Aerospace Systems Division

NO. ASTIR-TM-24-1	REV
PAGE I OF	
DATE 2/8/74	

MILEY

EVALUATION OF SYSTEMS ENGINEERING APPROACHES

(PRELIMINARY REPORT)

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CONTENTS

1.0 INTRODUCTION

Systems Engineering is that part of a technical program 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 the theoretical aspects of Systems Management, reviews the Systems Engineering approach used on the ALSEP program and concludes with recommendations for future programs.

2.0 SYSTEMS ENGINEERING MANAGEMENT

.1 OBJECTIVES

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

a. Insure 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.

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1. Shinners, S. M., Techniques of System Engineering (McGraw-Hill Book Co. (1967)
2. Air Force Systems Control Manual. AFSCM 375-4, Part 1 (M... 1966)

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.

The Military Standard for Systems Engineering (3) states that "The contractor's system engineering process shall be a logical sequence of activities and decisions leading to the definition of configuration, usage and support of a system and the technical program for acquiring the system".

2.2 ORGANIZATION AND RESPONSIBILITIES

The operation of an organization can be viewed as a multiple feedback loop control system which makes continuous comparisons between the actual and desired system parameters and takes action to correct for differences between the two.

A program basically consists of four phases, which are (1) definition of the 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.

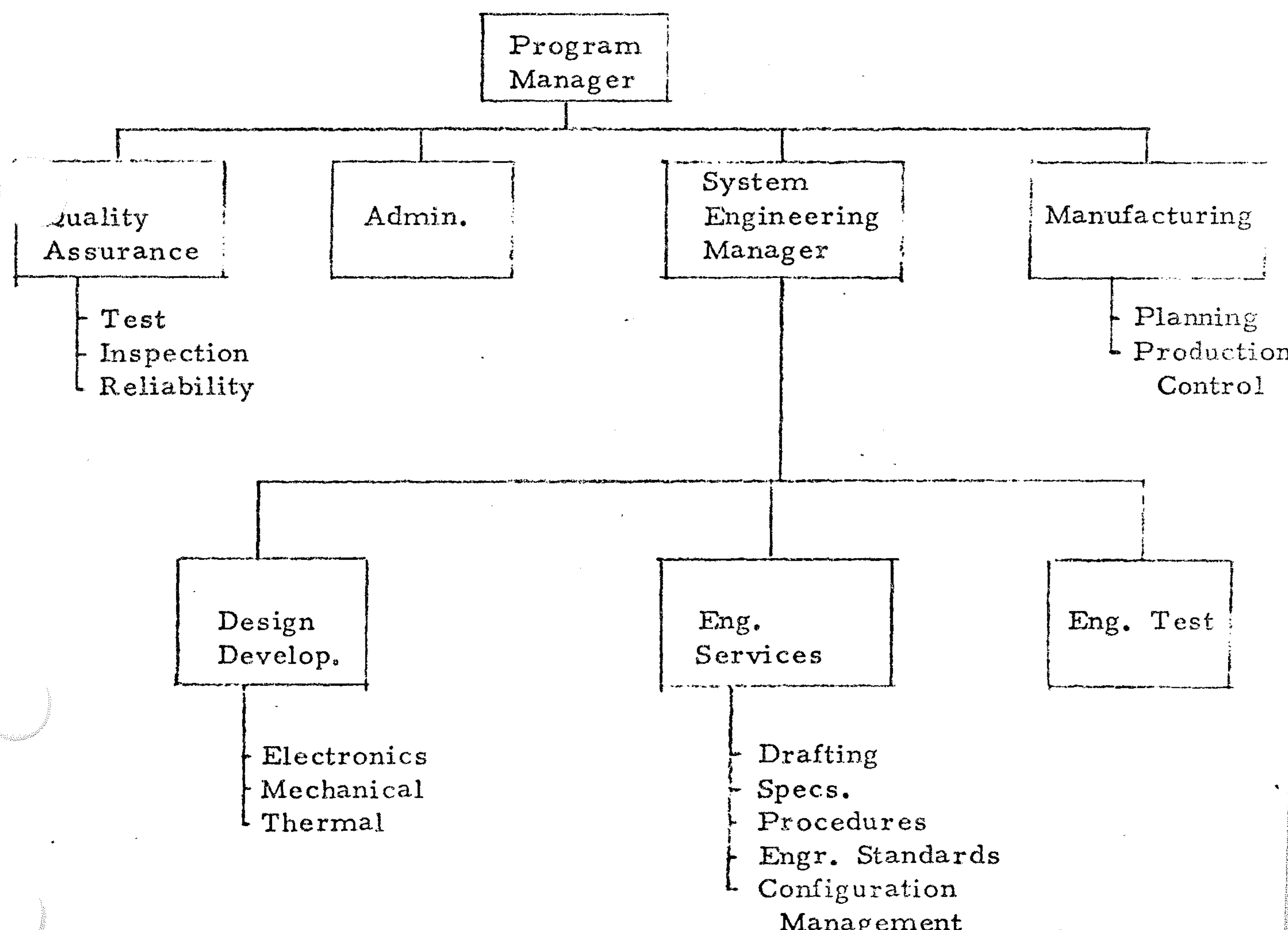
The main elements of an engineering organization consist of engineering, drafting and manufacturing. These groups are supplemented by the quality control and reliability, service groups.

