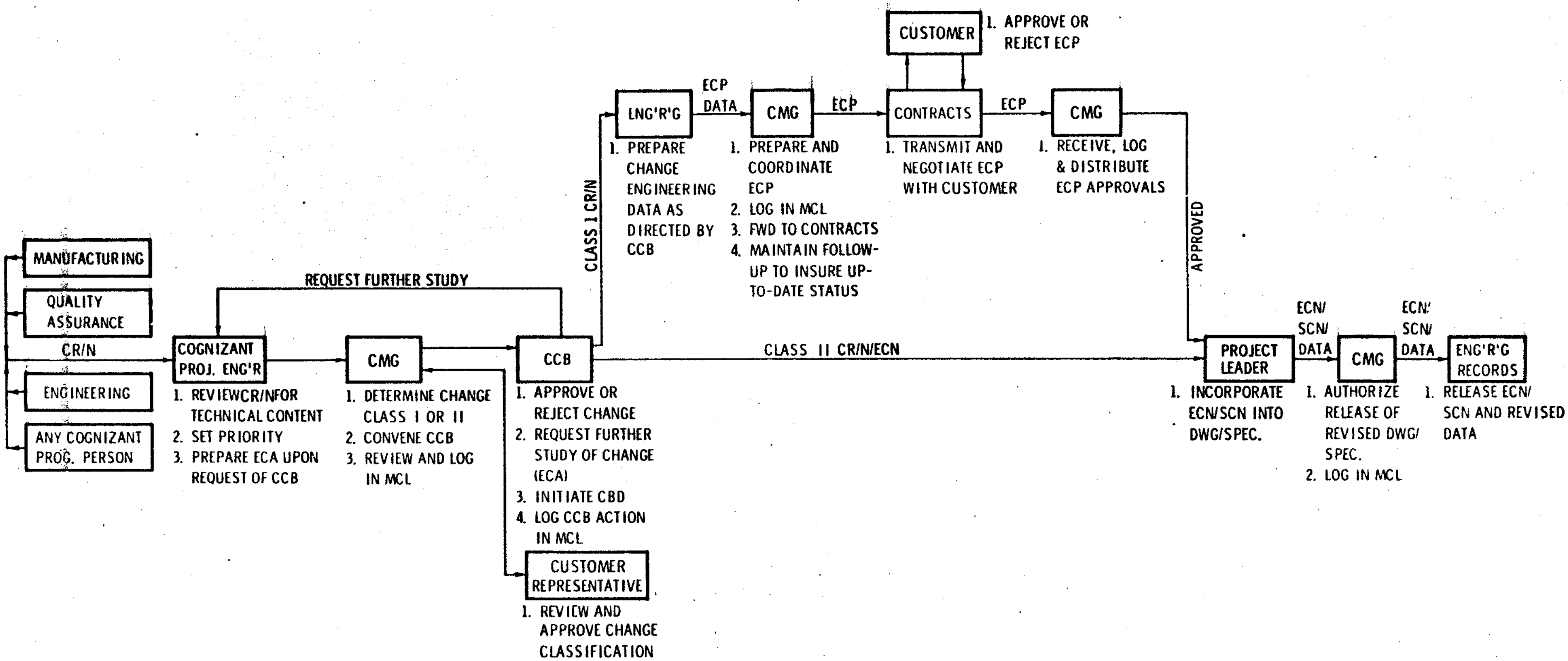



Figure 2-11 Engineering Change Flow

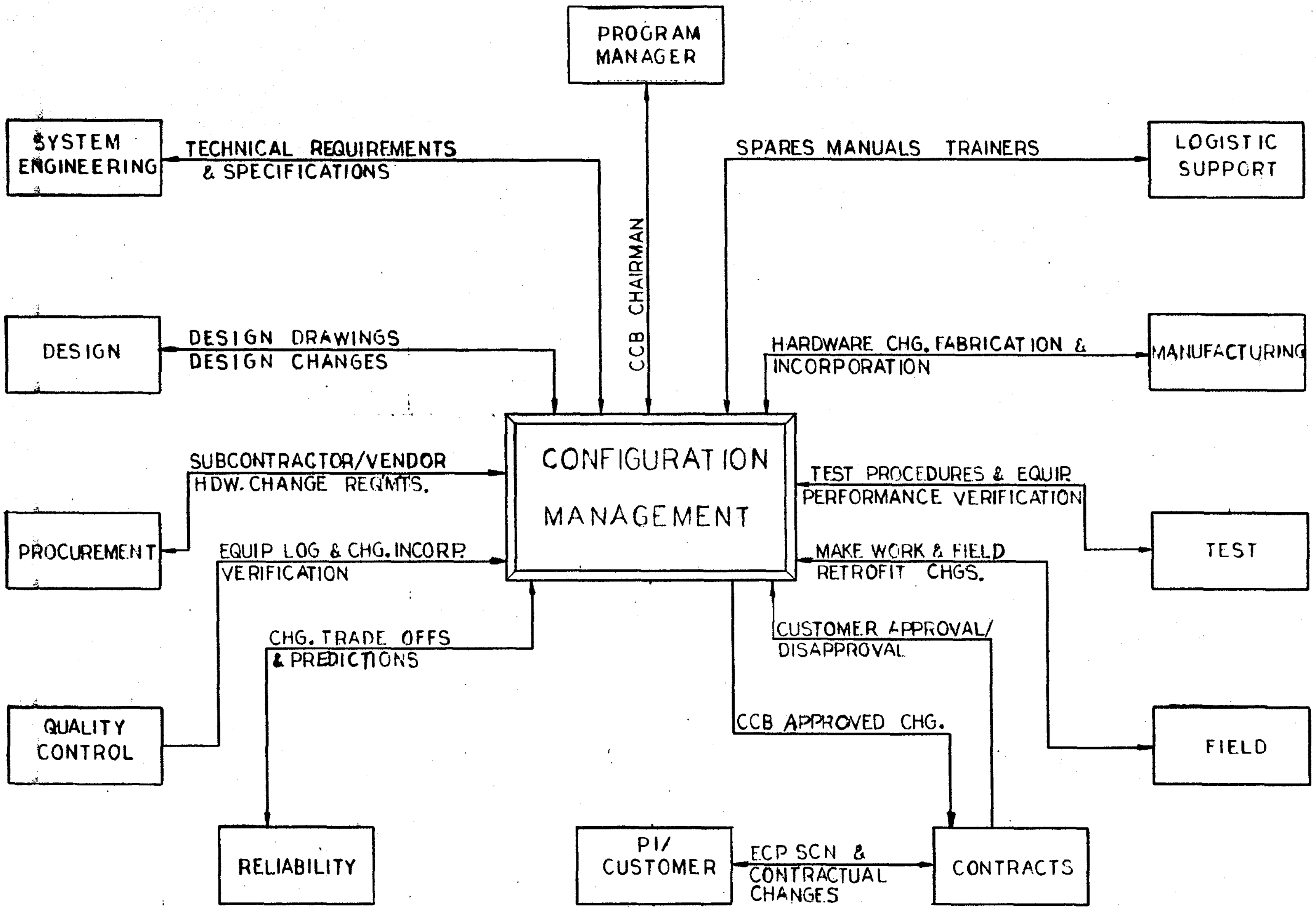



Figure 2-12 Configuration Management Interrelationships

## 2.5 PERFORMANCE/COST/SCHEDULE TRADEOFFS

A new approach being followed by military departments is called Design to Cost.[5] The concept, which is in its early phases, is being effectively used by the military. The guide has been approved by the Chiefs of the Military Commands for use in all procurement activities. The intent is to establish cost goals that are realistic, achievable, and represent an appropriate value for the money which the Government is willing and able to afford. In addition, the performance should be optimized within the established cost goals, and although tradeoffs are required between cost, schedule, and performance, the minimum essential performance requirements must not be sacrificed.

The fundamental thrust of the design to cost concept is described below:

a. Why Design to a Cost?

(1) Policy - Unit costs of weapon systems have risen to such an extent and funds available have become so limited that a considerable disparity between requirements and resources has developed. This was recognized by the DOD in July 1971, when DOD Directive 5000.1, "Acquisition of Major Defense Systems", was published. The paragraph of this directive pertinent to Design-to-Cost states that:

"Cost parameters shall be established which consider the cost of acquisition and ownership; discrete cost elements (e.g., unit production cost, operating and support cost) shall be translated into "design to" requirements. System development shall be continuously evaluated against these requirements with the same rigor as that applied to technical requirements. Practical tradeoffs shall be made between system capability, cost, and schedule. Traceability of estimates and costing factors, including those for economic escalation, shall be maintained".

