NAS9-10925

SD 71-292-6

Pre-Phase A Study for an Analysis of a Reusable Space Tug

FINAL REPORT

VOLUME 6
PLANNING DOCUMENTS
MARCH 22, 1971

APPROVED BY

G.M. Hanley, Program Manager
Reusable Space Tug

DIRECTED BY

F.G. Springer, Task Leader
Planning Documents
Reusable Space Tug

Space Division
North American Rockwell

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FOREWORD

This volume presents a planning documents analysis of the Prephase A Study for an Analysis of a Reusable Space Tug. This study was conducted by the Space Division of North American Rockwell Corporation, Seal Beach, California, for the National Aeronautics and Space Administration, Manned Spacecraft Center., Houston, Texas. The effort was performed under Contract NAS9-10925. The six volumes comprising this final report include:

Volume 1.	Management Summary	SD 71-292-1
Volume 2.	Technical Summary	SD 71-292-2
Volume 3.	Mission and Operations Analysis	SD 71-292-3
Volume 4.	Spacecraft Concepts and Systems Design	SD 71-292-4
Volume 5.	Subsystems Analysis	SD 71-292-5
Volume 6.	Planning Documents	SD 71-292-6

ACKNOWLEDGEMENTS

Many individuals within the Space Division of North American Rockwell Corporation, Seal Beach, California, Space Division devoted their efforts and professional knowledge to the Reusable Space Tug Study. However, those persons whose names appear here were the most heavily involved in development and operational planning.

Schedules, design plan, and system description	D. E. Nelson
Operational schedules and program categories	A. D. Kazanowski
Manufacturing plan	M. E. Hunsaker, E. M. Merrifield
Testing plan	G. W. Kindelberger, E. Wescombe
Ground operations plan	S. F. Zavisa, E. Wescombe
Supporting research and technology plan	J. O. Matzenauer G. C. McGee
NASA key decisions	H. L. Johnson, J. O. Matzenauer
Program cost estimates	G. J. Frassinelli, A. A. Kendrick

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ABBREVIATIONS

The following abbreviations are used in this document:

AB	Approved bidders
ACS	Attitude control system
APU	Auxiliary propulsion unit
CA	Contract award
CAM	Cargo module
CC	Change control
CCB	Change control board
CDR	Critical design review
CI	Configuration item
CIS	Chemical interorbital shuttle
CLS	Chemical lunar shuttle
CM	Crew module
C/O	Checkout
CSM	Command service module
DET	Detail part fabrication
ECLSS	Environmental control and life support system
EO	Earth orbit
EOPD	Earth-orbital propellant depot

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EOS	Earth-orbital shuttle (two-stage reusable)
EOSS	Earth-orbital space station
ESS	Expendable second stage
FRR	Flight readiness review
ICD	Interface control document
IM	Intelligence module
IPP	NASA integrated program plan
IOC	Initial operational capability (date)
IRU	Inertial reference unit
LEO	Low earth orbit
LG	Landing gear kit
LM	Lunar module
LOPD	Lunar-orbital propellant depot
LSB	Lunar surface base
MK	Manipulator kit
MU	Mockup
NC	Number of contracts
NHU	Number of Hardware units to be procured
OLF	Orbiting lunar facility
OLS	Orbiting lunar station
OMS	Orbital maneuvering system
OSSA	Office of space station applications

P	Denotes procurement decisions occurring in sets, indicated by decimals over a period of time
PCA	Product configuration audit
PD	Planning document
PDR	Preliminary design review
PE	Program element
PL	Payload
PM	Propulsion module
PP&C	Program planning and control
RNS	Reusable nuclear shuttle
RST	Reusable space tug
SDR	System design review
SRR	System readiness review
SvsM	Entire tug system versus module procurement
TC	Type of contract
TDRSS	Tracking and data relay satellite system
T-V	Thermal vacuum
T/W	Thrust to weight
UP	Unmanned payloads

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ILLUSTRATIONS

TABLES

INTRODUCTION

The planning documents (PD's) included in this report were prepared in accordance with the requirements of Task 4 of the contract (NAS9-10925) Statement of Work. The purpose of the PD's is to provide NASA with information that will (1) enable NASA management to decide whether or not to proceed with subsequent phases of the Reusable Space Tug (RST) Program and (2) guide NASA management to the key decisions to be made and to the critical technology development requirements. The PD's describe a logical, integrated set of activities and events necessary to accomplish mission and operational requirements. The PD's include realistic schedules and cost estimates for budgetary and planning purposes and essential related program information for economical and high-quality development and operations. The PD's cover preliminary analysis, definition, design, manufacture, test, ground operations, flight operations, refurbishment, and related activities for the reusable space tug (NASA Phases A, B, C, and D). The PD's cover the three major RST study development categories (unmanned earth-orbital tug, manned earth-orbital tug, and manned lunar tug) and the three selected design concepts (1, 5, and 11). The time period covered in this effort is from the start of Phase A (assumed as 1 June 1971) through 31 December 1989.

The planning documents are thoroughly integrated and consist of six principal elements:

1. Work breakdown structure

2. Schedules

    Program development schedule

    Operational schedule

    Operational flight vehicles production schedule

3. Preliminary plans

    Design

    Manufacturing

    Testing

Ground operations

Supporting research and technology

4. Decision matrix

5. System description

6. Program cost estimates

The Space Division of North American Rockwell Corporation prepared the planning documents using the approach shown in Figure 1. This approach is discussed in detail under the various sections of the PD's. Provisions are made for a soft mockup to facilitate design engineering and manufacturing planning and to familiarize NASA with the reusable space tug (RST) design. Test hardware requirements and test operations are based on a test philosophy that will minimize cost while ensuring reliability and system safety. Production requirements for operational flight vehicles are based on anticipated mission and operational requirements. The scheduling analysis (performed in conjunction with the preparation of the program development schedule and the schedules of the manufacturing and testing plans) shows that it is feasible to achieve initial operational capability (IOC) dates for the unmanned earth-orbital tug of 1 January 1980, for the manned earth-orbital tug of 1 December 1980, and for the manned lunar tug of 1 April 1983.

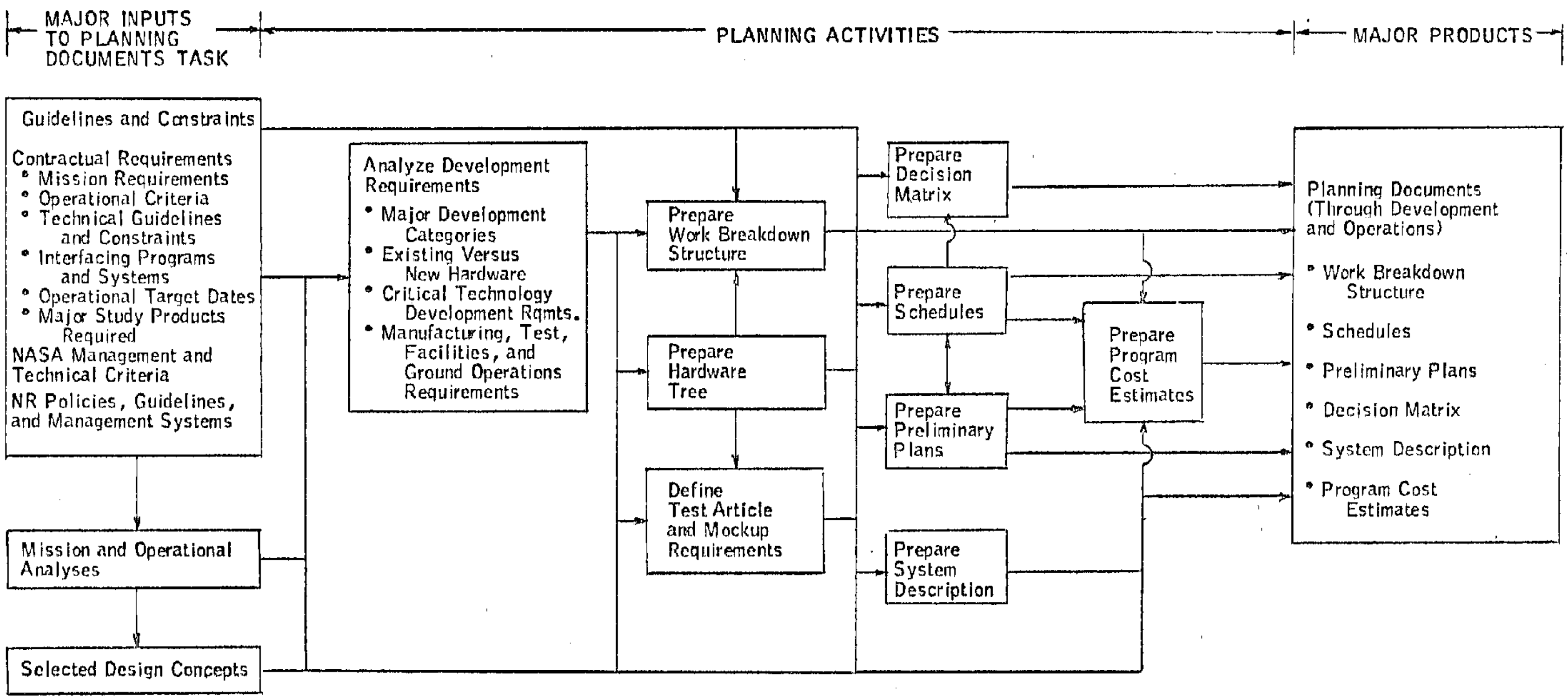

Figure 1. Planning Documents Approach

1.0 WORK BREAKDOWN STRUCTURE

The work breakdown structure (WBS) lists the principal categories of RST-supported programs, related program elements, and the principal categories of hardware, services, and related work tasks involved in RST development and production. The WBS (Figure 2) is hardware-oriented to the major subsystem level (level 5) and provides a frame of reference for preparing the program cost estimates, schedules, preliminary plans and decision matrix.

The WBS is structured in a manner similar to other current NASA programs. The WBS hardware portion reflects a hardware tree derived from an analysis of selected RST design concepts. The WBS is applicable to all three selected design concepts and all three major development categories. To facilitate identification of development (nonrecurring) and production (recurring costs), the WBS contains separate breakdowns for test and flight hardware.

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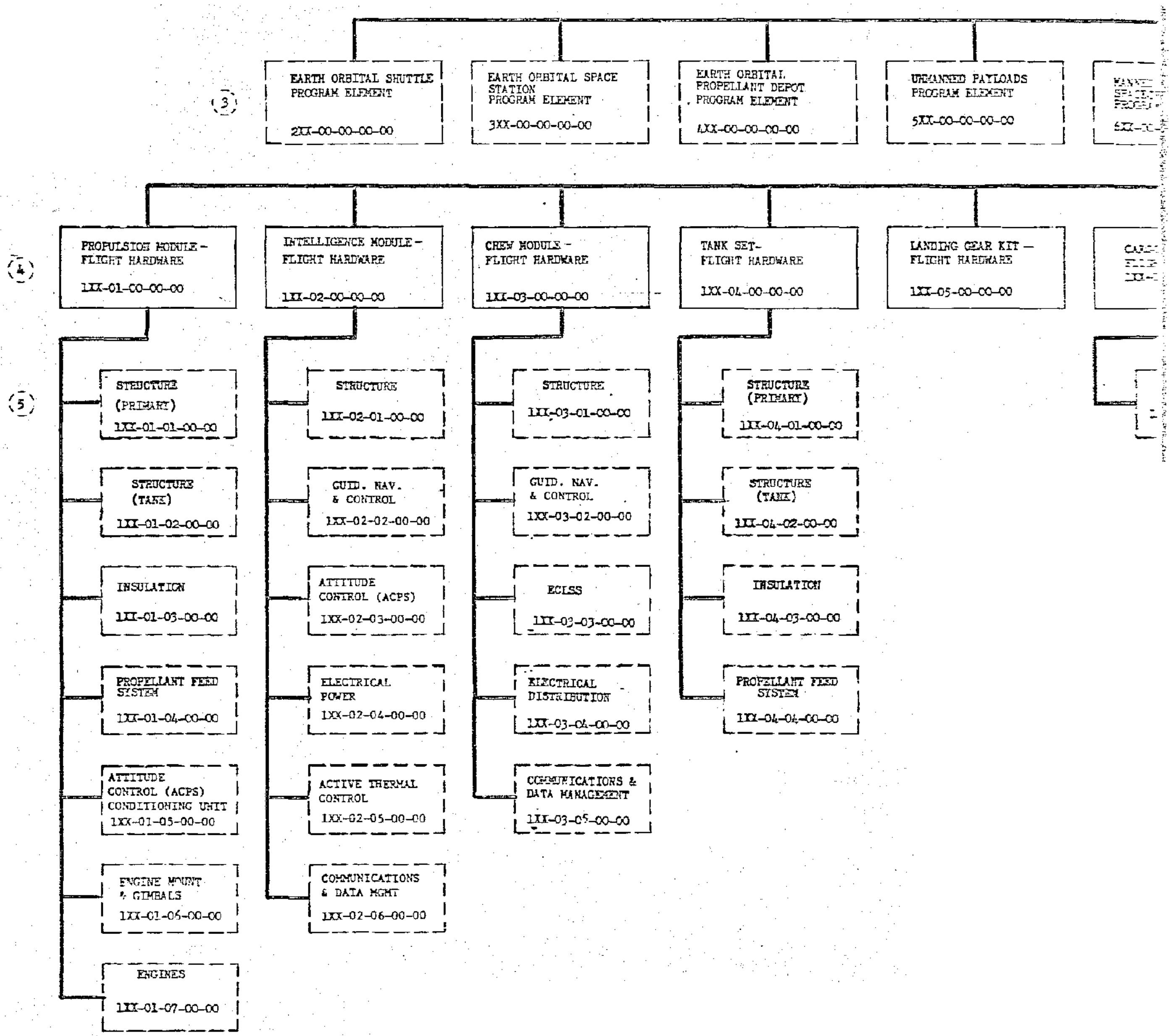

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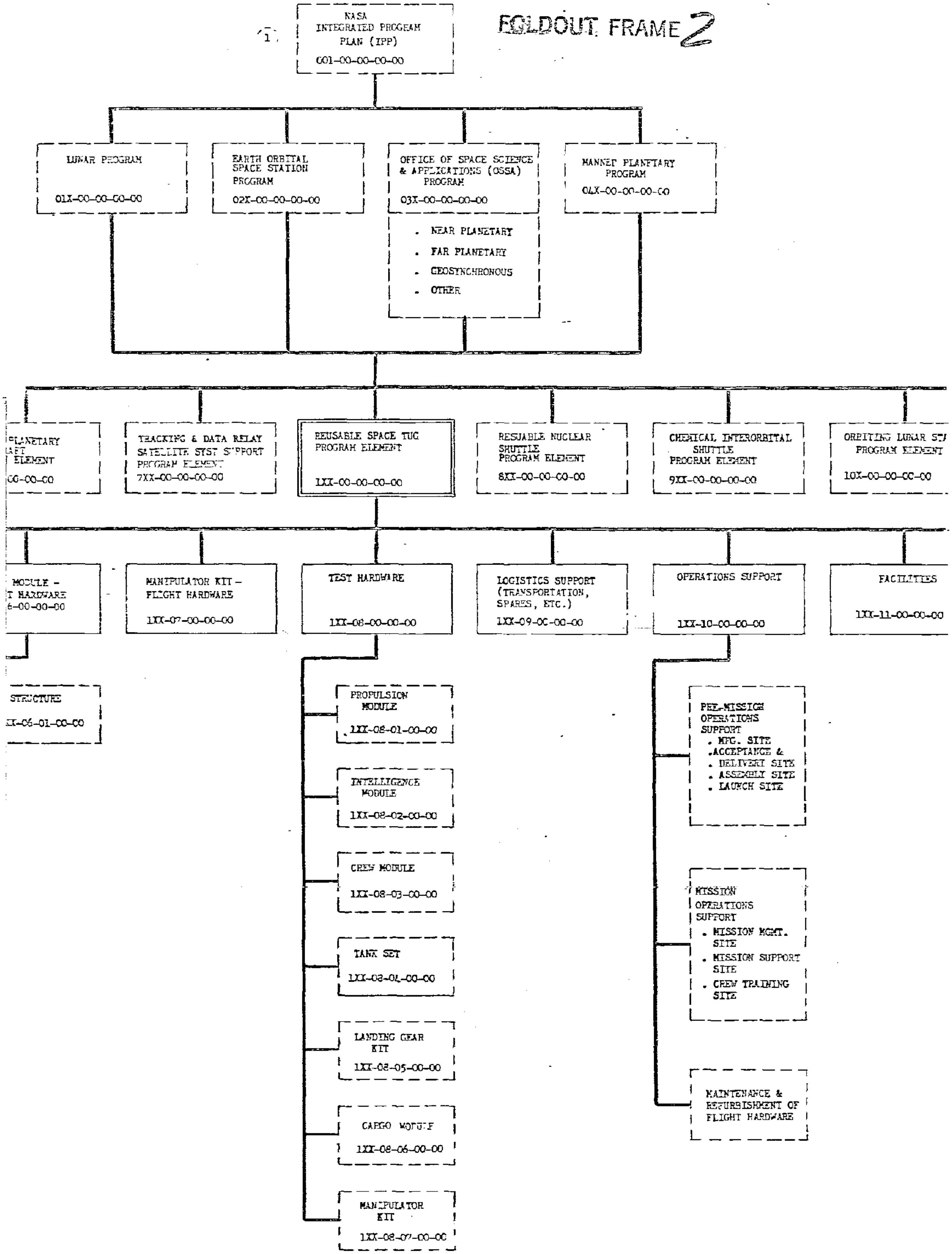