In a small program one individual may provide the systems engineering management, provide the direction and coordination for the various groups. In a large program one individual cannot perform the various system engineering management functions required to satisfy the requirements of the different

3. MIL-STD-499 (USAF) (17 July 1969) Page 11.

phases. The transitions between phases must be anticipated and the lower management adjusted accordingly by the Program Manager.

A typical large program might have three organizational levels, from Program Manager, through System Engineering Manager to the design level, as shown below.



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

2.3 SYSTEMS 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".[4]

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:[5]

i) Qualification

ii) Iteration

iii) Interdisciplinary approach

iv) Interface analysis

v) Maintenance of communications feed back loops.

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4. MIL-STD-499 (USAF) Military Standard System Engineering Management (Page 11)

The extent to which particular system engineering tasks are applied 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.

2.4 PERFORMANCE/COST/SCHEDULE TRADEOFFS

In private industry, especially in the consumer sector, companies are cost conscious and attempt to reduce operating costs to increase profits. In government military and space programs the tendency has been to strive for perfection in performance with less emphasis on cost, but in the present -a of limited budgets much attention is being given to cost and schedule.

One new approach being followed by the military departments is called Design to Cost [6]. 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 activites. The intent is to establish cost goals which are realistic, achieveable, represent and appropriate value for the money and 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 following are quotes from the Guide:

1. Design-To-Cost Concept

A. Why Design to a Cost?

(1) <u>DOD Policy:</u> Unit costs of weapon systems have risen to such an extent and funds available to DOD 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

6. Joint Design-To-Cost Guide (A Conceptual Approach for Major Weapon System Acquisition), Procurement Associates Inc. (24 Sept. 1973)

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) <u>"Design-to-Cost" Definition</u>: Design-to-Cost is a process utilizing 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 of 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 within DOD should assist in countering high unit production cost and unnecessary system sophistication and complexity.

(3) Need for Flexibility. The Program Manager (PM) and each completing 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 PM 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 tradeoff desired performance to achieve the cost goal while assuring a viable weapon system design is obtained. To this end, both 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 which 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. ariations 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 should be applied but will be subordinate to performance requirements in program decisions.

b) Similarly if project completion is imperative by a certain date, 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 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 which were emplaced on the moon with a total of twenty nine experiment packages, including three laser reflectors. The first package, EASEP, was deployed on July 20, 1969 while the last Array E was deployed on December 10, 1972.

The program started out in March 1966, to produce four ALSEP flight packages, the first of which was to be delivered to NASA on 14 July 1967. The accident at 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 o 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 3.1-1.

3.2 SYSTEM ENGINEERING ROLE IN PROGRAM DEVELOPMENT

The Systems Engineering group acted as the coordinator for all the technical aspects of the program. Their detailed activities varied throughout the course of the project but were mainly concerned with the electrical functions of the system.

When the program started in March 1966, the Systems Engineering Group was a part of the Engineering Department. (Figure 3.2-1). Their charter was to: "Control the configuration of all designs, models and blocks. The Systems 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".[7]

The functions of Systems Engineering were further clarified in ATM 170[8] 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, trade-off, tolerance control and performance analysis to verify conformance with SS100,000.