While the above directive states that "operating and support costs" should be included along with "unit production cost" as "design-to" requirements, this guide is directed specifically toward unit production costs. However, unit production costs are part of life cycle costs and must be considered in context therewith. Unit production cost must become a primary design parameter. But this emphasis should not be construed to imply that the unit cost is the sole driving consideration in systems acquisition. Acquisition cost reductions must not be achieved at the expense of increased ownership costs or through the sacrifice of performance essential for mission accomplishment. The DOD shall continue to strive toward refining ownership costs to a degree equal with acquisition cost.

b. What is Design-to-Cost?

(1) "Design-to-Cost" Definition – Design-to-Cost is a process using unit cost goals as thresholds for managers and as design parameters for engineers. A single cumulative "Average Unit Flyaway Cost" goal is approved for the program. This goal is then broken down into unit production cost goals by the Program Manager and provided to each contractor or in-house source for the appropriate major subsystem. The dollar value for each goal represents what the Government has established as an amount it can afford (i.e., is willing and able) to pay for a unit of military equipment or major subsystem which meets established and measurable performance requirements at a specified production quality and rate during a specified period ot time.

(2) Reducing, Not Justifying Costs – A Design-to-Cost approach requires that the cost of production be reduced or maintained to the level of a pre-established goal by effectively managing the design effort preceding such production. This is in contrast to designing a weapon system to meet the highest possible level of performance with little regard to unit production cost goals, and upon completion of the design, attempting to justify the procurement cost. Design-to-Cost has been used extensively by industry as one means of meeting the challenge of the market place. The application of Design-to-Cost should assist in countering high unit production cost and unnecessary system sophistication and complexity.

(3) Need for Flexibility - The Program Manager and each competing contractor must have maximum freedom to provide their version of the best possible design to perform the mission at the established cost goal. This requires that the unit production cost goal be related to an economical production schedule (quantity and rate) and only the minimum number of essential performance requirements (speed, range, payload, etc.). This will allow the Program Manager and contractor the flexibility needed to make tradeoffs among cost, schedule, and performance (including maintainability and reliability). The design must be iterated until cost, schedule, and performance requirements are met. If redesign cannot achieve the unit production cost goal, there must be a willingness to trade off desired performance to achieve the cost goal while assuring that a viable weapon system design is obtained. To this end, both the contractor and Service Project Manager must have early visibility of the expected unit production costs associated with the emerging design.

The concept also considers life cycle costs. The impact of design decisions on program life cycle costs should be monitored on a continuing basis to ensure that unit production cost, schedule, and performance goals are not achieved at the expense of total system operating costs. During development, it is necessary that adequate money be available to solve design problems that threaten the achievement of the goals, but this expenditure should result in lowering of production costs so that the total program cost goal is maintained or lowered.

The concept can be applied to all types of project-managed programs. Variations of the concept to suit individual programs can be applied as follows:

a. Where performance is essential and design is pushing the state of the art, cost goals are applied and should not necessarily be subordinate to performance requirements in program decisions.

b. Similarly, if project completion by a certain date is imperative, decisions should favor schedule over cost goals.

c. In programs where a limited quantity of an item are to be produced and development costs are high, program organization cost goals should be set rather than unit production cost goals.

The cost goals, together with minimum performance requirements and schedule, should be established during the conceptual phase. These goals may be modified during design and development but should not change during the production or final development phase.

The concept can provide cost-effective programs, providing that realistic goals are set, everyone on the program supports the concept, adequate tracking and documenting of decisions is maintained, and good contract incentives are set to motivate the program manager.

## 3.0 ALSEP PROGRAM REVIEW

### 3.1 PROGRAM DEVELOPMENT

The ALSEP program developed seven flight systems. Six of these were emplaced on the moon with a total of 29 experiment packages, including three laser reflectors. The first package, EASEP, was deployed on 20 July 1969 while the last, Array E, was deployed on 10 December 1972.