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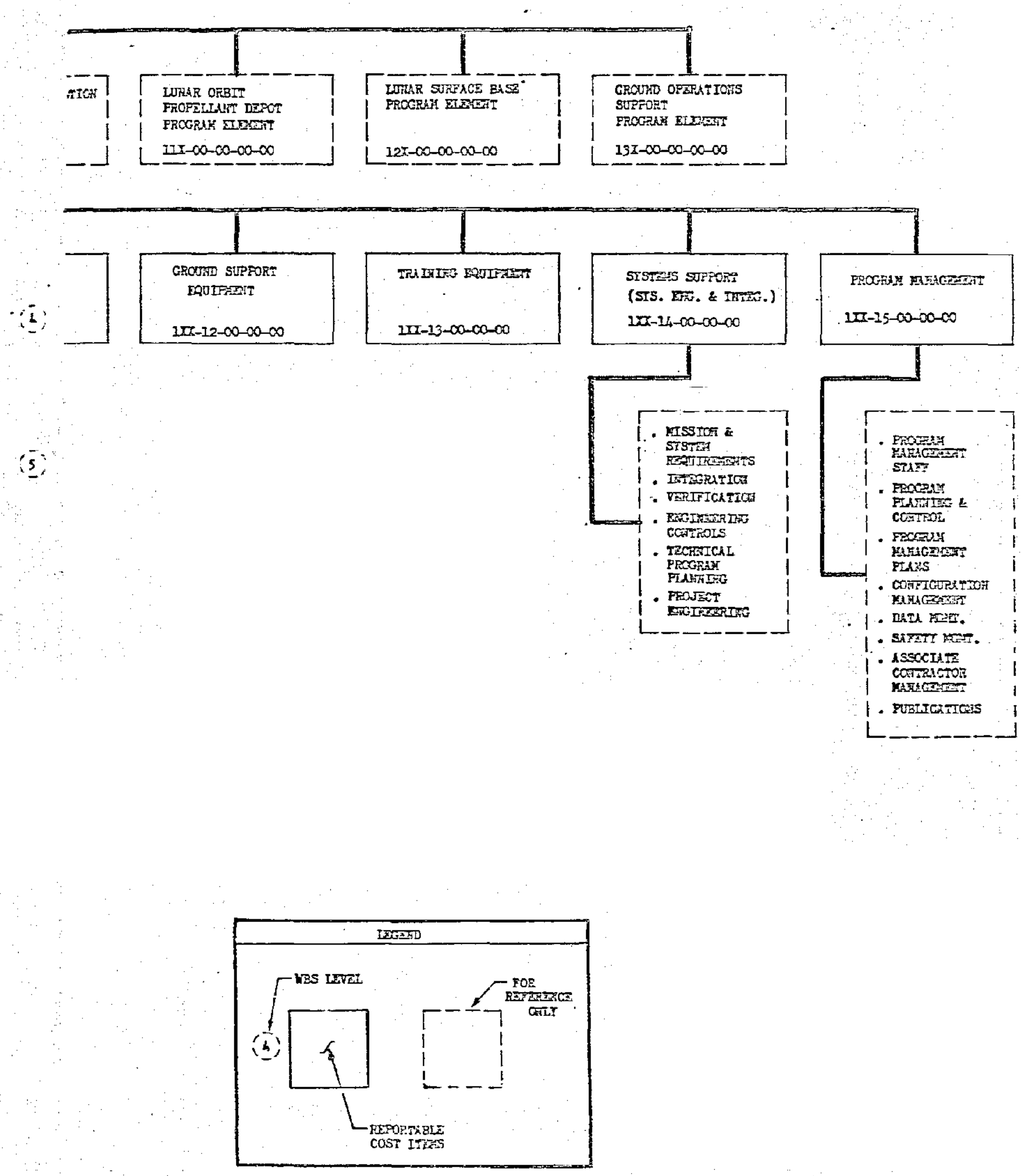

Figure 2. Work Breakdown Structure - Reusable Space Tug

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2.0 PROGRAM SCHEDULES

The following start and completion dates reflect an analysis of manufacturing and test requirements for the reusable space tug (RST) and the constraints imposed by the tug's lunar landing operations as compared with its earth-orbital operations:

1. Current Prephase A study — started 8 June 1970; completed 8 March 1971.

2. All three major development categories

   Phase A — Start 1 June 1971; to be completed 29 February 1972

   Phase B — Start 1 June 1972; to be completed 31 May 1973

3. Unmanned earth-orbital tug

   Phase C — Start 1 December 1973; to be completed 30 November 1974

   Phase D — Start 1 December 1974 through 31 December 1989

   IOC — 1 January 1980

4. Manned earth-orbital tug

   Phase C — Start 1 December 1975; to be completed 30 November 1977

   Phase D — Start 1 December 1977 through 31 December 1989

   IOC — 1 December 1980

5. Manned lunar tug

   Phase B-1 — Start 1 December 1976; to be completed 30 November 1977

Phase C — Start 1 April 1978; to be completed 31 March 1979

Phase D — Start 1 April 1979 through 31 December 1989

IOC — 1 April 1983

2.1 PROGRAM DEVELOPMENT SCHEDULE

The program development schedule has been prepared in two forms: a master detailed schedule (Figure 3) and a summary schedule (Figure 4). It should be noted that the schedule includes major milestones and reflects the requirements for test articles and mockups. The schedule includes one operational flight vehicle for each of the three major RST development categories (unmanned earth orbital tug, manned earth orbital tug and manned lunar tug).

2.1.1 Ground Rules and Assumptions

The following ground rules and assumptions were established for preparation of the preliminary program development schedule:

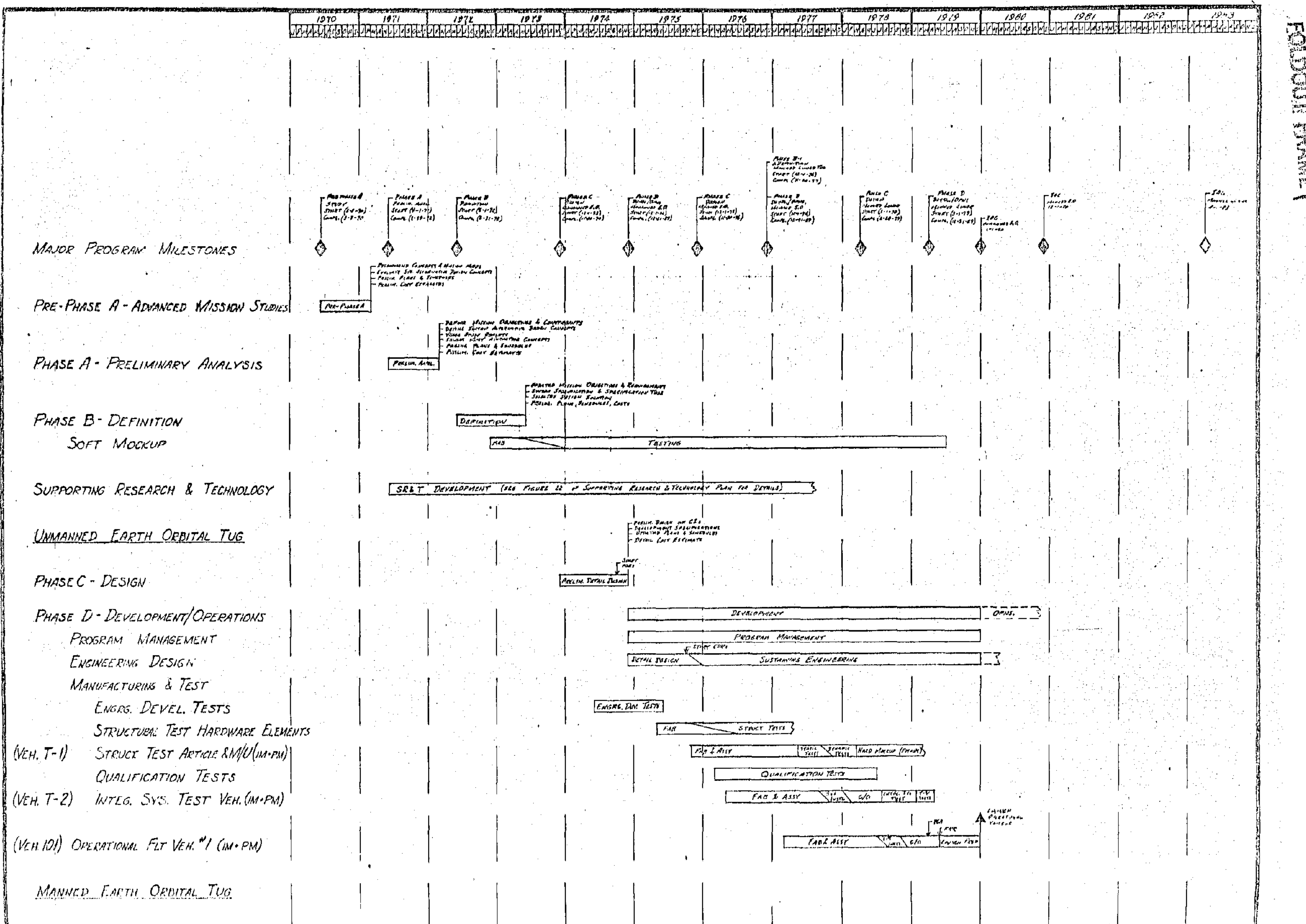
1. The schedule will define the orderly, economical evaluation of events that lead to the realization of the operational system and mission objectives.

2. A four-phased program for developing the reusable space tug will be followed with the first phase (Phase A) to start on 1 June 1971 following a three-month evaluation period of the Prephase A study.

3. A nine-month preliminary analysis is allowed for Phase A.

4. A 12-month Phase B definition period is allowed following a three-month Phase A evaluation analysis. The definition phase will cover all three major development categories and all candidate design concepts to ensure maintenance of the system approach. The output will be a recommended single, basic design concept.

5. A 12-month preliminary detail design (Phase C) period is allowed for the unmanned earth-orbital tug following a 6-month evaluation of the Phase B definition study. Phase C for the manned earth orbital tug and the manned lunar tug will start one year and 3 years and four months, respectively, after completion of


1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
MAJOR PROGRAM MILESTONES
PRE-PHASE A - ADVANCED MISSION STUDIES
PRE-PHASE A
PHASE A - PRELIMINARY ANALYSIS
PRELIM. ANAL.
PHASE B - DEFINITION
DEFINITION
SOFT MOCKUP
FAB
TESTING
SUPPORTING RESEARCH & TECHNOLOGY
SR&T DEVELOPMENT
UNMANNED EARTH ORBITAL TUG
PHASE C - DESIGN
PRELIM. DETAIL DESIGN
PHASE D - DEVELOPMENT/OPERATIONS
DEVELOPMENT
OPNS.
PROGRAM MANAGEMENT
ENGINEERING DESIGN
DETAIL DESIGN
SUSTAINING ENGINEERING
MANUFACTURING & TEST
ENGRG. DEVEL. TESTS
ENGRG. DEV. TESTS
STRUCTURAL TEST HARDWARE ELEMENTS
FAB
STRUCT TESTS
(VEH. T-1) STRUCT TEST ARTICLE &M/U (IM+PM)
FAB & ASSY
HARD MOCKUP (PHASE)
QUALIFICATION TESTS
(VEH. T-2) INTEG. SYS. TEST VEH. (IM+PM)
FAB & ASSY
C/O
(VEH 101) OPERATIONAL FLT VEH. #1 (IM+PM)
FAB & ASSY
C/O
MANNED EARTH ORBITAL TUG
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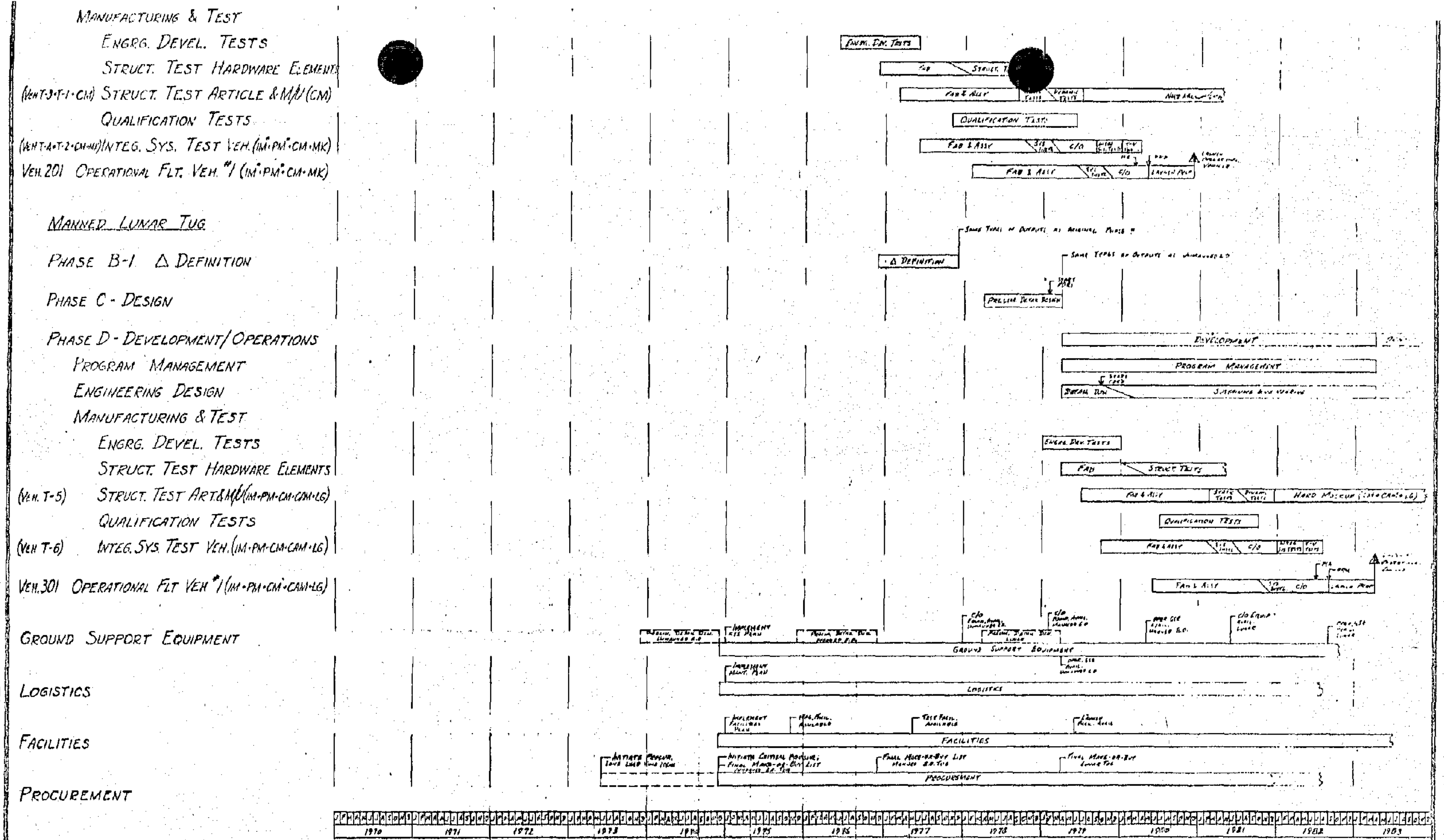

DATE: 1-15-71

LEGEND

IM = INTELLIGENCE MODULE
PM = PROPULSION MODULE
CM = CREW MODULE
CAM = CARGO MODULE
MK = MANIPULATOR KIT
LG = LANDING GEAR KIT

PDR = PRELIMINARY DESIGN REVIEW
CDR = CRITICAL DESIGN REVIEW
PCA = PRODUCT CONFIGURATION AUDIT
C/O = CHECKOUT
M/U = MOCKUP
FRR - FLIGHT READINESS REVIEW

GSE = GROUND SUPPORT EQUIPMENT
OPNS = OPERATIONS
T-V = THERMAL - VACUUM
CI = CONFIGURATION ITEM
E.O. = EARTH ORBIT
FAB & ASSY = FABRICATE & ASSEMBLE

NOTE: MODULES WITH * ARE THOSE USED IN TESTS FOR THE PREVIOUS MISSION CATEGORY DEVELOPMENT PLUS ANY M/U REQUIRED

THE SCHEDULE SHOWN IS APPLICABLE TO ALL THREE CONFIGURATIONS DEVELOPED DURING THE PRE-PHASE A STUDY.

Figure 3. Preliminary Program Development Schedule

FRAME 2

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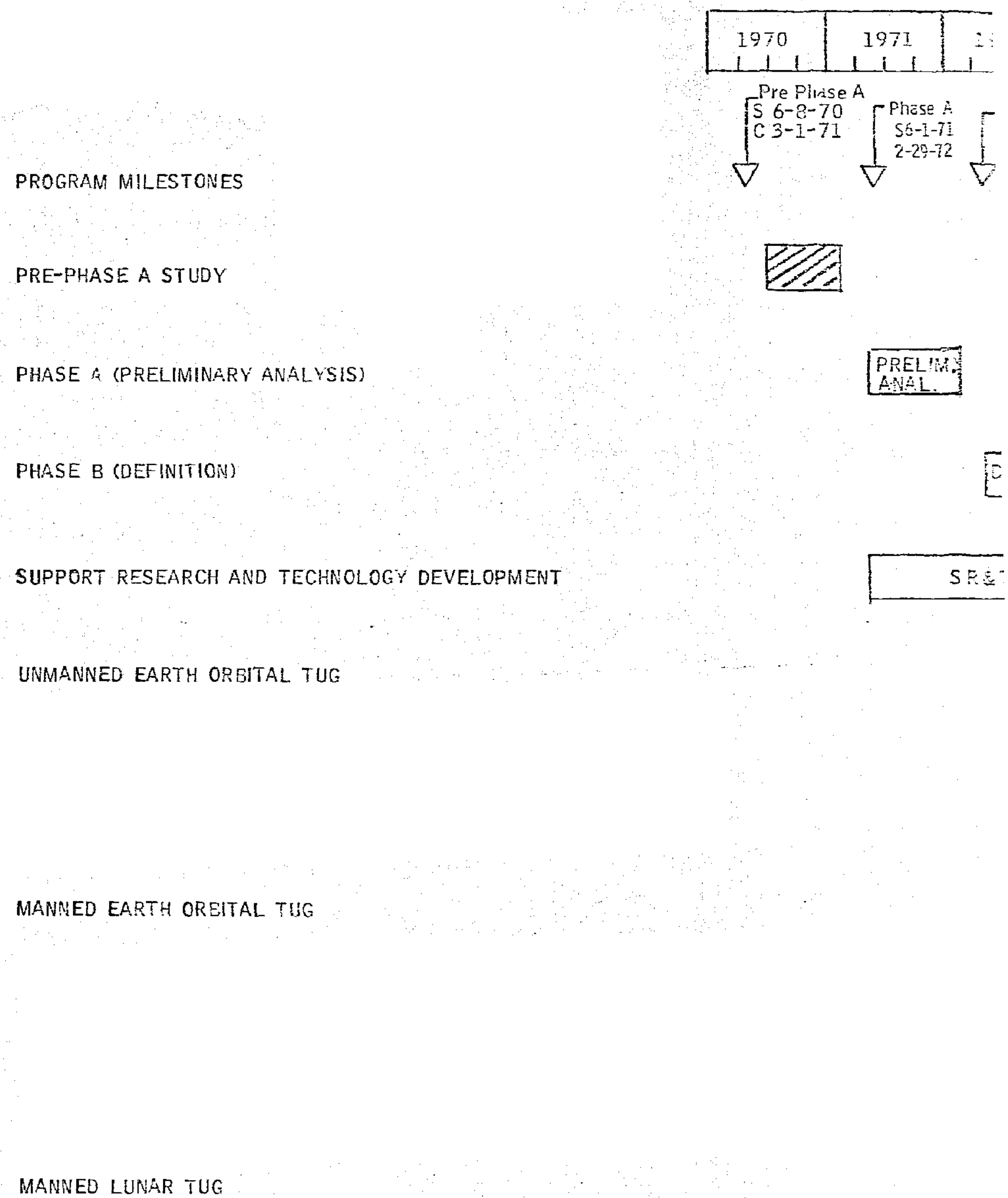
FOLDOUT FRAME 1