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7. Clayton, J. F., ALSEP Management Plan, ATM 60, October 1965
8. Shay, R. W., Engineering Plan, ATM 170, December 1965

ARRAY / MODEL	DEMO MOCKUP	TRAINER	BREADBOARD BRASSBOARD	ENG MODEL	PROTO TYPE	QUAL	FLIGHT
EASEP	✓	✓		✓		✓	A-11
A	✓	✓	✓	✓	✓	✓	A-12
B	✓	✓			✓	✓	A-13
C	✓	✓			✓	✓	A-14
A-2	✓	✓				✓ Subpack 2	A-15
D	✓	✓				✓ Subpack 2	A-16
E	✓	✓	✓			✓	A-17

Table 3.1-1

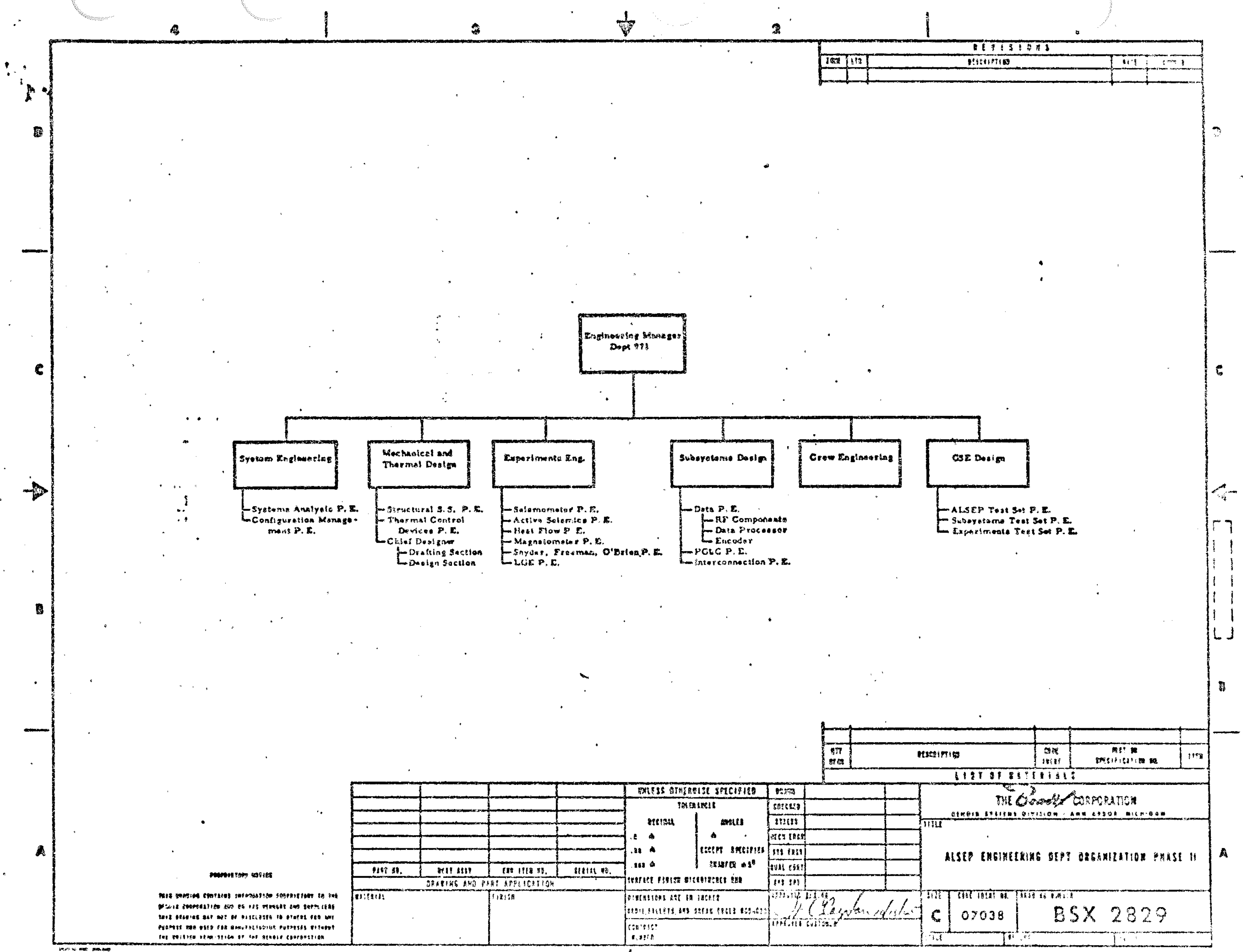

Engineering Manager
Dept 971
System Engineering
Systems Analysis P. E.
Configuration Management P. E.
Mechanical and Thermal Design
Structural S. S. P. E.
Thermal Control Devices P. E.
Chief Designer
Drafting Section
Design Section
Experiments Eng.
Seismometer P. E.
Active Seismics P. E.
Heat Flow P. E.
Magnetometer P. E.
Snyder, Freeman, O'Brien P. E.
LGE P. E.
Subsystems Design
Data P. E.
RF Components
Data Processor
Encoder
PCLC P. E.
Interconnection P. E.
Crew Engineering
GSE Design
ALSEP Test Set P. E.
Subsystems Test Set P. E.
Experiments Test Set P. E.
REVISIONS
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED
THE Bendix CORPORATION
ALSEP ENGINEERING DEPT ORGANIZATION PHASE II
C
07038
BSX 2829

Figure 3.2-1

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 analyze all changes.