The program began in March 1966 and was to produce four ALSEP flight packages, the first to be delivered to NASA on 14 July 1967. An accident which occurred at Kennedy Space Center (KSC) and changes in NASA policy resulted in the first flight system being delivered in April 1969. This first system was EASEP, a much less comprehensive instrument system than initially planned. The original systems were flown on following missions and new systems were added to the original four, to be used on subsequent flights.

The program's prime purpose was to produce seven flight model systems. A test program was implemented which sequentially checked the design at each stage of development, qualified each system, and culminated in the acceptance of each flight array. The models produced and used throughout the development of each system are indicated in Table 3-1.

Table 3-1

ALSEP Program Hardware Models

| Array / Model | Demo Mockup | Trainer | Breadboard Brassboard | Eng Model | Proto Type | Qual | Flight |
|---|---|---|---|---|---|---|---|
| EASEP | X | X | | X | | X | A - 11 |
| A | X | X | X | X | X | X | A - 12 |
| B | X | X | | | X | X | A - 13 |
| C | X | X | | | X | X | A - 14 |
| A - 2 | X | X | | | | X Subpack 2 | A - 15 |
| D | X | X | | | | X Subpack 2 | A - 16 |
| E | X | X | X | | | X | A - 17 |

## 3.2 SYSTEM ENGINEERING ROLE IN PROGRAM DEVELOPMENT

The System Engineering Group coordinated all technical aspects of the program. When the program started in March 1966, the System Engineering Group was a part of the Engineering Department (Figure 3-1). Their charter was to: "Control the configuration of all designs, models, and blocks. The System Analysis Project Engineer is responsible for ALSEP Specification SS100,000 (BSX 2625 Specification Tree) and for conducting analytical studies of errors, tolerances, and performance options as necessary. The Configuration Management Project Engineer is responsible for carrying out the configuration management program in accordance with the Configuration Management Plan".[6]

The functions of System Engineering were further clarified in ATM 170 (Ref. 7) and shown to include the following responsibilities.

a. Overall configuration and hardware characteristics; weight and power budget.

b. Specification SS100,000 and all Interface Control Documents for functional, electrical, or mechanical interfaces between ALSEP subsystems, or between ALSEP and the Ground Support Equipment (GSE), Manned Space Facility Network (MSFN), and launch complex (KSC).

c. Analytical studies, tradeoffs, tolerance control, and performance analysis to verify conformance with SS100,000.

d. All system performance tests on brassboard and engineering models concerned with system performance validations.

e. Engineering support to the Test Department on the performance of all System Qualification and Acceptance Testing.

f. Configuration Management and preparation of all ICD's and specifications including those for GSE and MSFN. Control of top assembly installation and deployment drawings, special handling and electrical power and signal distribution systems and analysis of all changes.

- Engineering Manager Dept 971
  - System Engineering
    - Systems Analysis P. E.
    - Configuration Management P. E.
  - Mechanical and Thermal Design
    - Structural S. S. P. E.
    - Thermal Control Devices P. E.
    - Chief Designer
      - Drafting Section
      - Design Section
  - Experiments Eng.
    - Seismometer P. E.
    - Active Seismic P. E.
    - Heat Flow P. E.
    - Magnetometer P. E.
    - Snyder, Freeman, O'Brien, P. E.
    - LGE P. E.
  - Subsystems Design
    - Data P. E.
      - RF Components
      - Data Processor
      - Encoder
    - PG&C P. E.
    - Interconnection P. E.
  - Crew Engineering
  - GSE Design
    - ALSEP Test Set P. E.
    - Subsystems Test Set P. E.
    - Experiments Test Set P. E.

**Figure 3-1 ALSEP Engineering Department Organization Phase II (Ref. Drawing BSX 2829)**

The Configuration Management tasks of Specification Control, Drawing Control, and Weight Control were removed from the jurisdiction of System Engineering and transferred to a staff group in July 1966.

The System Engineering Group remained in essentially the same form until after EASEP and Flight 1 had been delivered. Their main tasks at that time were system test support and analysis, and documentation for mission support. The system group and test group were amalgamated, about June 1969, under one manager, who reported to the program director. This allowed for more efficient control of test planning, procedure preparation, and test support. This arrangement was retained until the start of the Array E program, when system engineering again reported to the engineering manager.