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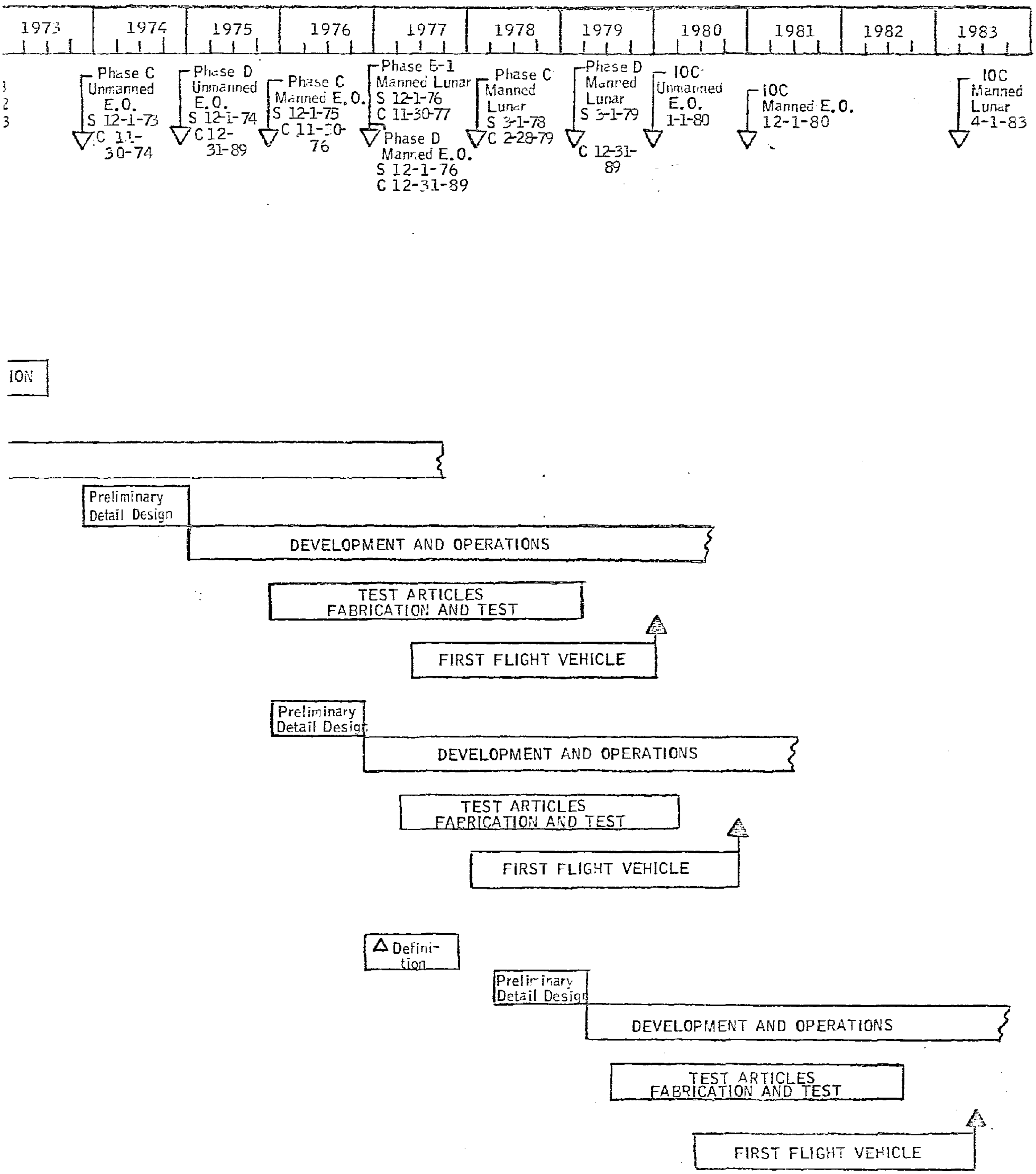

Figure 4. Preliminary Program Development Summary Schedule

Phase C for the earth-orbital tug. The Phase C periods for these tugs are staggered to allow completion of the detail design portion of Phase D (development and operations) of the previous development category and thus maximize the use of experience gained from prior designs.

6. The following initial operational capability (IOC) dates are assumed:

   a. Unmanned earth-orbital tug - 1 January 1980

   b. Manned earth-orbital tug - 1 December 1980

   c. Manned lunar tug - 1 April 1983

7. The initial flight of the vehicle may be an operational flight. All subsystems will be modifications or extensions of the technology used in other NASA programs developed previously (e. g., earth-orbital space shuttle, space station, etc.,); and thermal-vacuum tests may be accomplished by flights in the space shuttle.

8. Insertion into earth orbit will be accomplished by the earth-orbital space shuttle, and transportation to lunar orbit will be by the reusable nuclear shuttle or by the chemical interorbital shuttle.

9. Existing facilities are available or can be obtained in time for all manufacturing, testing, production, deployment, and maintenance operations.

10. A delta-definition Phase B-1 will be conducted for the manned lunar tug to ensure incorporation of the latest state-of-the-art advancements subsequent to design of the earth-orbital tugs.

11. A soft mockup (wood) of the vehicle will be built during the Phase B definition study and will be updated during subsequent phases.

12. The structural test article for each module will be converted into a hard mockup following completion of all static and dynamic tests.

13. The test modules for the unmanned earth-orbital tug will be modified as necessary and reused in the manned earth-orbital tug testing program. New test modules will be required for the manned lunar tug.

2.1.2 Discussion

The preliminary program development schedule shows the major milestones and program activities for the engineering, development and qualification testing, acceptance testing, production, deployment, and maintenance functions; but the schedule does not give precise milestones.

Preliminary design reviews (PDR's) will be held during the Phase C preliminary detail design study for each configuration item (CI) with the first PDR scheduled to start approximately 2 months prior to the end of the phase. The PDR's for more than one CI may be held concurrently. Major outputs during Phase C will include preliminary design of the CI's and their subsystems, CI development specifications, updated program plans and schedules, and detailed cost estimates for Phase D.

Critical design reviews (CDR's) will be held for each CI during Phase D. These reviews will start when the detail drawings and product specifications are complete enough (approximately 80 percent) to determine acceptability of detail design, performance, test, production, and deployment characteristics. The CDR's of more than one CI may be held concurrently. A program development schedule analysis indicates that RST development is entirely feasible from a scheduling viewpoint. An orderly progression of events is shown from the unmanned earth-orbital tug to the manned earth-orbital tug to the manned lunar tug. This program development schedule is based on Concept 1, but there are no significant scheduling differences between any of the three selected design concepts. The manufacturing plan includes a preliminary breakdown of the manufacturing processes and schedules. Preliminary test procedures and schedules are included in the test plan.

The supporting research and technology (SR&T) study required to advance the RST design technology to the 1973-1974 base is shown starting at the same time as does the Phase A study. SR&T development details are given in the supporting research and technology plan. The latter plan includes an integrated and composite schedule showing the interrelationships of required development times (duration) and available dates for critical technologies as dictated by the overall program development schedule.

2.1.3 Summary Schedule

Figure 4 summarizes the major features of the program development schedule associated with development of the flight vehicles.

2.2 OPERATIONAL SCHEDULE

The reusable space tug operational schedule (Figure 5) was derived from the baseline traffic model (Table 1). The schedule is constructed by using a bar for each mission category. Because of the large number of missions in each category, the missions are not scheduled within a calendar year; however, the total missions scheduled for each year are noted in each bar. A range of unmanned earth-orbital missions within the calendar year is occasioned by the possibility of clustering payloads for the geosynchronous OSSA misssions. This clustering could reduce the missions from 160 to as few as 27.

2.3 OPERATIONAL FLIGHT VEHICLES PRODUCTION SCHEDULE

2.3.1 Number of Required Vehicles

The following assumptions were used to determine the number of flight vehicles required to fulfill the operational schedule shown on Figure 5:

1. The number of times the propulsion modules and intelligence modules may be reused is dependent upon the mission delta V requirements.

   Low ($\Delta V < 1600$ fps) - approximately 100 reuses per module

   Moderate ($\Delta V \approx 3500$ fps) - approximately 50 reuses per module

   High ($\Delta V > 7000$ fps) - variable, up to 18 reuses, dependent on length of useful life.

2. All modules will be limited to a 3-year useful life.

3. It is assumed that missions may be combined for geosynchronous orbit. An average between the minimum of 27 and the maximum of 160 ($\approx$ 93 flights) was used.

4. Two manned earth-orbital tugs will be docked to the space station at all times for emergency rescue.

5. Two lunar tugs will be expended in building the lunar base.

6. Five unmanned earth-orbital tugs are expended on far planetary missions. Tugs selected for these missions will be those that have expended most of their useful life in other mission applications.

Table 1. Summary of Baseline Traffic Model

Mission Category	Year 1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	Total
OSSA:											
Geosynchronous	20	16	19	12	15	15	15	15	21	12	160
Planetary	0	3	1	2	3	2	4	0	4	4	23
Spacecraft maintenance(3)	1	3	4	9	9	10	10	10	10	10	76
Other	6	5	5	3	6	5	7	4	6	4	51
Space station (complement)	(12)(1)	(12)	(12)	(25)(2)	(37)(2)	(50)(2)	(75)(2)	(100)	(100)	(100)	
Basic support	3	6	6	11	14	18	26	33	33	33	183
Detailed satellite maintenance	14	47	60	60	60	60	60	60	60	60	541
Lunar landings				1	4	4	7	6	6	6	34
Lunar support to propellant transfer system station				56	83	107	126	124	118	118	732
Manned Mars									26	26	52
Total	44	80	95	154	194	221	225	252	284	273	1852

(1) For 6 months
(2) Average during buildup
(3) Performed from Space Station

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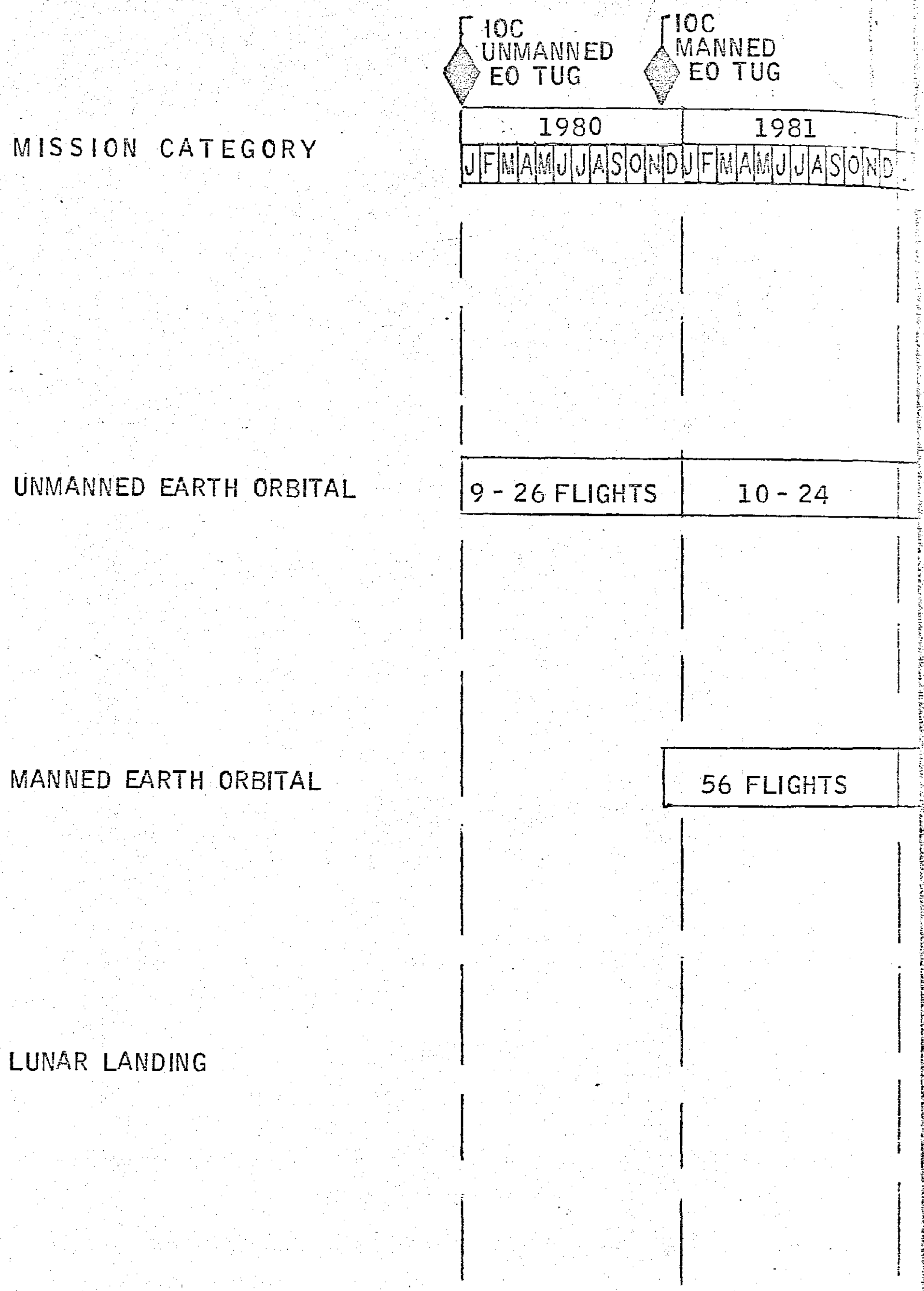

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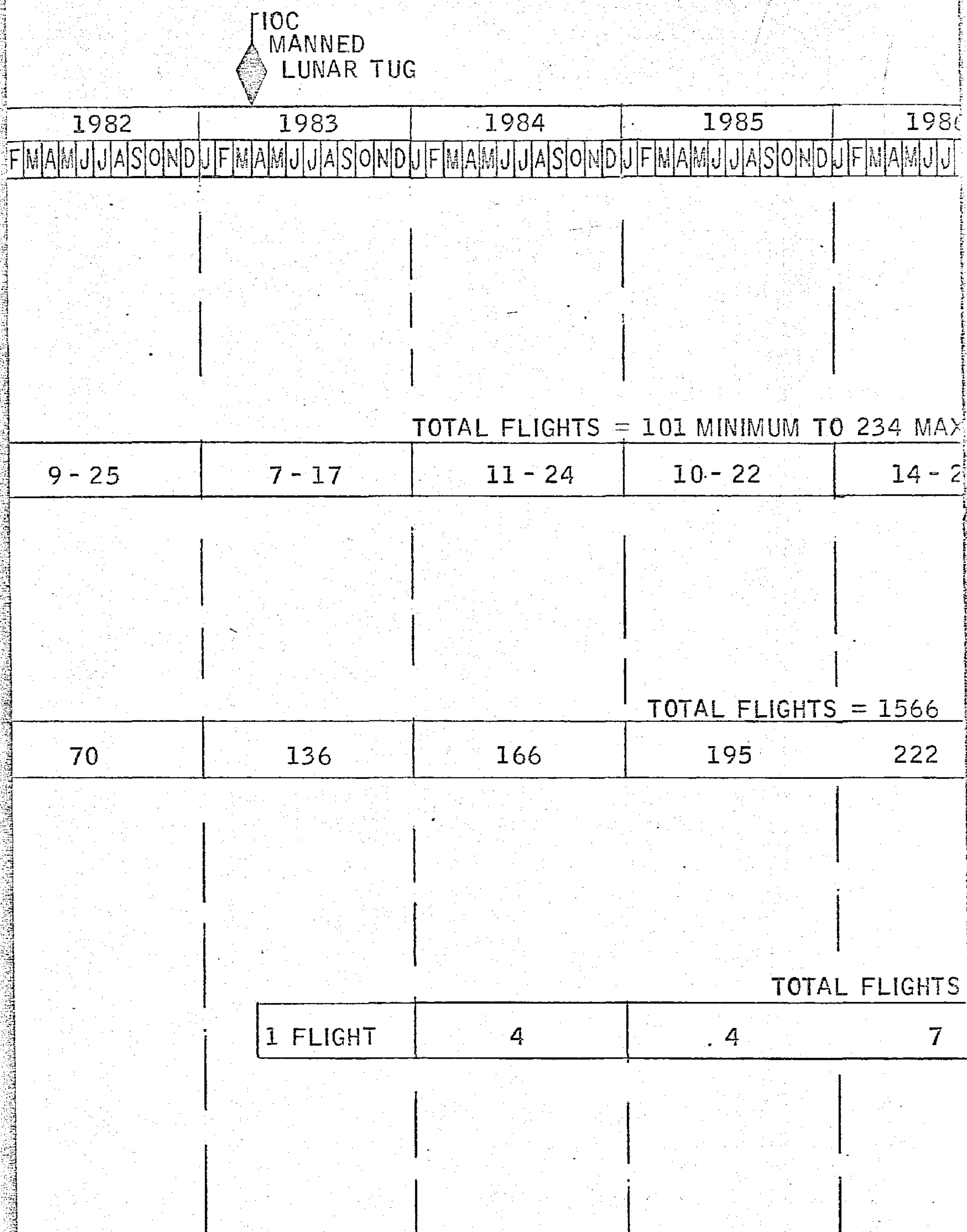

Figu

FOLDOUT FRAME 3

6	1987	1988	1989
A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D

IMUM

6	7 - 19	14 - 31	10 - 20

	227	247	247

= 34

6	6	6

re 5. Reusable Space Tug Operational Schedule

7. Lunar tugs will be used only for lunar landing missions. Earth-orbital tugs may be used for any earth-orbital mission (i.e., tugs are not restricted to a single-type mission).

8. A method will be available to determine the amount of life remaining in a vehicle after each mission.

9. Module and tank set requirements for the three selected design concepts are defined as follows:

Concept 1 - Single propulsion module on all missions

Single intelligence module on all missions

Single crew module on all manned missions

Concept 5 - Single propulsion module on all low earth-orbital missions

Reusable tank set added for lunar landing missions

Two propulsion modules on each unmanned planetary and geosynchronous mission

Two intelligence modules for each planetary and Geosynchronous mission

Single intelligence modules for lunar landing and low earth-orbiting missions

Single crew module on all manned missions

Concept 11 - Single small propulsion module on all missions

Large expendable tank set on geosynchronous and planetary missions

Large reusable tank set for lunar landing missions

Single intelligence module on all missions

Single crew module on all manned missions

Based upon the previously listed assumptions, the baseline traffic model (Table 1) was analyzed. Table 2 is used to determine the number of vehicles required for each concept. The latter numbers are combined under the three development categories in Table 3.