The Configuration Management tasks of Specification Control, Drawing Control, and Weight Control were removed from the jurisdiction of Systems Engineering and transferred to a staff group, in July 1966 (Figure 3.2-2).

The Systems 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 systems group and test group were amalgamated around 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 systems engineering again reported to the engineering manager in a similar organization to that used on the original ALSEP program.

4.0 OBSERVATIONS AND CONCLUSIONS

There have been a large number of books and articles written about Systems Engineering. The "Systems" approach is the moden panacea for management of every type of job or institution. The approach is applied not only to hardware engineering but to cost as well. While procurement costs are important, the total costs including the life cycle costs, which include installation, operation and maintainance are of more significance to the contracting agency. There is more emphasis recently on thorough design and analysis during development phases to ensure that the product will meet the specification, before contracting for the final item of production, even to the extent that more than one contractor may be funded to develope a prototype design. The final choice is then made by selecting

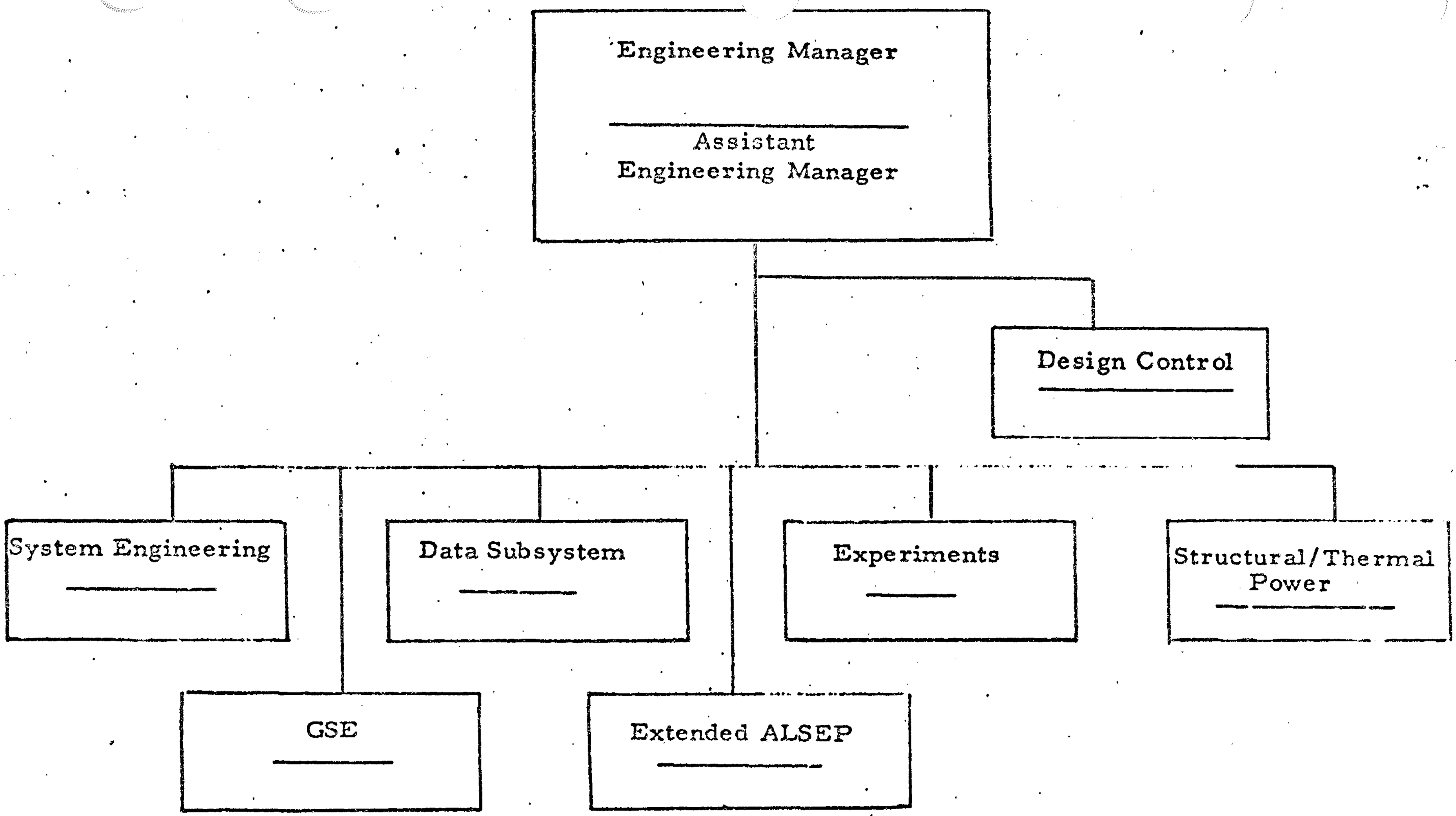

Engineering Manager
Assistant
Engineering Manager
Design Control
System Engineering
Data Subsystem
Experiments
Structural/Thermal
Power
GSE
Extended ALSEP

Figure 3.2-2

the cheapest overall program that will meet the requirements.