The relative weighting of the System Engineering Group under Array E was modified to some extent as indicated by the organization chart in Figure 3-2. The system engineering responsibilities were considered primarily an extension of design integration activities rather than overall technical cognizance of all design aspects. Individual experiment program managers were assigned to emphasize the development of the new experiment, and each of these organizations included a system engineering activity for the respective experiment. Management and direction of the total system from a technical standpoint was accomplished by the program director's office with inputs from the first line managers. Recommendations for overall system requirements were processed from the design integration group, through the engineering manager to the program director for action and direction to the individual design activities.

## 3.3 EVALUATION OF SYSTEM ENGINEERING ROLE

From an academic viewpoint, the ALSEP program was performed in accordance with the basic principles of organizational structure and responsibility as noted in Section 2.0. The original program organization delegated all development responsibilities to the engineering manager. The system engineering staff in this organization performed the overview tasks and maintained a close communication with the engineering manager's office. The effects of this communication could be immediately evaluated and processed by the cognizant technical activities. A normal phasing of system engineering tasks into the design integration role was accomplished with the end result supporting the system verification activities and performing the mission planning.

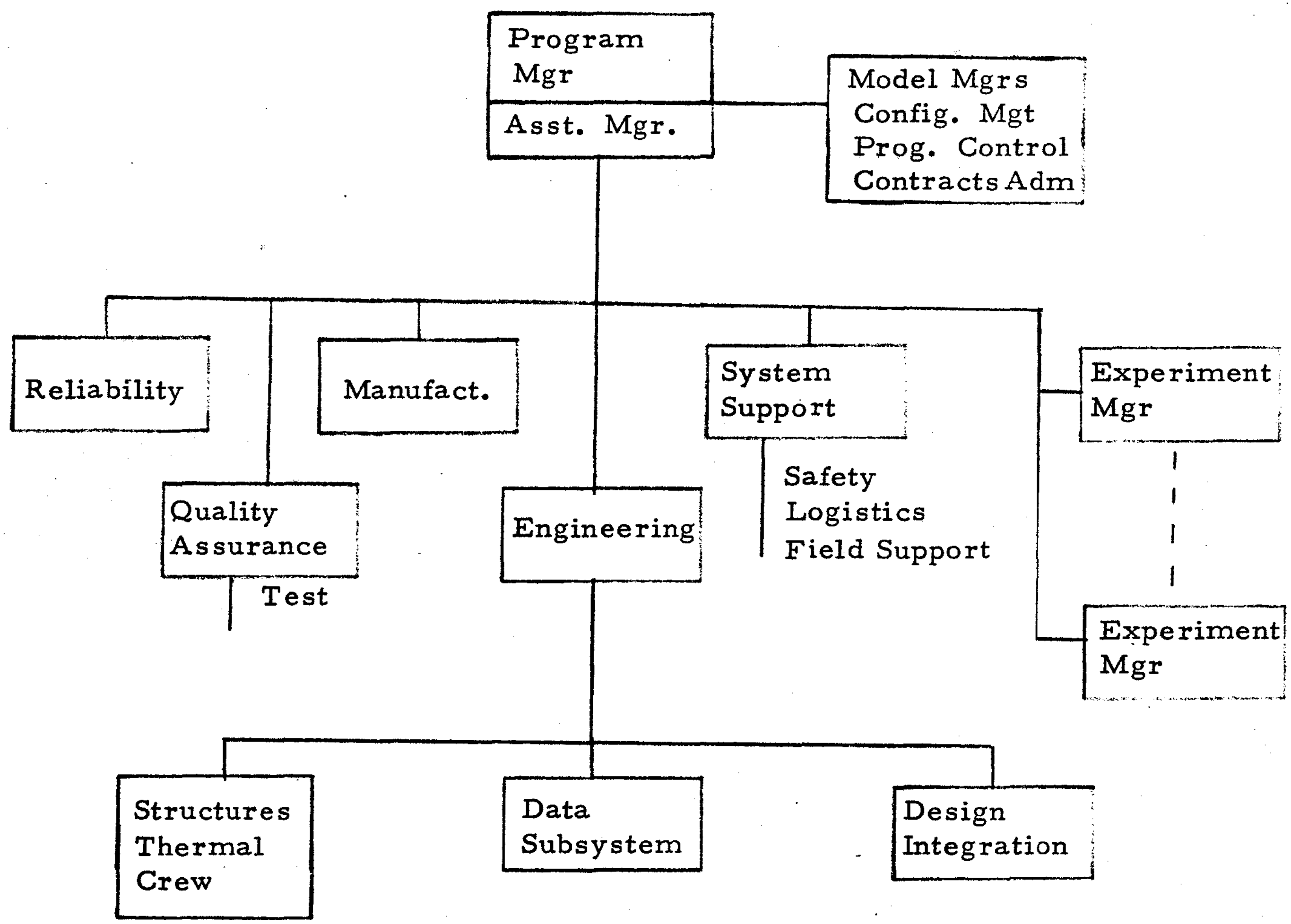



Figure 3-2 Array E Program Organization

Evaluation of the Array E organization structure indicates that the same processes occurred but with longer communication links. This type of structure provided adequate effectiveness for Array E since the system was basically an adaptation of previous developments.