2.3.2 Production Rates

The time spans and production rates to produce the required number of modules and tank sets for each configuration concept are based on the following assumptions:

1. The longest single step in the production process (final assembly or systems installation) for the complete vehicle will determine the rate at which modules and tank sets will come off the "production line."

2. Production of all modules and tank sets is to be completed prior to 31 December 1989.

3. All modules and tank sets will be produced in a continuous run and placed into storage as required.

4. A 90-percent learning curve is applicable.

5. One-, two-, and three-shift operations will be used as required to complete vehicles within the required time spans.

6. First and second shifts are considered equally productive. The third shift is assumed to increase productivity by 35 percent over a two-shift operation.

7. Multiple "production lines" will be used if required.

8. The production of the tank sets for Concept 5 will be included with the production of the propulsion modules, because installation of the engines is not the pacing item.

The numbers of modules and tank sets for which production is to start each year are shown in Figure 6.

Table 2. Vehicle Requirements by Mission Category

Mission Category	Number of Flights	Average Number of Reuses	Configuration Concept 1	Configuration Concept 5	Configuration Concept 11
Unmanned flights					
Geosynchronous orbit	93	18	5 PM's 5 IM's	10 PM's 10 IM's	93 tank sets 5 PM's
Planetary + miscellaneous	74	18(1)	4 PM's 4 IM's	8 PM's 8 IM's	74 tank sets 4 PM's
Lunar landing	14	7(2)	2 PM's 2 IM's	2 PM's 2 tank sets 2 IM's	2 tank sets 2 PM's 2 IM's
Manned Flights					
Space station basic support (+2 for rescue)	180	60	5 PM's 5 IM's 5 CM's	5 PM's 5 IM's 5 CM's	0 tank sets 5 PM's 5 IM's 5 CM's
Satellite maintenance	602	100	6 PM's 6 IM's 3 CM's	6 PM's 6 IM's 3 CM's	0 tank sets 6 PM's 6 IM's
Lunar landing (+ 2 expended for lunar base)	20	10(2)	4 PM's 4 IM's 4 CM's	4 tank sets 4 PM's 4 IM's 4 CM's	4 tank sets 4 PM's 4 IM's 4 CM's
Lunar support + manned Mars	784	98	8 PM's 8 IM's 3 CM's	8 PM's 8 IM's 3 CM's	0 tank sets 8 PM's 8 IM's 3 CM's

PM - propulsion module; IM - intelligence module; CM - crew module

(1) For Concept 1 and 11, eight vehicles are expended completely for far planetary and solar system escape missions. For Concept 5, eight PM's and eight IM's are expended, and eight PM's and eight IM's are recovered for far planetary and escape missions.

(2) Number of vehicles required determined by module life limitation

Table 3. Vehicle Requirements by Development Category

Development Category	Configuration Concepts 1	5	11
Unmanned earth-orbital tug	9 PM's 9 IM's	18 PM's 18 IM's	167 tank sets 9 PM's 9 IM's
Manned earth-orbital tug	19 PM's 19 IM's 12 CM's	20 PM's 20 IM's 12 CM's	0 tank sets 19 PM's 19 IM's 12 CM's
Manned lunar tug	6 PM's 6 IM's 4 CM's	6 PM's 6 tank sets 6 IM's 4 CM's	6 tank sets 6 PM's 6 IM's 4 CM's
Total	34 PM's 34 IM's 16 CM's	44 PM's 6 tank sets 14 IM's 16 CM's	173 tank sets 34 PM's 34 IM's 16 CM's
PM - propulsion module IM - intelligence module CM - crew module			

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
DESIGN CONCEPT 1													
PROPULSION MODULE TOTAL		3	4	5	2	3	3	3	3	3	3	2	
UNMANNED EO		3	2	2		1		1					
MANNED EO			2	3	1	1	2	1	2	2	3	2	
MANNED LUNAR					1	1	1	1	1	1			
INTELLIGENCE MODULE TOTAL		3	4	5	2	3	3	3	3	3	3	2	
UNMANNED EO		3	2	2	1			1			1		
MANNED EO			2	3		2	2	1	2	2	2	2	
MANNED LUNAR					1	1	1	1	1	1			
CREW MODULE TOTAL			1	2	3	3	3	3	1				
MANNED EO			1	2	2	2	2	2	1				
MANNED LUNAR					1	1	1	1					
DESIGN CONCEPT 5													
PROPULSION MODULE TOTAL		4	5	5	5	4	3	3	4	4	5	2	
UNMANNED EO		4	3	3	2	1	1	1	1	1	1		
MANNED EO			2	2	2	2	1	1	2	2	4	2	
MANNED LUNAR					1	1	1	1	1	1			
TANK SET TOTAL					1	1	1	1	1	1			
MANNED LUNAR					1	1	1	1	1	1			
INTELLIGENCE MODULE TOTAL		3	4	5	5	6	6	3	3	3	3	3	
UNMANNED EO		3	2	2	2	2	2	1	1	1	1	1	
MANNED EO			2	3	2	3	3	1	1	1	2	2	
MANNED LUNAR					1	1	1	1	1	1			
CREW MODULE TOTAL			1	2	3	3	3	3	1				
MANNED EO			1	2	2	2	2	2	1				
MANNED LUNAR					1	1	1	1					
DESIGN CONCEPT 11													
PROPULSION MODULE TOTAL		2	3	3	3	4	4	3	4	4	4		
UNMANNED EO		2	2	1		1	1		1		1		
MANNED EO			1	2	2	2	2	2	2	3	3		
MANNED LUNAR					1	1	1	1	1	1			
TANK SET TOTAL		10	12	14	16	16	16	16	18	18	18	19	
UNMANNED EO		10	12	14	15	15	15	15	17	17	18	19	
MANNED LUNAR					1	1	1	1	1	1			
INTELLIGENCE MODULE TOTAL		3	4	5	2	3	3	3	3	3	3	2	
UNMANNED EO		3	2	2		1		1					
MANNED EO			2	3	1	1	2	1	2	2	3	2	
MANNED LUNAR					1	1	1	1	1	1			
CREW MODULE TOTAL			1	2	3	3	3	3	1				
MANNED EO			1	2	2	2	2	2	1				
MANNED LUNAR					1	1	1	1					

NUMBERS IN BLOCKS DEPICT MODULES STARTED DURING THE YEAR

Figure 6. Preliminary Operational Flight Vehicles Production Schedule

3.0 PRELIMINARY PLANS

The purpose of the RST project preliminary plans is to set and communicate a course of action for achieving mission and operational requirements (1) at the lowest practical overall development, production, and refurbishment costs, (2) on time with respect to the operational target dates, (3) in accordance with the NASA's quality standards, and (4) with the utmost safety. The plans also provide a basis for realistic schedules and program cost estimates and ensure functional integration of the various RST project parts and activities.

The scope of the RST project planning activity is extremely broad and encompasses: (1) ground and flight operations; (2) all technical and management functions, including system engineering and design, manufacturing, test, facilities, ground support equipment, logistics support, refurbishment, cost and schedule control, configuration management, etc.; and (3) supporting research and technology requirements. In accordance with contractual requirements, NR Space Division has prepared five preliminary plans that NASA considers most useful at this time and commensurate with the objectives of the Prephase A study contract. These plans include those for design, manufacturing, testing, ground operations, and supporting research and technology. Although these plans are preliminary in nature, they are defined in sufficient detail to demonstrate and verify the RST project approach, formulate the basis for schedule and cost estimating, and guide NASA in technology planning. During subsequent phases of this project, these plans will be updated and expanded, and additional plans will be prepared as required.

The plans cover RST project Phases A, B, C, and D; and NR has thoroughly integrated their (the plans) preparation with the other contractual activities. The plans basically reflect current contract requirements and the overall RST project. The requirements were evolved from technical analyses conducted during the study. The plans reflect the three selected design concepts (1, 5, and 11) and the three major development categories (unmanned earth-orbital tug, manned earth-orbital tug, and manned lunar tug) and include any major variations necessitated by differences in the selected design concepts and development categories. The plans are consistent with the work breakdown structure, which exerted an integrating influence on plan preparation. The plans reflect the requirements for mock-ups and test articles and highlight significant problem areas and issues.

The individual plan schedules and milestones were evolved in consonance with the evolution of the overall program development schedule. NR integrated the preparation of each preliminary plan with the other plans. These preliminary plans conform with applicable NASA management and technical criteria and NR management systems and guidelines. The plans also reflect NR's broad, past experience in planning and implementing major programs. The balance of this section covers the individual plans.

3.1 DESIGN PLAN

3.1.1 Purpose

The purpose of the design plan is to identify the requirements for planning, organizing, directing, and controlling the engineering process for developing the reusable space tug. The design plan presents task descriptions applicable to all phases of the program, and it will evolve during Phase C into the engineering management plan.

3.1.2 Scope

The design plan spans all engineering activities, including (1) the plan definition for the technical program and design efforts; (2) definition of system performance and configuration requirements; (3) documentation of configuration design and acceptance tests; (4) integration of changes, problem definition and studies, and interface control; and (5) verification and evaluation during all program phases.

3.1.3 Engineering Requirements

System Design Approach

The mission operations Prephase A study resulted in the selection of three major mission categories (unmanned earth orbit, manned earth orbit, and manned lunar landing) as representative of the range of capabilities required by a reusable space tug. Three configuration concepts were selected for further study.

High priority will be given to an investigation of commonality of requirements with other NASA and USAF programs for all system elements (equipment, personnel, facilities, software, and procedural data) to reduce to a minimum the design and development time of all components and subsystems. Whenever possible, equipment developed on other programs will be utilized on the tug.

Task Summary

Figure 7 shows the basic engineering process to be followed during the four phases of the program. The chart illustrates the iterative nature of both the requirements analysis and the design engineering activities within program phases and between phases. More detail requirements and solutions are provided with proper regard to (1) types of system functions and their "pecking order" (e.g., definition of test functions depends upon detail information regarding equipment to be tested), and (2) level of definition within each system function (subsystem, black box, or component) as well as the completeness of coverage of each system function. Design requirements definition progresses in an orderly manner through all study phases from the overall approach to a comparative, to an integrated, and finally to a verified approach (tests and design reviews).

The iterative nature of the engineering process is further illustrated by the schematic in Figure 8, which shows the progression from planning the efforts through the development of the various functional requirements to the detail design of elements and to fabrication and development test. At any point in the process, recycling may become necessary.

Figure 9 shows the technical functions required to fulfill the engineering commitments in the program. The activities have been organized into the basic modules: requirements definition, planning, design and integration, and verification. The detailed task descriptions are discussed in the following paragraphs.

Requirements Definition

Mission Operations Requirements. Portray graphically and sequentially (functional flow block diagrams) all detailed mission functions that must be satisfied by system elements; define and investigate alternative functions that offer significant benefit; develop design requirements (system and development specifications) for mission operations end items; develop requirements for mission operations personnel and training programs; select flight hardware approaches; and identify high-risk and long lead-time items.

Test Requirements. Portray graphically the test functions required to verify the mission operations solutions; define and investigate an alternative means and location for performing the test functions; develop design requirements for test end-items; prepare system test plans; develop personnel and training requirements for test operations; develop requirements for test facilities; select test hardware and facilities approaches; and identify high-risk areas and long lead-time items.

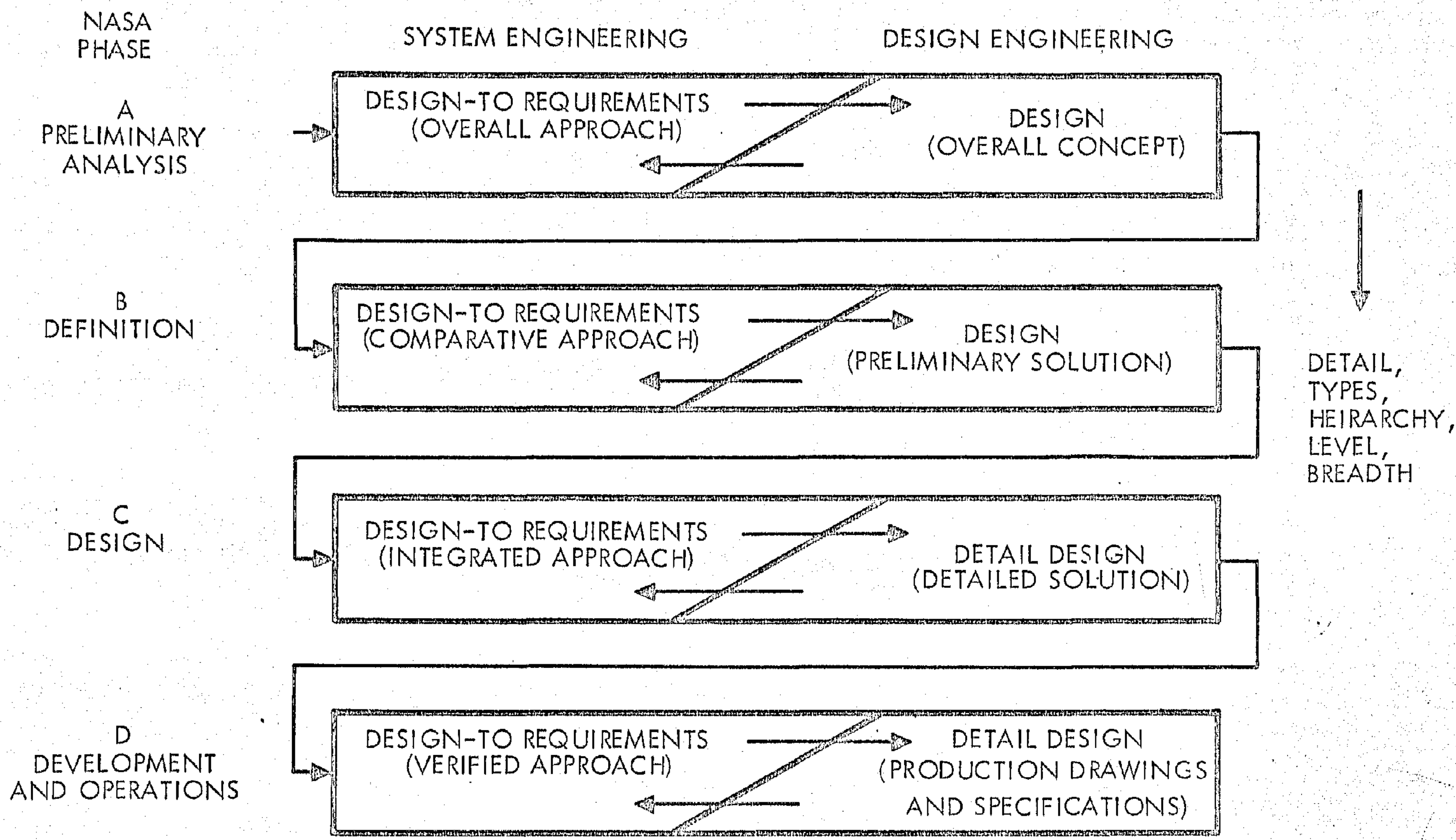

Figure 7. Basic Engineering Process

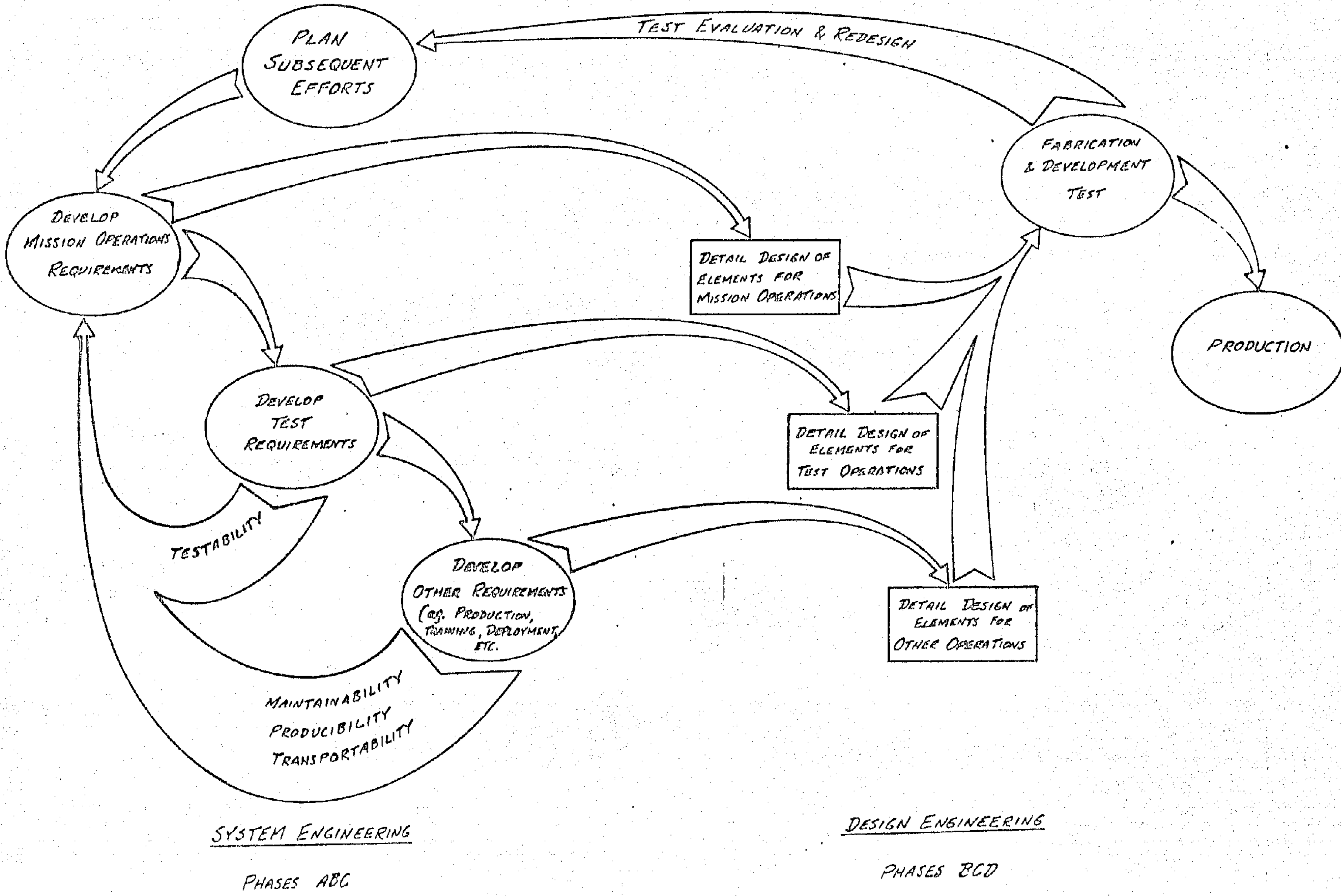

Figure 8. Engineering Process Schematic

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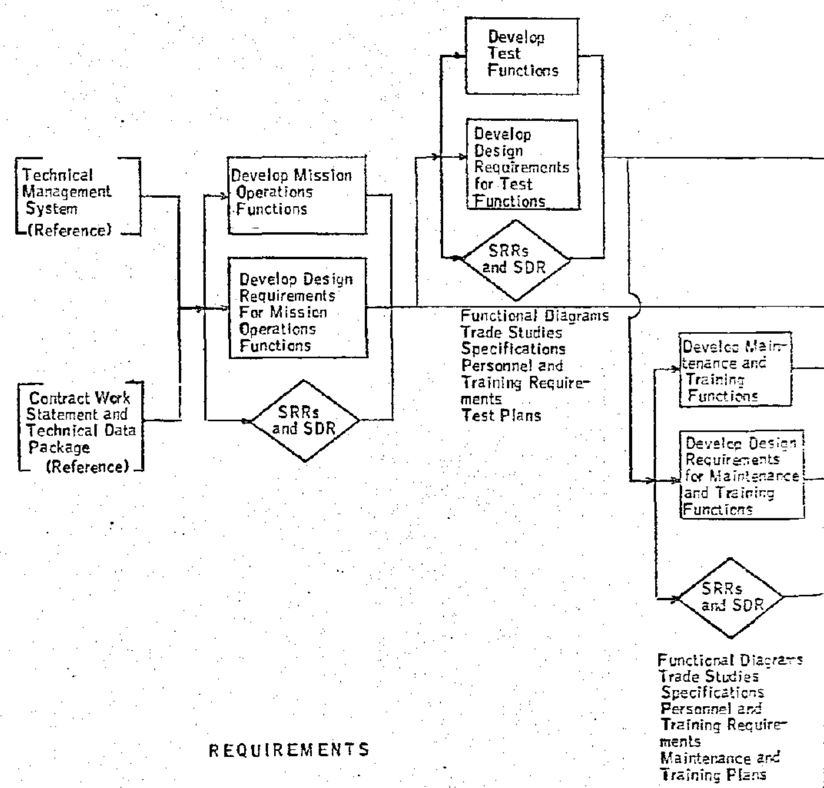