The ALSEP Systems Engineering effort was organized on standard but conservative lines. In similar future programs consideration should be given to funding a larger group of qualified engineers. This will allow more analysis of design and earlier specification of requirements to cover all necessary facets of the program. This in turn, will allow in depth coverage of wider, but necessary, fields, including areas such as performance requirements, interface definitions and planning for integration, requirements and designs for GSE, mission operations, and data handling. The early analysis of likely problem areas, like EMI, can save much time which is often spent later in troubleshooting and applying fixes. Much useful work was performed in the areas of interfaces, standard flat cable connections, test organization and documentation, but even more could have been done, with probable cost savings, in the area of standardization, had funding been available. The large percentage of GFE experimentation also restricted standardization and control.

A modest review of shuttle payload configurations was performed by Bendix, late in 1973. The documentation which was reviewed was the latest available at that time and had been prepared for various NASA agencies. The purpose of the review was to provide an independant assessment of requirements and activities for definition and implementation of shuttle payloads and to recommend an approach for definition of organization and responsibility.

The results of this review were a set of objectives, methods and possible organizational approaches, which are outlined below:

<u>Objectives of Shuttle Payload Program</u>

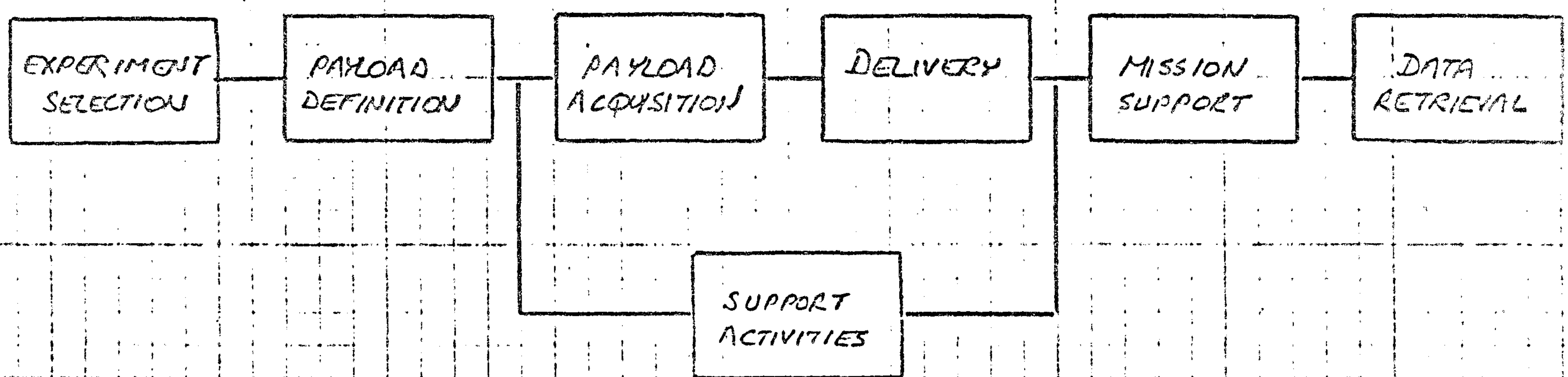
- Timely development of cost effective - useful payloads
- Available to all and easy to use
- Provide flexibility for experiment accommodation
- Interface compatibility with shuttle vehicles, operations and communications/data systems
- Economical - conform to projected budgets