Analysis of these two basic organizations indicates that the most efficient operation for a large development program can be gained under an organization that is structured to optimize communications between groups with similar objectives, i.e., Figure 2-4 (a). Variations of the detailed tasks and identification of groups responsible for these tasks can be made based on the nature of the particular program, as long as the basic communications are made direct and the authorities and responsibilities are clearly defined.

## 4.0 SYSTEM ENGINEERING FOR FUTURE PROGRAMS

### 4.1 COST-EFFECTIVE SYSTEM ENGINEERING

System engineering is a means for accomplishing the orderly development of complex technical systems. Since it is a management technique, it is difficult to form sharp, black and white judgments on the amount of effort required for success or to evaluate the cost/risk tradeoffs.

The amount of formally identified system engineering is significantly dependent on project size and objectives. A program such as Viking cannot afford schedule slippage as a 2-year delay may be incurred while awaiting the next opportunity. System incompatibilities therefore become extremely expensive and a strong system organization is required to minimize the risks. On the other hand, a less important project, such as an instrument probe launched by rocket, may be fund-limited and since multiple opportunities usually exist greater risks may be acceptable.

### 4.2 SYSTEM ENGINEERING TASK MATRIX

Table 4-1 is a matrix depicting system engineering tasks for three typical payload classes. The matrix was developed: to show the diversity of programs, objectives, and requirements; and to obtain a quantitative definition of system engineering requirements. Descriptions of the classes of payloads follow:

| | PAYLOAD CLASS I | II | III | REMARKS |
|---|---|---|---|---|
| **SPECIFICATIONS** | | | | |
| CEI | A | A | A | |
| SUBSYSTEM | A | X | X | A APPLIES TO MAJOR SUBSYSTEMS ONLY (E.G., INSTRUMENT ASSEMBLIES). |
| GSE | A | X | X | RECOMMEND A ONLY IF DELIVERABLE. |
| TRAINING MODEL | A | X | X | A ONLY IF TRAINING REQUIRED OTHER THAN CONTRACTOR. |
| INTERFACE | A | A | A | A APPLIES TO EXTERNAL INTERFACES ONLY. |
| **PLANS** | | | | |
| MGT CONTROL (MCP'S) | A | X | X | |
| DATA MGT | A | A | X | A AS APPLICABLE TO INTERFACING AGENCIES/OTHERWISE, X. |
| CONFIG MGT | A | X | X | ASSUME USE OF EXISTING CONTRACTOR PLAN. |
| DOCUMENTATION | X | X | X | CONTRACTOR CONTROL ONLY IN ACCORDANCE WITH CONTRACT REQ'TS. |
| SAFETY | A | X | X | |
| **SYS. DESIGN DEVELOPMENT TASK/DOCUMENTS** | | | | |
| MISSION OPS. ANALYSIS | X | X | X | PART OF SE TASKS TO DEFINE HARDWARE REQ'T AND INPUT TO OFS PLAN AND ICS. |
| SYS. DESIGN/ANALYSIS | X | X | X | |
| DATA MGT COORD. | X | X | X | |
| SYSTEM SOFTWARE | X | X | X | PROPERLY DOCUMENTED UNDER CONTRACTOR CONTROL/A IF DELIVERABLE. |
| MEASUREMENTS REQ'T | A | A | A | A ONLY IF APPLICABLE TO INTERFACING AGENCIES. |
| COMMAND LIST | A | A | A | A ONLY IF APPLICABLE TO INTERFACING AGENCIES. |
| DESIGN ANALYSIS REPORT | I | X | X | X - AVAILABLE TO CUSTOMER AS REQ'T. I - INFORMATION COPY TO CUSTOMER. |
| SYSTEM DESIGN MONITOR | X | X | X | |
| DRAWINGS AND DWG CHANGES | A | A | X | A BASED ON CDR OR FACI/OTHERWISE MAINTAINED UNDER CONTRACTOR CONTROL. |
| WEIGHT, POWER CONTROL | A | A | A | A ONLY IF EFFECT ON HIGHER LEVEL SYSTEM INTERFACE. |
| EMI CONTROL | A | A | X | A ONLY IF EFFECT ON HIGHER LEVEL SYSTEM INTERFACE. |
| PROGRAM REVIEWS & REPORTS | I | I | X | MINIMIZE TO ESSENTIAL FOR CUSTOMER COMMUNICATION. |
| CUSTOMER LIAISON | X | X | X | |
| PI LIAISON | X | X | X | |
| SUBCONTRACT MONITOR | X | X | X | |
| SUB/VENDOR REPORTS/DATA | III | I | X | INFORMATION COPIES AS REQ'D - CONTRACTOR RESPONSIBILITY. |
| BREADBOARD TEST SUPPORT/ANALYSIS | X | X | X | |
| RELIABILITY | A | X | I | |
| MAINTAINABILITY | X | X | I | |
| SAFETY | A | A | X | |
| LOGISTICS | A | X | I | |
| HUMAN ENGINEERING | X | X | I | |

TABLE 4-1

SYSTEM ENGINEERING REQUIREMENTS MATRIX

| | PAYLOAD CLASS I | PAYLOAD CLASS II | PAYLOAD CLASS III | REMARKS |
|---|---|---|---|---|
| **SYSTEMS INTEGRATION TASKS/DOCUMENTS** | | | | |
| ENG MODEL FAB/TEST SUPPORT/DATA | I | I | X | TEST RESULTS PRESENTED AT DESIGN REVIEWS - HARDWARE ONLY IF REQ'D. |
| PROTO MODEL FAB/TEST SUPPORT/DATA | I | I | X | TEST RESULTS PRESENTED AT DESIGN REVIEWS - HARDWARE ONLY IF REQ'D. |
| QUAL MODEL FAB/TEST SUPPORT/DATA | A | A | X | MULTIPLE USE OF MODELS POSSIBLE FOR ALL CLASSES. A INDICATES FORMAL QUAL. |
| FLIGHT MODEL FAB/TEST SUPPORT/ DATA | A | A | A | DELIVERABLE END ITEM. |
| **SYSTEM TEST PROCEDURES AND SPECS.** | | | | |
| ACCEPT. TEST REPORTS AND DATA | A | I | — | |
| QUAL TEST REPORTS | A | I | — | |
| DCRR | A | — | — | REQUIREMENT MAY BE REDUNDANT WITH OTHER PROGRAM DOCUMENTATION. |
| FIELD TESTS | X | X | X | |
| **MISSION PLANNING TASKS/DOCUMENTS** | | | | |
| OPS PLAN | A | A | A | A ONLY IF INTERFACING AGENCIES INVOLVED WITH OPS/X OTHERWISE. |
| CAL DATA | A | A | A | A ONLY IF INTERFACING AGENCIES INVOLVED WITH OPS/X OTHERWISE. |
| SODB | A | I | X | |
| CONTINGENCY PROCEDURES | A | A | A | A ONLY IF INTERFACING AGENCIES INVOLVED WITH OPS/X OTHERWISE. |
| TRAINING | X | X | X | |
| TECHNICAL MANUAL | X | X | I | |

A = APPROVAL BY CUSTOMER REQUIRED

X = ACTIVITY/DOCUMENT APPLICABLE

I = INFORMAL AND ONLY AS REQUIRED FOR ENGINEERING PURPOSES.