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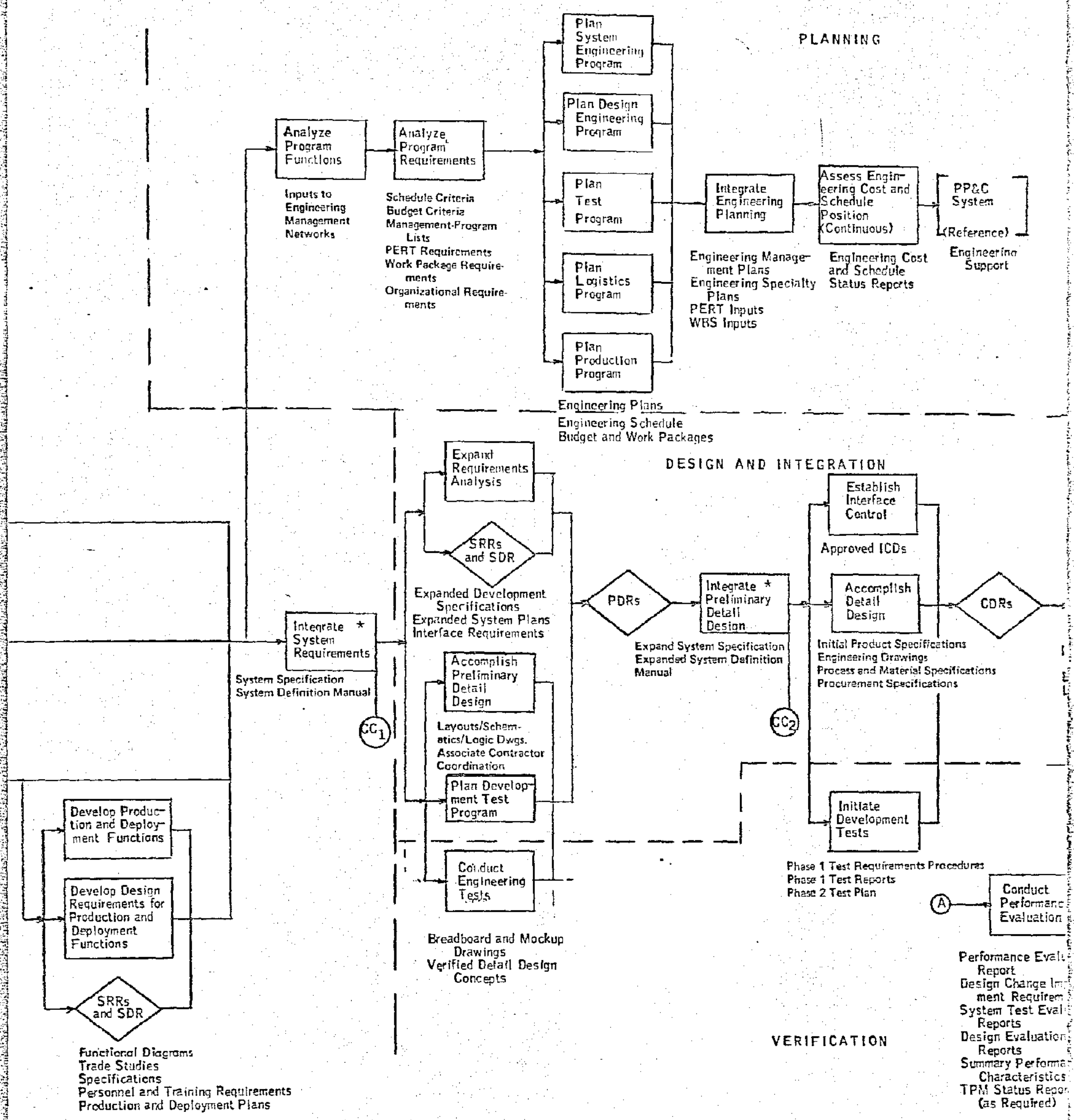

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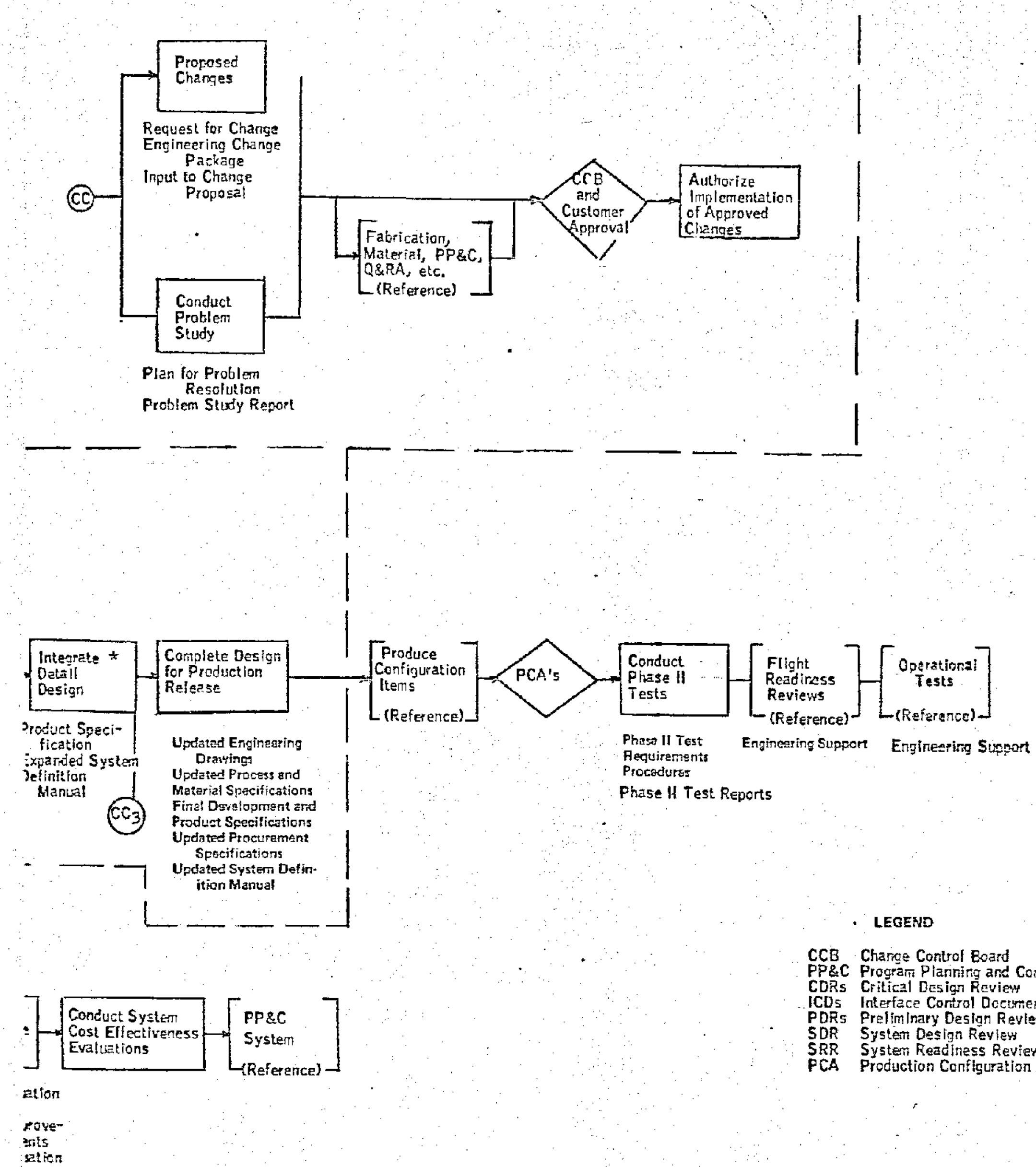

LEGEND

CCB	Change Control Board
PP&C	Program Planning and Control
CDRs	Critical Design Review
ICDs	Interface Control Document
PDRs	Preliminary Design Review
SDR	System Design Review
SRR	System Readiness Review
PCA	Production Configuration Audit

NOTES:

1. The symbol (A) presents the functional flow diagram for the performance evaluation measurement verification function.
2. The symbol (CC) indicates initiation of formal change control for:
   - (CC1) System Specification
   - (CC2) Development Specifications
   - (CC3) Product Specifications and Drawings
3. The review functions (SRR, SDR, PDR, CDR, and PCA) are a part of verification.

*4. Because iterations of the System Engineering Process will follow the same logic as does the initial sequence of activities, the iterations will not be shown. Successive iterations will be made throughout all phases of the program.

ure 9. Engineering Process Functional Flow Block Diagram

Maintenance and Training Requirements. Prepare functional diagrams of all maintenance and training functions required to support the mission operations; select and investigate alternate locations (space and ground) and procedures for performing maintenance and training functions; develop design requirements for maintenance and training end items; develop facility requirements associated with maintenance and training functions; select maintenance and training hardware and facilities approaches; prepare maintenance and training plans; and identify high-risk and long lead-time areas.

Production and Deployment Requirements. Prepare functional diagrams defining all production (manufacturing, assemblying, etc.) and deployment (transportation, installation, checkout, etc.,) functions; perform trade studies to determine preferred methods (module versus complete stack) of assembly, installation, checkout, and transportation; develop requirements for production and deployment end items and facilities; develop requirements for production and deployment personnel; select production and deployment hardware and facility approaches, and identify high-risk and long lead-time areas.

System Requirements. Prepare the initial system specification that states the technical and mission requirements for the system, allocates requirements to functional areas, and defines the interface between and among functional areas; and establish the System Definition Handbook as a repository of the system requirements documentation (e.g., functional diagrams, requirements allocations, interface control documents, schematic block diagrams, design sheets, and system plans) required to establish system requirements.

Planning

Engineering Program. Identify the tasks and align them to program milestones and production schedules; provide the detail planning that contributes to further definition of the master schedule; and provide the engineering management networks.

Engineering Planning. Establish compatibility and consistency between schedules, budget breakdowns, and work packages; and provide adequate and clearly defined interfaces with the other program planning functions.

Engineering Specialty Plans. Describe in the engineering management plan (to be developed in Phase C) the integration of program efforts for the engineering specialty areas with the detailed specialty programs included as subplans. The specialty areas and their governing documents are:

Reliability - NPC 250-1

Maintainability - MIL-STD-470, 471, MIL-HDBK-472

Personnel subsystem and human factors

System safety - Safety Program Directive No. 1A and No. 2, MSC M-8080

Standardization

Electromagnetic compatibility

System mass properties

Producibility

Transportability

Engineering Cost and Schedule Positions. Determine current progress with respect to cost and schedule estimates, and provide reports that can be used as a basis for effective corrective action, if required.

Design and Integration

Expand Requirements Analysis. Develop lower levels of system requirements, and update development specifications and the system plans; identify detailed interface requirements based upon coordination with those responsible for design of the interfacing items.

Preliminary Detail Design. Prepare and update the layouts, schematics, and logic drawings expressing the design solution; prepare interface control drawings.

Development Test Program. Integrate the system test program by examining all test and checkout requirements and identifying the test program plans to be prepared.

Integrate Preliminary Detail Design. Expand and update the specifications and the System Definition Handbook. As requirements documentation is incorporated into the system and development specifications, remove the documentation from the System Definition Handbook and replace with a reference to the specifications.

Establish Interface Control. Prepare, negotiate, and release interface control documents.

Accomplish Detail Design. Prepare the engineering drawings and the product specifications for the design solutions satisfying the design-to requirements; prepare material and process specifications for make items; and prepare specifications for the procurement of buy items.

Production Release. Provide production drawings, material and process specifications, final development and product specifications, and updated lower tier specifications; and update the System Definition Handbook.

Verification

Engineering Tests. Conduct engineering breadboard and mockup operations for the purpose of: (1) verification of detail design configurations, interface design including equipment installation locations, and clearances; and (2) aiding the manufacture of cable harnesses.

Development Test Program. Verify the designs under both static and dynamic conditions: assure that qualification requirements are satisfied; assure achievement of reliability goals; determine suitability of design configurations with respect to physical, functional, procedure, and environment interfaces; and verify selected technical characteristics.

System Test Program. Review system verification test plans and procedures. Provide engineering assistance during complete-system operational testing, and assure efficient feedback of test results for technical evaluation.

Performance Evaluations. Analyze and report the performance of the system and its elements; determine design improvement requirements; evaluate the results of system tests; evaluate and report the adequacy of the design solutions; and plan and execute a technical performance measurement effort, if required.

Effectiveness Evaluation. Evaluations shall be conducted to provide the optimum combination of system elements to meet the objectives and support requirements in terms of system and cost effectiveness.

System Requirements Review. A technical review shall be conducted of the system functional requirements as documented in the System Definition Handbook or system specification which specify the performance characteristics, definition, and operability of the system, system design and construction standards; requirements for system, and development testing.

System Design Review. A technical review shall be conducted of the system design approach proposed as the design solution to the system design requirements in the system and development specifications.

Preliminary Design Review. A review of the preliminary design of each item shall be conducted to establish system compatibility and adequacy of design, identify specific engineering documentation, and confirm interface requirements between each item and other items or facilities.

Critical Design Review. A detail design technical review of each item shall be accomplished to determine the acceptability of detail design, characteristics depicted by the design solution specified in the product specification, accompanying drawings, and other engineering documents prior to complete commitment of the design to production.

Critical System Design Issues

The Prephase A study mainly investigated the mission operations functions and vehicle configurations required to perform the missions. Investigation into other system functions and elements was left largely for later program phases. However, a preliminary analysis was made of the development, qualification and acceptance test functions, the maintenance function, and the production functions to gain insight into the critical issues associated with these functions. The resulting issues are presented in the plans for testing, ground operations, and manufacture. The reusable space tug was determined to require a propulsion module, an intelligence module, a crew module, a tank set, a lunar landing gear kit, a cargo module, and a manipulator kit. The issues and considerations affecting the development of the space vehicle are presented in the following paragraphs.

General Issues

Influence of lunar missions on design of the modules designed for earth orbit.

The rendezvous and docking techniques required

The lifetime requirements of the various modules

The effect of maintenance philosophy on design of the system

Ground communications capability required

Commonality of mission requirements between NASA and DOD operations

Commonality of subsystem design requirements between the space tug, the space shuttle, and other NASA programs.

Propulsion Module (PM)

Structural Design for minimum weight, meteoroid protection, thermal problems, and concentrated loads for the engine, docking maneuvers, and the lunar landing gear

Engine selection for type, number, arrangement and location, plume effects, redundancy requirements, and thrust-to-weight optimization

Intelligence module (IM) integration into propulsion module (PM) GO_2 and GH_2 propellant storage (in IM or PM), location top or bottom, and dispersion

Attitude control propulsion system (ACPS) conditioning unit for duty cycle, capacity, and redundancy

Crew Module (CM)

Structural design for load paths in a top or bottom location, landing gear fittings, docking, and pressurization

Best interior arrangement

Visibility for docking and landing

Crew transfer docking provisions

Intelligence Module (IM)

IM depth required

Docking integration

GO_2/GH_2 storage tank size versus ACPS conditioning unit cycle

RCS jet configuration for location and stowage

Antenna location for stowage

Access for servicing

Structural design for best structural load paths

Integral versus submodule packaging

Kits

Radiator kit for lunar operations

Landing gear for integral or separate assembly

Manipulator kit for manned or unmanned operations

Lunar antenna if high data rates are to be transmitted to earth

3.1.4 Engineering Program Management

Design Reviews

Phases A and B. During study Phases A and B, combined program and design reviews should be held on a regular and frequent schedule to ensure the adequacy of the efforts to identify (from the concepts examined in the Prephase A study) those RST approaches worthy of further refinement to arrive at a single project approach. These reviews will not involve contractual changes and will be classified as technical interchanges, which normally consist of followup actions generated by scheduled reviews. Changes in requirements resulting from these in-process (work not interrupted) reviews should be formalized by technical directives.

Phase C. During the Phase C study, system requirements reviews (SRR's) should be held whenever a significant part of the system functional requirements has been established and documented. After the alternative design approaches that include the corresponding test requirements have been considered and the system elements have been defined and selected, a system design review (SDR) should be instituted to ensure that a technical understanding has been reached on the allocation of requirements to (1) the system segments identified in the system specification, and (2) the configuration items (CI's) identified in the development specifications. The SDR is followed by a preliminary detail design period, and the phase is terminated by a preliminary detail designs review (PDR) of each CI. The PDR evaluates the progress, consistency, and technical adequacy of the selected design and test approach and establishes compatibility with program requirements and the preliminary design. Action items from the PDR will be contractually binding on all participants following action by the Contracting Officer.

Phase D. Following completion of detail design for each CI, a critical design review (CDR) will determine the acceptability of detail design, performance, test, and production characteristics depicted by the design solution specified in the product specification, accompanying drawings, and other engineering documentation. CDR action items will be contractually binding on all participants following action by the Contracting Officer.