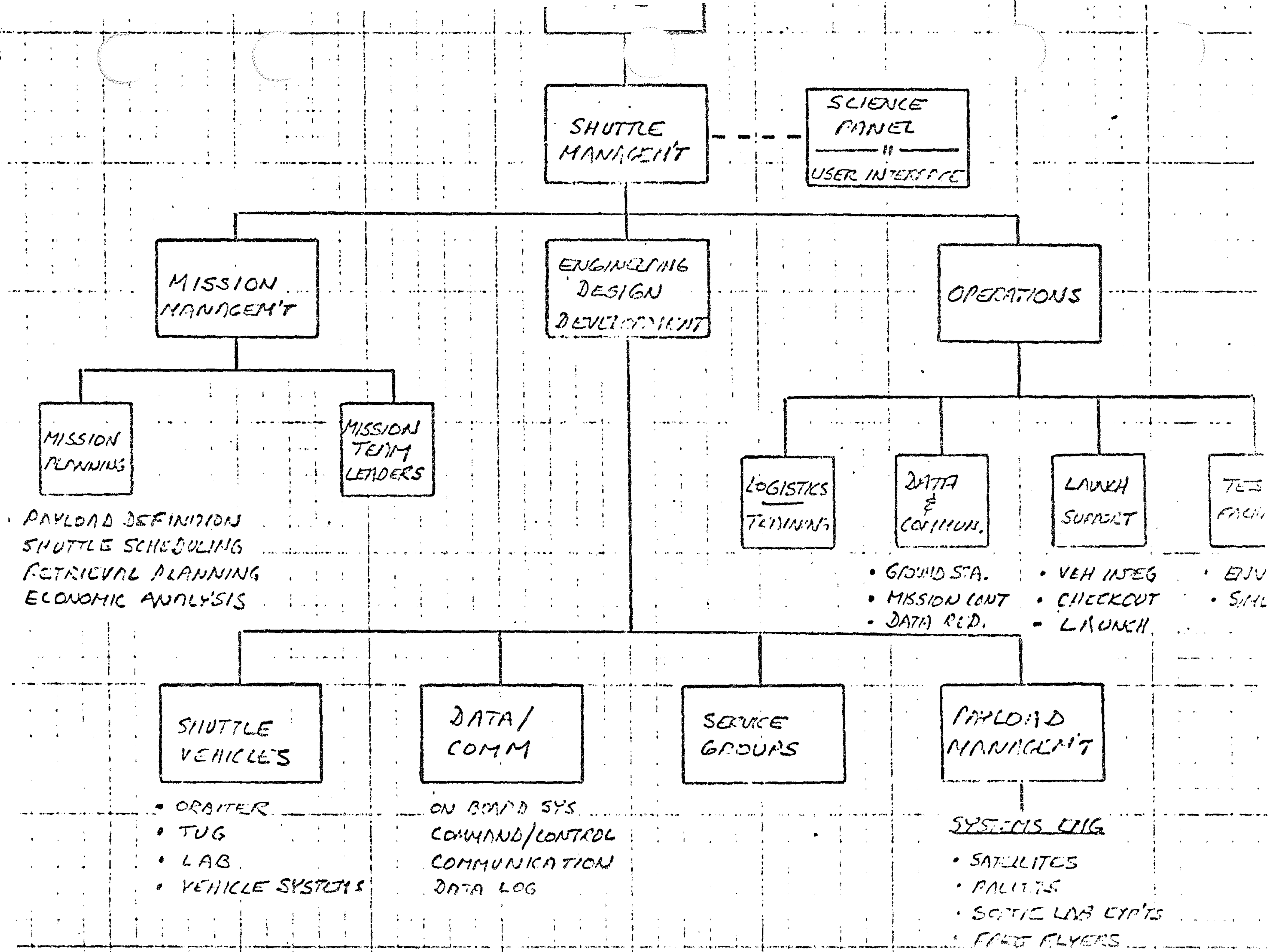
- Available on schedule
- Adequate definition to produce realistic mission planning
- Simplify experiment design and interfacing.