TABLE 4-1 (CONT.)

SYSTEM ENGINEERING REQUIREMENTS MATRIX

a. Class I Payload

(1) Important single scientific opportunity.

(2) Relatively high investment involved in deployment (i.e., launch vehicle, support systems, etc.).

(3) Payload equipment is nonrecoverable, nonmaintainable.

(4) Highest achievable reliability in payload is primary driver.

b. Class II Payload

(1) Scientific objective is secondary mission objective, i.e., mission investment not significantly compromised by loss of science.

(2) Multiple scientific opportunities exist.

(3) Payload can be maintained in flight or recovered and re-furbished for subsequent missions.

(4) Medium to low investment to deploy science payload.

(5) Cost-effectiveness is primary driver.

c. Class III Payload

(1) Multiple scientific opportunities exist.

(2) Deployment investment is minimal.

(3) Low-cost payload development is primary driver.

## 4.3 PROGRAM GUIDELINES

Program philosophy guidelines applicable to the above subdivision are:

a. General - applicable to all classes

(1) Program planning approach on System Engineering Management Basis.

- Organization and responsibilities clearly defined.
- Basic plans for engineering, manufacturing, test, R&QA, system support, logistics.
- Program schedules.
- Task statements.
- Budgets.

(2) Engineering activities.

- Definition of requirements and interfaces.
- Design and analysis.
- Manufacturing drawings.
- Test and verification.
- Configuration management.

(3) Documentation (deliverable).

- Status reports (frequency variable).
- Financial reports.
- System specification.
- Interface documents.

(4) Deliverable hardware quantities assumed small for all payload classes (i.e., one or two of a kind).

b. Class I Payload

(1) Full hi-rel program requirements.

(2) Full customer/contractor program office interfacing.

(3) Full documentation, reporting.

(4) Formal approvals required.

- Design.
- Parts and materials.
- Program plans.
- Test results.

(5) Customer witness for inspection, test, acceptance.

(6) Full-up configuration management with FACI.

(7) Formal design reviews, readiness reviews, acceptance reviews.

(8) Full-up R&QA safety and maintainability requirements.

(9) Examples - ALSEP, Viking, LST, HEAO.

c. Class II Payload

(1) Program oriented for cost effectiveness.

(2) Minimal organization - program manager with engineering, R&QA, manufacturing supervisor is typical.

(3) Reduced customer/contractor interfacing requirements.

(4) Contractor QA only inspection, test, acceptance.

(5) Documentation minimized to that which is absolutely essential.

(6) Reduced formal meetings.

(7) Use of existing (acceptable) contractor plans/procedures.

(8) Reduced configuration management (no FACI).

(9) Test program performed under engineering cognizance, minimal QA.

(10) Manufacturing documentation and controls minimized to "good commercial practice".

(11) Reliability engineering performed as basic design discipline but formal reporting/documentation reduced to essential only.

(12) Typical program examples: ASTP, Shuttle Sortie Mission Experiments, Skylab Experiments.

d. Class III Payload

(1) Low-cost program.

(2) Complete project performed on an engineering/model shop basis.

(3) All activities under engineering management.

- Project management.
- Design, parts/materials selection.
- Fabrication, assembly, test.
- Configuration control.
- QA function.

(4) Minimal documentation, reporting.

(5) Rocket payloads - typical Class III example.

## 4.4 REFERENCES


1. Shinners, S. M., Techniques of System Engineering, McGraw-Hill (1967).

2. Air Force Systems Command Manual, AFSCM 375-4, Part 1 (May 1966).

3. MIL-STD-499 (USAF) 17 July 1969 - Military Standard Systems Engineering Management, Page 11.

4. Kestenbaum, R., Electronics, Vol. 24, No. 9 (April 28, 1969).

5. Joint Design-to-a-Cost Guide, Procurement Associates, Inc. (Sept. 1973).

6. Clayton, J. F., ALSEP Management Plan, ATM 60 (October 1965).

7. Shay, R. W., Engineering Plan, ATM 170 (December 1965).