Change Control

Until approval of the system specification at the end of Phase B, Change Control should be informal with all changes documented in the System Definition Handbook. Following system specification approval, a change control system is required for formal approval by the Contracting Officer of all changes to the requirements in the system specification. This change control system shall be expanded to include the development specifications following establishment of the design requirements baseline at the start of Phase D and the product specifications following definition of the product configuration baseline in Phase D.

Organization and Schedule

The engineering organization and schedules required to perform the activities described in this plan will be developed during Phase A and incorporated in the plan at that time.

3.2 MANUFACTURING PLAN

3.2.1 Purpose

The manufacturing plan summarizes the orderly progression of manufacturing activities for conducting Phase A (preliminary analysis), Phase B (definition), Phase C (design), and Phase D (development and operations) for the RST. The objective of the plan is to identify and define the manufacturing requirements.

3.2.2 Scope

The manufacturing plan presents the preliminary manufacturing approach for the fabrication, qualification, checkout, acceptance, and refurbishment of RST flight spacecraft, test and qualification articles, and support equipment. It covers the manufacturing activities through all program phases to meet the specific RST program requirements. The plan covers the three selected design concepts and the three major development categories. The plan will be expanded to levels of greater detail during Phases A, B, and C and finalized in Phase D.

3.2.3 Task Descriptions

Requirements

The major hardware items covered in the manufacturing plan includes mockups and test articles as called for in the testing plan and one operational flight vehicle for each of the three major development categories. Based on these requirements, manufacturing tasks have been developed to establish the manner in which manufacturing resources and experience will be applied to satisfy program objectives.

Rationale for Selecting Tasks and Defining Scope

The rationale for identifying specific manufacturing activities for the RST is based on past NR experience.

Task Summary

The overall activities required to fulfill the manufacturing commitments in the RST program development are summarized below:

Mockup fabrication

Spacecraft fabrication

Test article fabrication

Support equipment fabrication

Manufacturing engineering

Production control

Refurbishment

Detailed descriptions of these tasks and related activities are described in the following paragraphs.

Mockups

Soft Mockups. During Phase B, a soft mockup (wood) will be fabricated to facilitate design, resolve anticipated problem areas (e.g., RCS installation), verify form and fit requirements, and verify accessibility of equipment and components for installation, inspection, maintenance, and ground system interface. The crew compartment will be used to evaluate habitability criteria, man-machine relationship, evaluate docking aids, and provide initial crew training. This mockup will be updated during subsequent phases of the program.

Hard Mockups. During Phase D, the modules used in the structural tests will be available for subsequent use as assembled hard mockups to provide fit and functional checkout station for spares, modification kits, and payload interface assessment.

Spacecraft Fabrication

The RST will be built in module and kit forms, which will consist of a propulsion module, crew module, intelligence module, cargo module, tank set, landing gear kit, and manipulator kit.

All primary structures of the modules will be fabricated from integrally stiffened skin panels with mechanically attached ring frames and longerons where required. It is anticipated that high performance insulation will be required. Environmentally controlled shops will be utilized where required during fabrication to assure the product integrity. The shops will be used during mating of structural assemblies, bonding, welding, insulation and systems and equipment installation. Manufacturing test and checkout will be conducted progressively through use of production test procedures (PTP). These procedures are necessary to verify that electrical, mechanical, and electromechanical subsystems and assemblies conform to engineering drawings and specifications. An analysis of system and equipment specifications will be initiated during Phases A and B and analyzed in depth during Phases C and D. These analyses will indicate the manufacturing complexity and determine subsystems assembly, test, and checkout requirements. Contractor manufacturing time spans and supplier or subcontractor subsystems delivery schedules will be established accordingly.

Test Article Fabrication

Test articles to satisfy the planned structural tests, qualification tests, and integrated systems tests will be fabricated during Phases C and D of each mission category.

The static structural test elements are as follows:

Unmanned earth-orbital tug

Thrust structure
Cargo bay support structure
Hatches and seals
Cryo tank and support structures
Insulation bond

Manned earth-orbital tug

Cargo bay supports structure
Hatches and seals
Crew compartment

Manned lunar tug

Cargo bay support structure
Hatches and seals
Landing gear kit
Cargo module

The dynamic structural test articles are as follows:

Unmanned earth-orbital tug

Propulsion module structure
Intelligence module structure
Simulated subsystems

Manned earth-orbital tug

Cargo module structure
Simulated subsystems

Note: The propulsion module and intelligence module structures from the unmanned earth-orbital tug are to be used for the manned earth-orbital tug.

Manned lunar tug

Propulsion module structure
Intelligence module structure
Cargo module structure
Simulated subsystems
All new structures

Qualification test hardware. The percentage of subsystems hardware required for a qualification test will be defined by Engineering during Phases C and D.

Integrated test vehicle requirements. An integrated test vehicle will be provided to satisfy space simulation tests for each development category. This effort will be accomplished during Phase D of the program.

Unmanned earth-orbital tug

Propulsion module
Intelligence module

Manned earth-orbital tug

Crew module
Intelligence module } To be used from unmanned
Propulsion module } earth-orbital tug
Manipulator kit

Manned lunar tug

Crew module
Propulsion module
Intelligence module } All new
Landing gear kit
Cargo module

Support Equipment Fabrication

There are two types of support equipment: nondeliverable and deliverable equipment. Nondeliverable equipment consists of special tooling, special test equipment (STE), and material handling and parts protection (MH/PP). Deliverable equipment consist of ground support equipment (GSE) needed to support the operational capability of a system.

Special Tooling. Weld jigs, assembly jigs, layup dies, detail tooling, templates, and drill jigs will be fabricated to assemble the RST modules. Control tooling will be fabricated for controlling the interfaces of (1) module to module (stack configuration), and (2) spacecraft to launch vehicle. Preliminary plans for their manufacture and use will be established during Phases A and B. Tooling lists, concepts, bar charts, and schedules will be finalized and implemented during Phase D.

Special Test Equipment. The requirements will be determined and designed by Engineering. This organization will be responsible for the integrity and verification of electrical, mechanical, and electromechanical subassemblies, and assembles. Engineering also will be responsible for the design of special test equipment for ground support. Details will be defined during subsequent phases of the program.

Material Handling and Parts Protection Equipment. It is necessary to identify and provide equipment to safely facilitate the flow of software and hardware through the stages of raw stock to end item. All design and fabrication are coordinated with the using department and other affected organizations, such as Product Engineering, Systems and Industrial Safety, Quality Assurance, GSE, and Dimensional Tooling. The details will be defined during subsequent phases of the program.

Ground Support Equipment. Requirements for GSE, determined by Engineering, will be negotiated as deliverable contractual end items. GSE equipment will support launch-site activity as well as refurbishment requirements. Details will be defined during subsequent phases of the program.

Manufacturing Engineering

The Manufacturing Engineering organization will cover manufacturing producibility, tool engineering, material handling and parts protection engineering, equipment engineering, manufacturing methods, tool planning, manufacturing order planning, and shop contact. This technical support will be provided to manufacturing departments responsible for the fabrication, assembly, installation, insulation, and testing of RST spacecraft and GSE equipment.

Manufacturing Producibility. Manufacturing Engineering will provide producibility support to Design Engineering during Phases B and C to provide design analysis from a fabrication tooling and production handling feasibility viewpoint. Manufacturing Engineering also will define the most practical approach to machining, forming, and processing the RST components.

Tool Engineering. Tool engineers will develop the basic manufacturing operational flow and major tooling concepts as the engineering design is developed.

Design Engineering. Design personnel will translate engineering design criteria into tool, material handling, and parts protection designs to assure the dimensional and operational integrity of contract end items.

Special Test Equipment Engineering. Subsystems analysis will be performed by Manufacturing Engineering to establish test sequence logic. Manufacturing Engineering will prepare test logic flow charts for manufacturing, and determine STE and Detail Checkout Specifications (DCS) requirements.

Production Control

Production Control assures the orderly and timely delivery of products in accordance with contractual commitments and the manufacturing baseline document. Responsibilities will include the development and monitoring of Manufacturing's master and detail schedules, hardware and work control, change control, evaluation and implementation of mechanized systems, and performance reporting.

Maximum use of computer technology and data processing techniques to improve efficiency and minimize costs will be implemented. Actual time versus time standards will be used as performance measurement criteria for work control and management visibility. The Change Control organization will be responsible for representing Manufacturing in change negotiations and monitoring change progress. Control points and a feedback system will be employed for performance and status reporting of actual production progress against schedule milestones.

Programming and Scheduling. Master programming and scheduling charts depicting long leadtime procurement requirements will be prepared during Phases A, B, and C. A master manufacturing development schedule will be prepared during Phases C and D to depict a coordinated plan for the fabrication of the soft mockups, test articles, and flight spacecraft.

Preliminary scheduling of the soft mockups, test articles, and first ship (operational flight vehicle) are shown in Figures 10, 11, 12, 13, and 14.

Control Systems. Various systems are available to control or monitor manufacturing activities and furnish management and the customer with accurate data and program visibility. Manufacturing data retrieval and production order location and report systems are two of the control systems that will be implemented in Phase D.

Refurbishment

Manufacturing activities for refurbishment will be defined during subsequent phases of this program. Ground support equipment will be required and will include such items as transportation equipment, handling devices, work stands and platforms, and nondestructive testing (NDT) equipment.

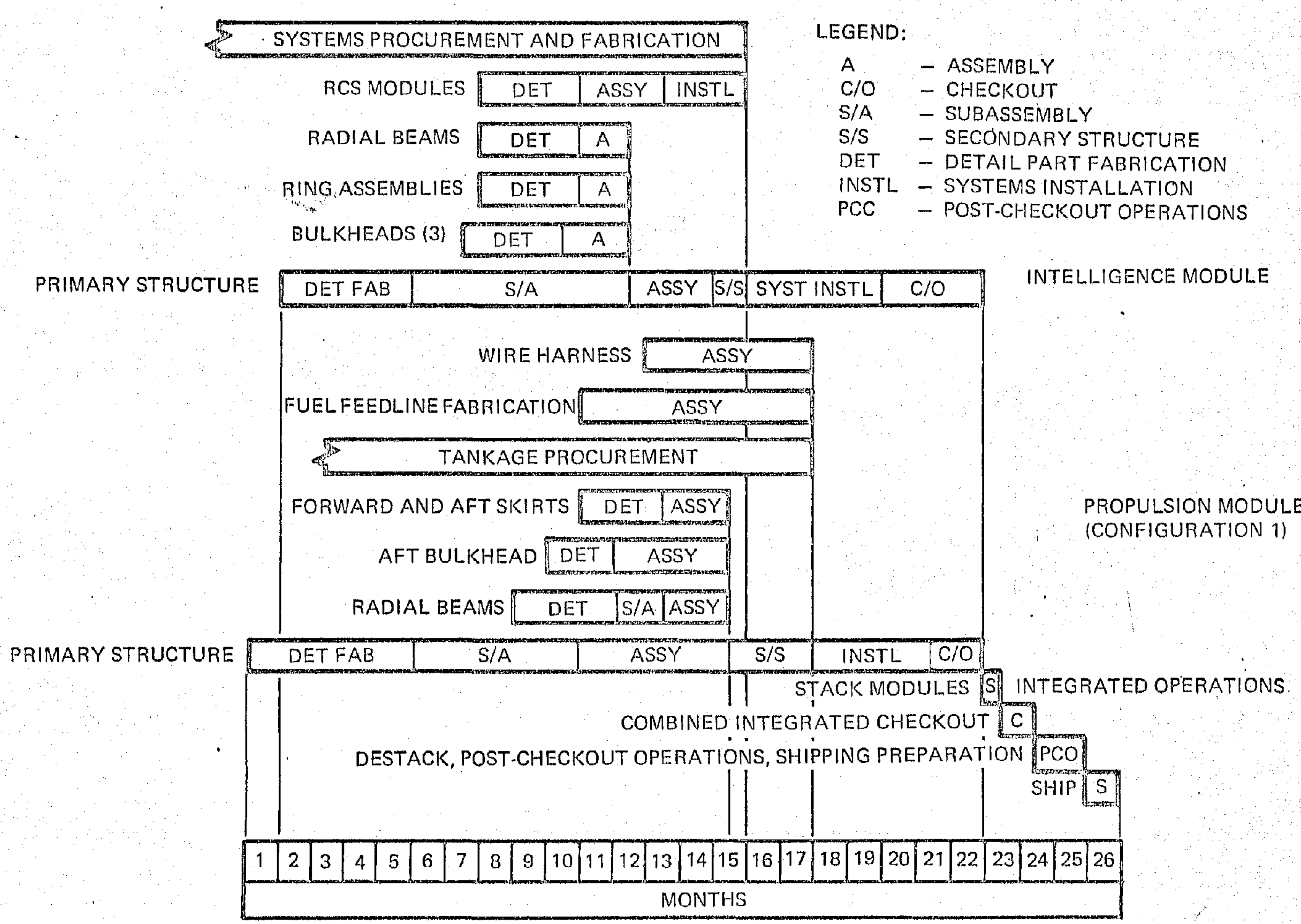

Figure 10. Preliminary Manufacturing First Ship Flow Plan — Unmanned Earth-Orbital Tug

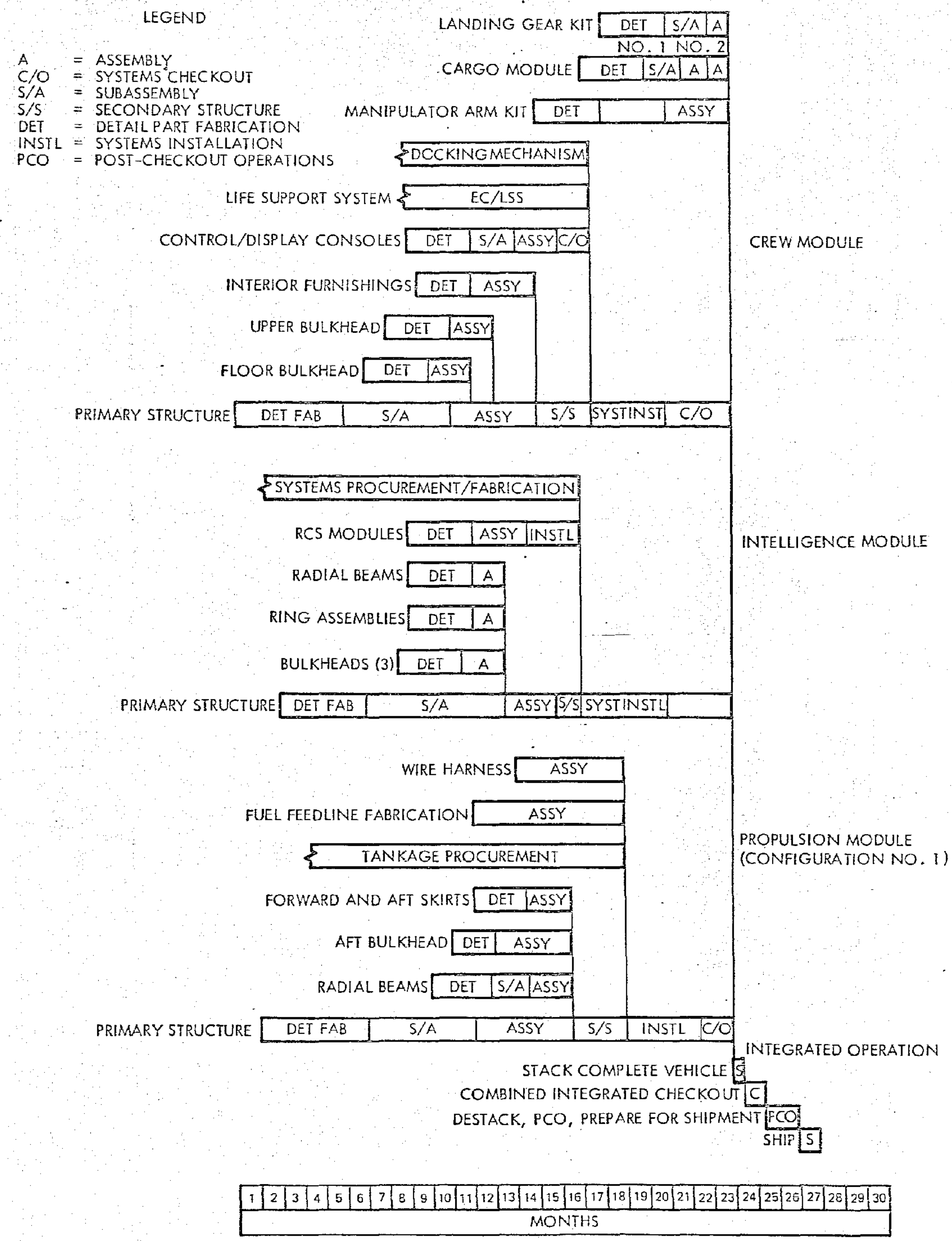

Figure 11. Preliminary Manufacturing First Ship Flow Plan — Manned Earth-Orbital and Manned Lunar Tug