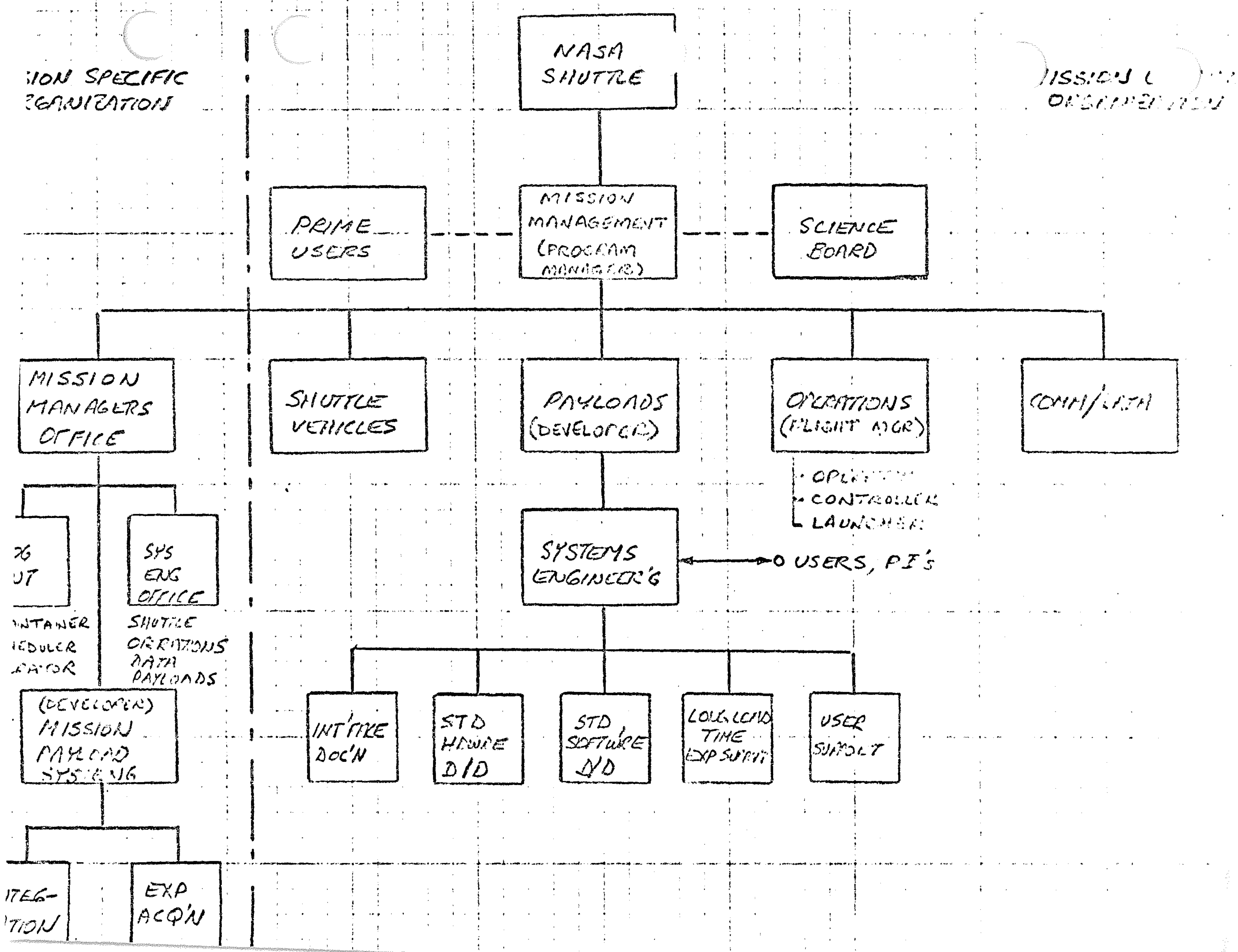
Method of Achieving Objectives

- Establish central systems engineering oriented organization to coordinate and direct activities
- Emphasize key issues in organization responsibilities and direction of approach
- Provide authority to allow organization to accomplish objectives across centers
- Back organization with total NASA commitment
- Highlight progress by measurement of specific results
- Make maximum use of existing resources and technical expertise
- Advertise/invite early participation from total science, technology, industrial users to accumulate mission requirements
- Rational, expedient selection process
- Reduce requirements on user for expt. consideration and approval
- Devise management system which allows component independence yet emphasizes integrated dependance for optimal economic results
- Single engineering management responsibility
- Service groups for assistance (no tail wagging the dog)
- Provide lenient environments to ease experiment design
- Minimize standard requirements to essentials.