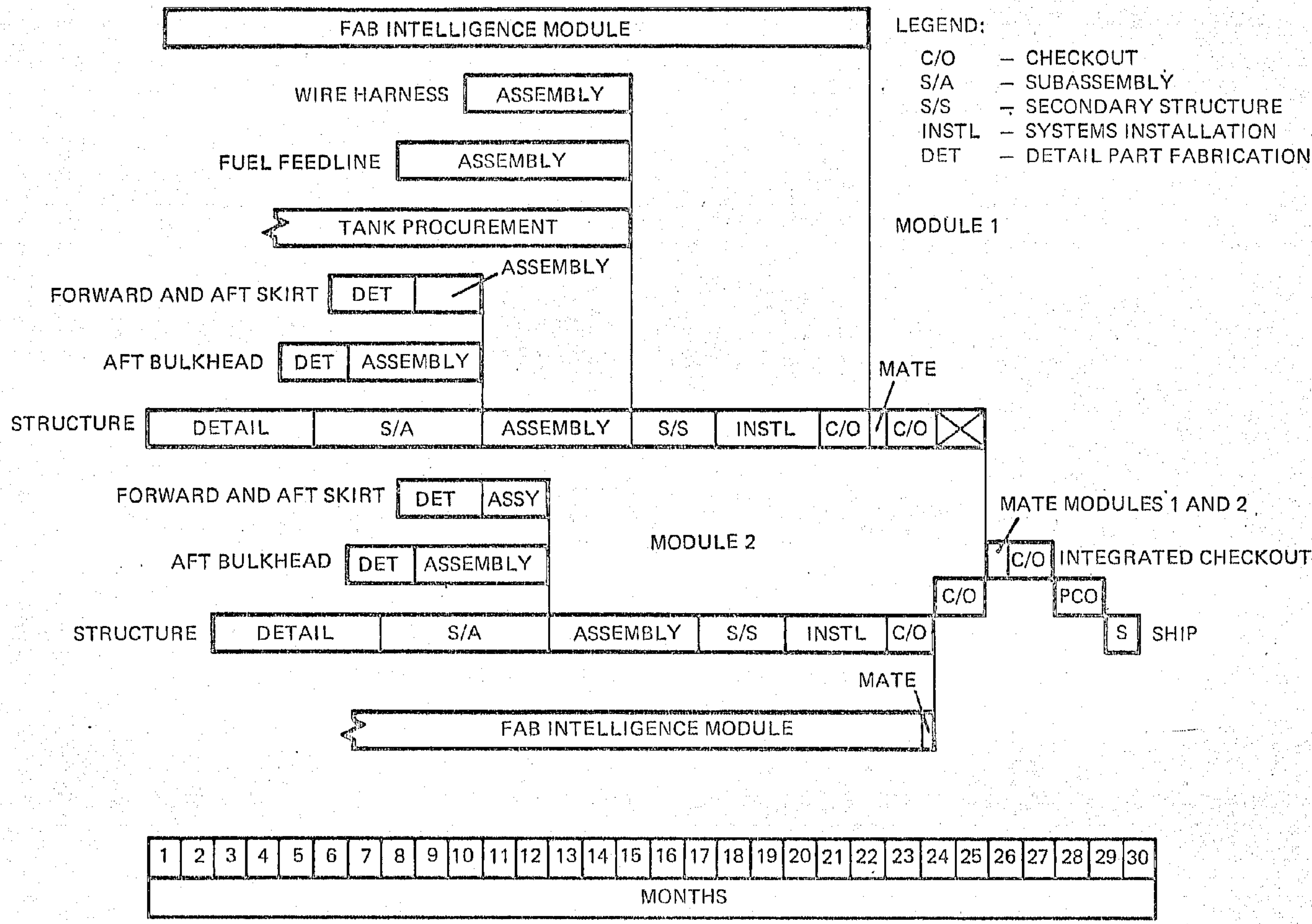

Figure 12. Preliminary Manufacturing Flow Plan – Propulsion Module (Design Concept 5)

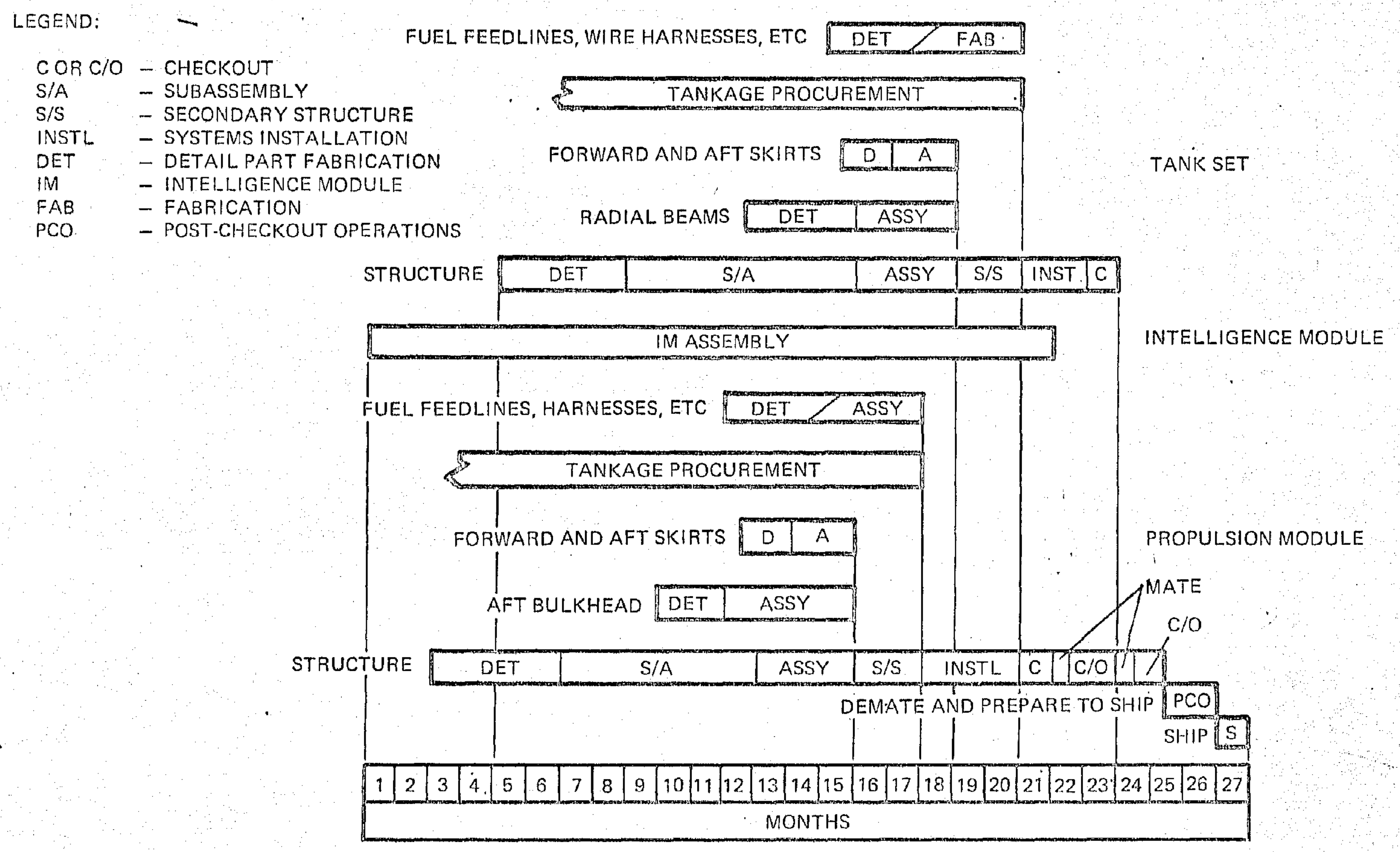

Figure 13. Preliminary Manufacturing Flow Plan – Propulsion Module (Design Concept 11)

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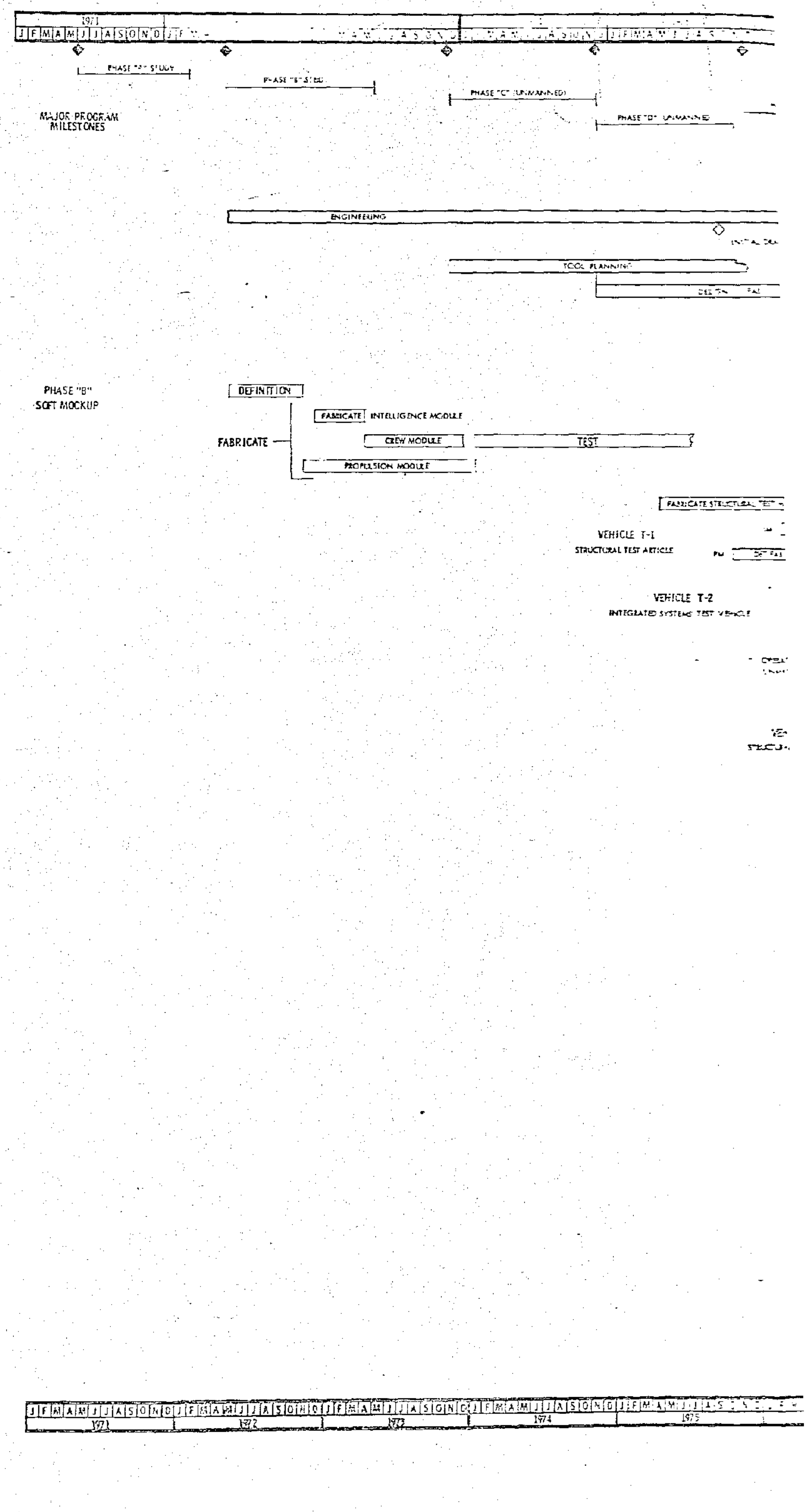

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Space Division
North American Rockwell

SPACE TUG

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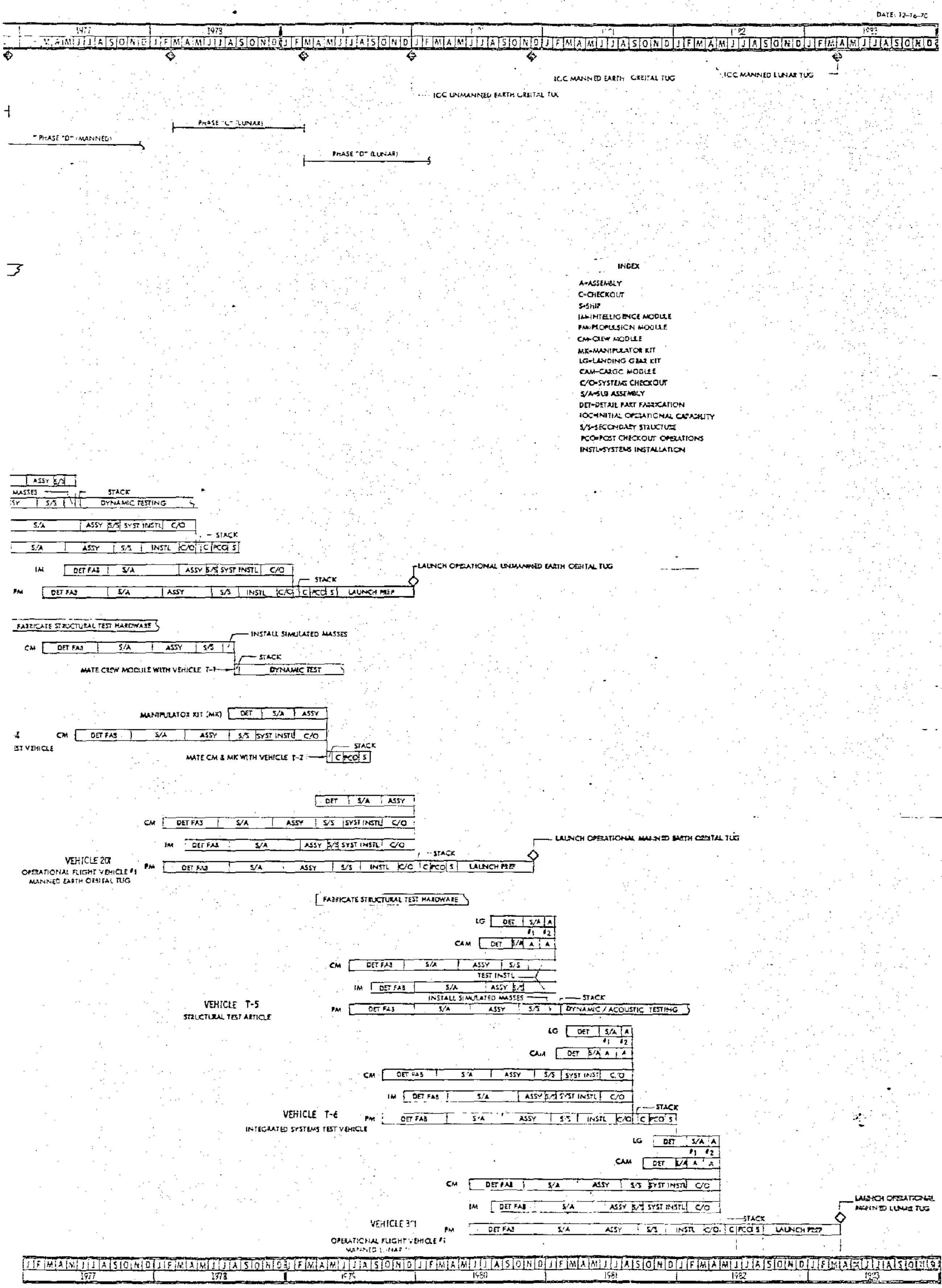

Figure 14. Preliminary Manufacturing Composite Schedule

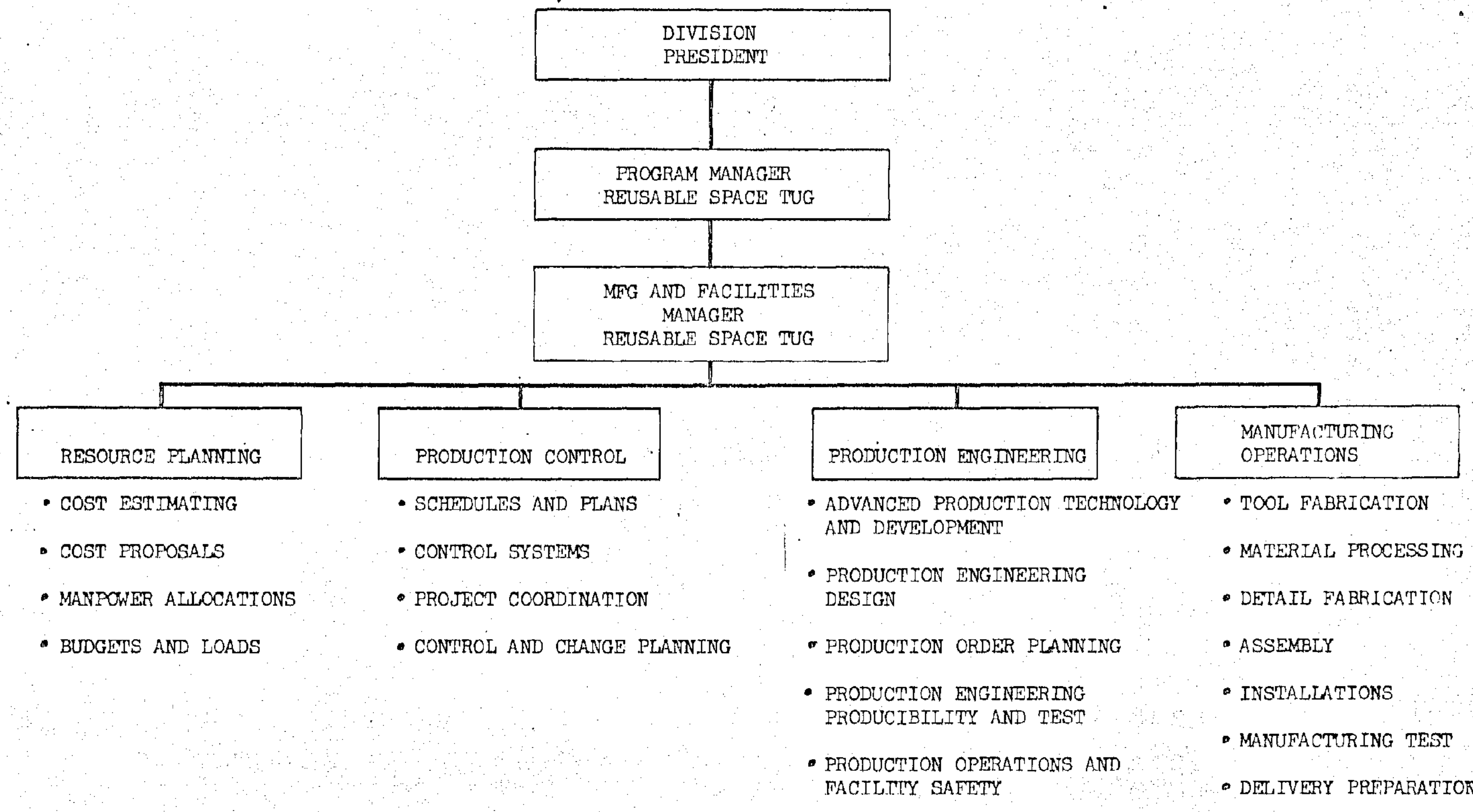

Figure 15. Manufacturing Organization Chart

3.2.4 Implementation and Management

Organization

A Manufacturing and Facilities manager will be appointed at the beginning of Phase B. He will report directly to the RST manager. Figure 15 shows the organizational structure and reporting channels.

Cost Effectiveness

Cost effectiveness will continue to be a major consideration as the manufacturing plan is developed. Cost reduction will be applied where audits, program reviews, or technical breakthroughs are identified.

Interface Requirements

Continuing interface with other program plans to assure complete coordination of all manufacturing effort will be established as soon as designs are sufficiently firm.

3.3 TESTING PLAN

3.3.1 Purpose

The purpose of the testing plan is to identify the development issues and test requirements and define the RST test activities to provide the desired operations reliability, safety, and confidence at minimum cost.

3.3.2 Scope

The testing plan describes the planning, analyses, and testing to be accomplished during Phases A through D of the program (preliminary analysis, definition, design, and development and operations). The plan is applicable to the three selected design concepts and covers the types of tests required for the three major development categories (i.e., unmanned earth-orbital, manned earth-orbital, and manned lunar tugs). The principal space tug test cagetories are the development, qualification, and integrated systems. During Phase A, there will be tradeoff studies to identify optimum test objectives. In subsequent phases, the test objectives will be the basis for defining the required tests and detailed test schedules to blend the test sequences into the overall updated program development schedule.