PAYLOAD DEVELOPMENT SEQUENCE




SHUTTLE MANAGEM'T
SCIENCE PANEL
USER INTERFACE
MISSION MANAGEM'T
ENGINEERING DESIGN DEVELOPMENT
OPERATIONS
MISSION PLANNING
MISSION TEAM LEADERS
PAYLOAD DEFINITION
SHUTTLE SCHEDULING
RETRIEVAL PLANNING
ECONOMIC ANALYSIS
LOGISTICS
TRAINING
DATA & COMMUN.
• GROUND STA.
• MISSION CONT
• DATA RED.
LAUNCH SUPPORT
• VEH INTEG
• CHECKOUT
• LAUNCH
SHUTTLE VEHICLES
• ORBITER
• TUG
• LAB
• VEHICLE SYSTEMS
DATA/ COMM
ON BOARD SYS
COMMAND/CONTROL
COMMUNICATION
DATA LOG
SERVICE GROUPS
PAYLOAD MANAGEM'T
SYSTEMS ENG
• SATELLITES
• PALLETS
• FREE FLYERS



ION SPECIFIC
GANIZATION
ISSION
NASA SHUTTLE
PRIME USERS
MISSION MANAGEMENT (PROGRAM MANAGER)
SCIENCE BOARD
MISSION MANAGERS OFFICE
SHUTTLE VEHICLES
PAYLOADS (DEVELOPER)
OPERATIONS (FLIGHT MGR)
COMM/DATA
CONTROLLER
SYS ENG OFFICE
SHUTTLE OPERATIONS DATA PAYLOADS
SYSTEMS ENGINEER'G
USERS, PI's
(DEVELOPER) MISSION PAYLOAD
INT'FACE DOC'N
STD HDWRE D/D
STD SOFTWRE D/D
LONG LEAD TIME
USER
EXP ACQ'N

Methodology Issues - 1

Experiment Selection

- Performed by shuttle management and science panel
- Cooperation and assistance of users
- Maintain objectives of shuttle era
- Accommodate requests from all sources.

Payload Definition

- Performed by mission management and systems engineering group of engineering design
- Assisted by science panel and users
- Perform trade-off studies and analyses to determine the most economic utilization of resources to achieve objectives.
- Studies to determine cost trade-offs between high and low orbit approaches
- Studies to determine traffic patterns for deployment/retrieval missions
- End results are mission plans with payload definitions of types experiment content.

Payload Acquisition

- Mission specification and funding by mission management
- Preliminary design studies by engineering design groups in concert
- Preparation of work statements and design specifications

- Payload group responsible for design, development and build of hardware
- Subcontract efforts as necessary
- Develop, test and qualify, components and systems
- Build and test flight components and systems
- Deliver to mission management

Mission Support

- Performs mission planning and support
- Assigns team leader responsible for coordination of a specific shuttle mission, hardware integration and overall mission success
- Assisted by representatives of relevant engineering design groups and operations group.

Support Groups and Operations

- Provide for vehicle integration and checkout
- Facility provision and maintenance for launch activities
- Ground station control and communications
- Data reduction on line and off line
- Test facility control
- Logistics - Spares, training

Features of Proposed Organization

Dual Structure

1. Systems Organization for definitions

- Shuttle vehicles
- Payloads
- Operations
- Communications data

2. Project organization for missions hardware acquisition and operation

Note: A "Mission" may be completed in one flight, alternatively require multiple flights.

In an ideal program sufficient time and funding should be allowed for a detailed system design study to be performed prior to any detailed design of component parts. A management organization should be planned at the start to ensure that duplication of effort is eliminated and that the objective will be achieved in the most economic way. The system study should cover all aspects of the system, including procurement, data handling, principal investigator interfaces, operation and maintenance as well as the normally considered tasks. Specifications should be prepared to the black box level to allow the next stage of development to proceed with confidence that the system black boxes will operate together as planned.

The efforts during the later development phases should include maintenance of interfaces and analysis of designs to ensure compatibility with system requirements.

The system engineering tasks for a typical program are identified below. The inclusion of some of these tasks is dependent upon program size and the overall scope of the engineering effort.

Systems Engineering Tasks

1. Systems concepts and design studies

2. Review all technical requirements in specifications, interface documents and work statements. Prepare listing of subtasks.

3. Define control budgets for power, weight and other interface items as applicable.

4. Prepare integration and test plans.

5. Prepare ground support equipment requirements for system level and review requirements for lower tiers and experiments.

6. Prepare system level procedures and review lower tiers and experiments procedures for adequacy to verify performance.

7. Analyze designs and test results to verify conformance of designs to requirements of performance specifications.

8. Generate plans for data handling from testing through mission support.

9. Generate software for data handling during test and development.

10. Control configuration through drawing and documentation control

11. Support system level testing.

12. Maintain cost/schedule control for system engineering operations

13. Represent systems engineering on Material Review Board.

14. Prepare mission analysis and operational technical requirements necessary to achieve scientific objectives.

15. Implement standardized designs and design practices throughout program for cost effectiveness.

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