3.3.3 Task Descriptions

Test Approach

The primary objective of the approach to be explored during Phase A will be to accomplish test planning to provide the maximum reliability, safety, and confidence levels with minimum cost and within schedule constraints. The test approach will be based on operational applications and requirements of the space tug development categories. An evaluation will identify the major testing differences between the selected configurations and operational applications. The test process is shown in Figure 16.

Minimizing Costs. The test objectives, and ultimately the test requirements, will be predicated upon previous testing and operational experience of equipment of similar construction or operational environments. The technology gained from tests and operational use on programs such as the Earth-Orbital Shuttle and Earth-Orbital Space Station will be available for analysis and application to the space tug. This technology will reduce substantially the testing required for space tug system development and qualification. Development and qualification verification that must be satisfied by test will be reviewed and analyzed to determine the most effective and economical means of accomplishment. Multiple reuse of major test articles will be a goal of the test program. In addition, the possibility of using the space shuttle or other vehicles expected to be operational in the time frame required for the space tug testing will be investigated as an alternative to simulation on the ground.

Test Philosophy

The RST test philosophy identifies the ground rules and criteria for test activities from material development through each mission qualification. Specific criteria to be applied to the program are described in the following paragraphs.

Development Testing. Development tests are those conducted to select and prove the feasibility of design concepts. These tests are concerned with engineering evaluation of hardware and software to acquire engineering data, identifying sensitive parameters, and evaluating the development configuration performance. Development testing will encompass materials, design feasibility, breadboards, and major test elements. The criteria to be applied to those tests shall include the following:

1. All design verification requirements will be satisfied by the maximum use of analysis and supported by development tests to the extent necessary.

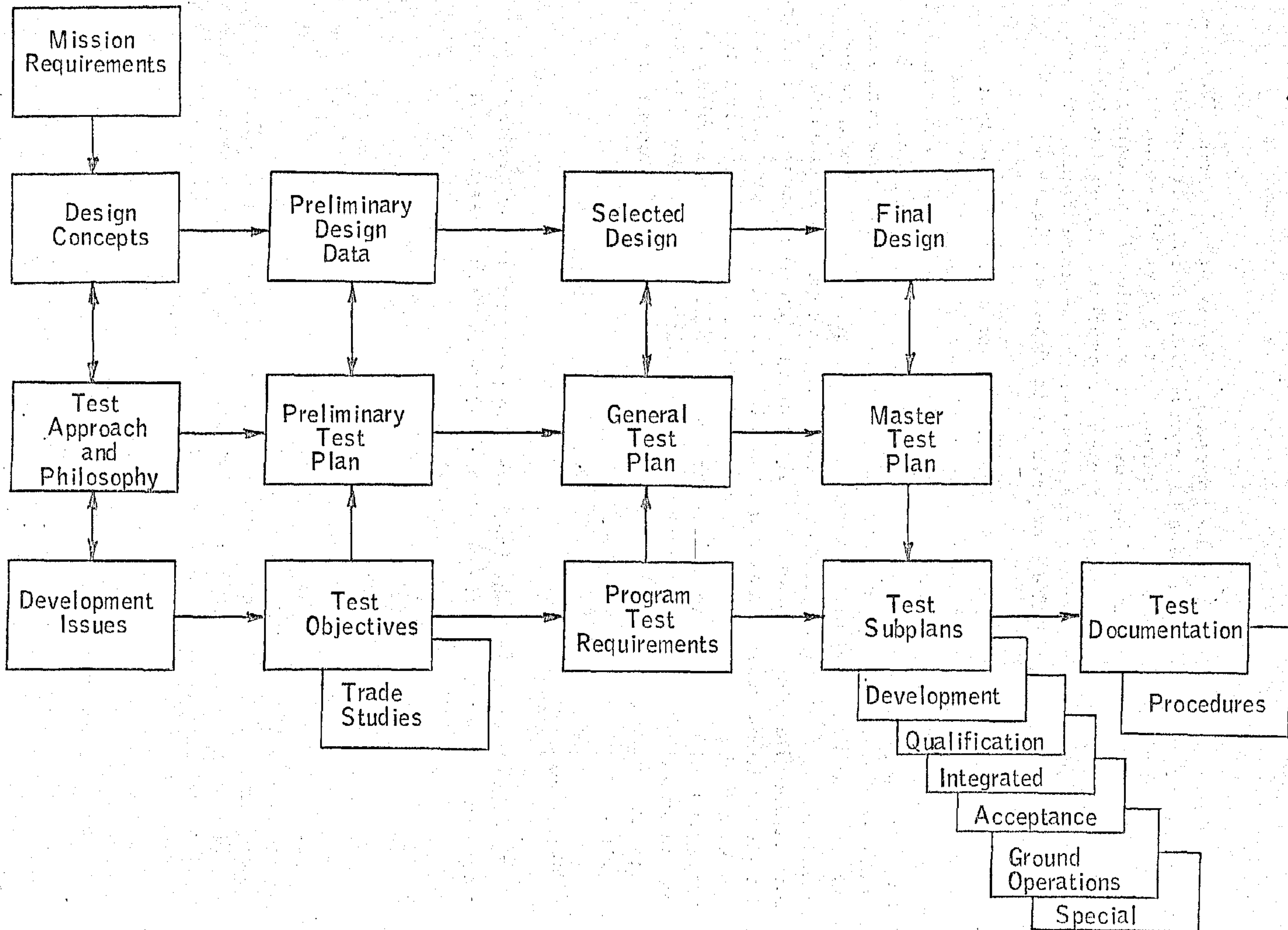

Figure 16. Reusable Space Tug Test Program Functional Flow

2. Structural testing on major test articles will verify a satisfactory design margin for operational vehicles. Potential reuse of test articles for subsequent tests requires that destructive testing be avoided.

3. Development testing may be used to qualify hardware in those instances where confidence is such that the probability of success is high and a cost savings is evident. Rigor and criteria of qualification testing also must be satisfied.

Qualification Testing. Qualification tests will be conducted with specific rigor on production specimens to verify the functional performance of components and subsystems in specified environments and to demonstrate compliance with design and performance specifications. The following criteria will be applied in the development of qualification test requirements:

1. Qualification requirements will be satisfied by analysis or test or combination of both. Maximum practical use will be made of test data from other programs to qualify RST hardware.

2. Qualification testing will be accomplished at the highest practical level of assembly. Test levels will be determined predicated on such factors as packaging, complexity, and test facility capability.

3. Mission life tests will be based on a maintenance cycle or multiples thereof, rather than on total life expectancy.

4. Qualification of subsystems will be based upon the criticality of the system. Criticality I hardware will be qualified to specified environments. Criticality I is defined as any essential function that, if inoperative, would cause loss of life or vehicle. Less stringent environments will be applied to hardware of lower criticality.

5. Qualification test levels will include safety margins but will not exceed design specification levels. This procedure will allow hardware reuse for other ground test programs if required.

Integrated Systems Tests. The integrated systems tests verify that the subsystems will operate simultaneously in accordance with the particular mission requirements without causing degradation to their functional performance. The tests also provide data to the design disciplines for subsystems refinement and for preparation of the operational test procedures. These tests further demonstrate that applicable ground support equipment is compatible with the integrated system. Tests and demonstration at the subsystem levels, including all alternate or redundant modes, will precede integrated systems testing.

The three vehicles planned for the integrated systems tests are described in subsequent paragraphs. Utilization of these vehicles after completion of testing for mockup purposes, modification kit proofing, or refurbishment to operational status will be examined during the study.

Task Summary

The tasks necessary for implementation of the test plan are summarized by phase in the following paragraphs.

Phase A Test Concepts and Analysis. The primary efforts during this phase are: to identify the test philosophy and approaches commensurate with overall program objectives; to evaluate the testability and feasibility of candidate concepts in relation to alternate test approaches; to identify critical test areas and development issues; and to support the program cost and schedule development.

Phase B Test Definition. During Phase B, the Phase A analysis will be expanded to justify a recommended test philosophy and approach to influence the selection of the end item concept for each major development category and to prepare a preliminary test plan for the selected configuration and mission category. The test plan will define the test philosophy and approach, test schedules, test articles, and test facilities.

Phase C Test Design. The primary objectives in Phase C will be to develop the general test program in support of the proposed Phase D effort and to assure that the test program defined is feasible and compatible with RST objectives and constraints.

Phase D Test Development and Implementation. The Phase D objective will be to implement the test program commensurate with the design specifications, master test plan, detailed test subplans, and defined program requirements and objectives. Documentation will be prepared to perform, document, and evaluate the testing process.

Detailed Task Descriptions — Test Requirements

Preliminary test requirements specified in the following paragraphs generally define the test categories and identify the test articles required. These requirements were developed using design Concept 1 as a baseline. The test categories will remain the same for each of the three selected concepts; however, the test requirements and articles will vary. The delta test requirements for the lunar lander modes of concept 5 include the

Table 4. Static Structural Test Hardware Elements

Item	Development Category		
	Unmanned Earth-Orbital Tug	Manned Earth-Orbital Tug	Manned Lunar Tug
Thrust structure	X	S(1)	S(1) X(2)
Shuttle interface structure	X	X	X
Hatches and seals	X	X	X
Cryogenic tanks and support structure	X	S(1)	S(1) X(3)
Insulation	X	S(1)	S(1)
Crew compartment		X	X
Landing gear			X
Cargo module			X

(1) S indicates verification by similarity and analysis.

(2) Design Concept 5

(3) Design Concepts 5 and 11

development and qualification of parallel propulsion stages or a tank set for single-stage propulsion. Concept 11 requires the development and qualification of a tank set for the lunar-lander mode. Significant differences in test requirements for the selected concepts also are noted in this document along with applicable tables and figures. Separate subplans will be developed for each test category in succeeding program phases.

Structural Tests. The purpose of the structural test is to determine the feasibility of design approach with regard to structure loads and stress simulating expected loads environment including launch, spaceflight, entry and landing.

Test Article Descriptions. Static structural tests will utilize test hardware elements listed in Table 4 and major test articles shown in Figure 17. Development testing to obtain empirical data for evaluation will be performed on selected elements to verify design concepts and to detect deficiencies and incompatible interfaces. Test vehicle T-1, consisting of the propulsion and intelligence modules, will be subjected to static and dynamic tests for the unmanned earth-orbital tug. Test Vehicle T-1 then will be used in the manned earth-orbital tug structural tests by integrating it with a crew module. This vehicle then will become Test Vehicle T-3. Additional tests will be conducted on Test Vehicle T-3 to verify (for the manned earth-orbital tug) delta loads and stress from the unmanned earth-orbital tug loads environment.

New modules (crew, intelligence, propulsion, and possibly a tank set, depending upon the concept selected) will be fabricated for the manned lunar tug structural tests. The requirement for new test articles in this mission category is predicated upon the significant configuration changes from prior categories. It is anticipated that the prime changes will be in systems arrangement rather than in new systems. Additional modules (landing gear and cargo) will be necessary.

Test Description. Static loads simulating acceleration loads and bending moments will be applied to module interface and attach fittings. Strain, load, and deflection data will be recorded. Dynamic tests will be conducted on the propulsion, intelligence and crew, landing gear, and cargo modules. Random and sinusoidal vibration will be conducted to verify module response and loads transmissibility. Launch, abort, spaceflight, entry, and landing environments will be simulated.

Development Tests. The most economical approach to verify RST hardware is to select proven materials, components, and techniques.

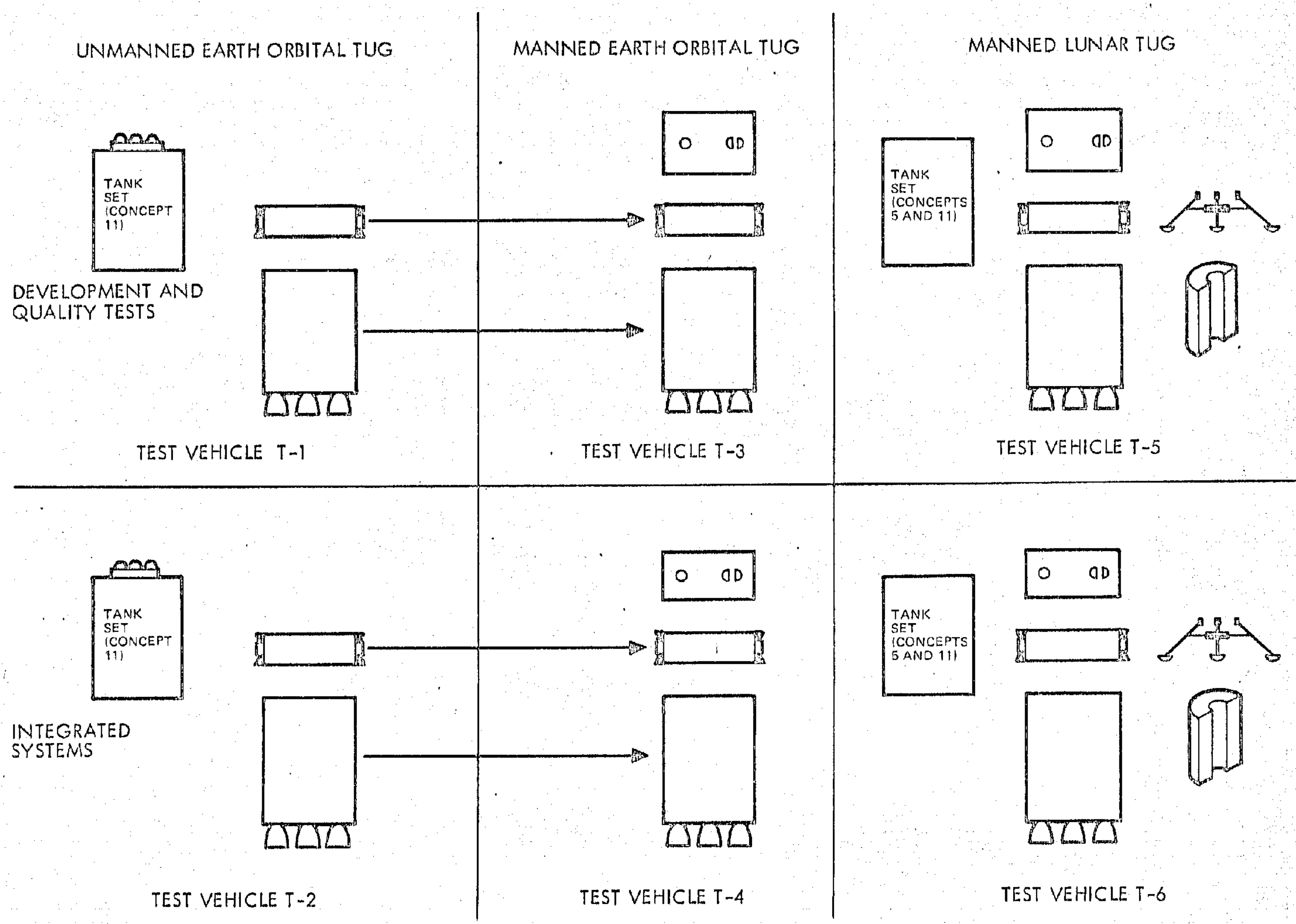

Figure 17. Major Test Articles

However, some development testing of new techniques or hardware will be required. The test philosophy in each case will be tailored to the specific requirement. In conducting the required development testing, the following objectives will be satisfied:

1. Feasibility of design approach
2. Performance of hardware under simulated or actual operational environments
3. Evaluation of test procedures and ground operations concepts for checkout
4. Determination of design readiness for qualification testing

Test Article Description. Development testing will consist of breadboards, prototypes, or off-the-shelf hardware tests conducted on new materials or techniques. Analysis of projected subsystems to identify the extent of development testing necessary indicates that a percentage of subsystems will require tests. The estimate for necessary testing is based on the subsystems concept complexity and new technology required. Table 5 lists the preliminary requirements for development testing hardware elements.

Test Description. Principal development tests to be performed will be of those materials, components, assemblies, and subsystems that have not been utilized in other programs, have greater environmental mission life requirements than those previously developed, or must function in a different manner when integrated with the RST system. Development of specific test objectives will be accomplished in concert with design progress.

<u>Qualification Tests</u>. The purpose of qualification tests is to verify the operational suitability of the RST flight and ground equipment. Qualification requirements will be based on an optional combination of analysis or testing intended to conclusively demonstrate, consistent with safety and reliability, that the ground and flight systems are capable of performing the particular missions of the three major development categories: unmanned earth-orbital tug, manned earth-orbital tug, and manned lunar tug.

Test Article Description. Qualification testing to the necessary levels and environments will require duplication of a flight vehicle for complete verification. Components and subsystems will be verified at the highest level

Table 5. Development and Qualification Testing Hardware Elements

Subsystem	Development Hardware (Percent)	Qualification Hardware (Percent)
Unmanned earth-orbital		
Propulsion module structure	10	100
Tank structure	10	
Thrust structure	10	
Propulsion subsystem	10	75
Engines	25 to 100	25 to 100
Intelligence module structure	10	100
Tank and shelf structure	10	
Electronics	20	80
G&N	10	80
RCS	10	80
Environmental control		10 to 50
Electrical power and distribution		10 to 50
APU		10 to 50
Docking	10	10 to 50
Manned earth-orbital		
Crew module structure	10	100
ECLSS		10 to 50
G&N		10 to 50
Electrical distribution		10 to 50
Displays and controls		10 to 50
Electronics		10 to 50
Manned lunar		
Propulsion module structure	10	100
Propulsion module structure (Concept 5)	20	100
Intelligence module structure	10	100
Crew module structure	10	100
Landing gear	25	75 to 100
Tank set (Concepts 5 and 11)	10	100
Cargo module	10	40 to 100
Electronics		20
Displays and controls		10

of assembly practical at the supplier and subcontractor facility at the prime contractor's facility. Table 5 lists a summary of subsystem qualification hardware requirements estimated to verify adequate operational suitability. In subsequent phases, specific ground rules and constraints for qualification test hardware and procedures will be developed. To quality the RST system, Test Vehicles T-2, T-4, and T-6 (Figure 17) will be used for subsystem, combined systems, and integrated systems tests. These tests will include space simulation or, if it proves more effective and economical through analysis and tradeoffs, tests in actual space environment. Structural qualification will be accomplished by using Test Vehicles T-1, T-3, and T-5.

Test Description. Qualification tests will be designed to verify that the component, assembly, subsystem, and integrated system functional performance will meet the requirements of the RST design mission specifications. The required hardware will be tested for functional performance in the anticipated mission environments. Tests will be conducted beyond the mission environments but within the design ultimate limits to demonstrate the hardware's capability to withstand more stringent environments and thereby increasing the safety, reliability, and probability of mission success. Mission simulation tests to demonstrate the operating life of the components and subsystems will be conducted in simulated or actual mission environment.

<u>Integrated Systems Tests.</u> The purpose of the integrated systems tests is to demonstrate the subsystems compatibility and ensure that there is no interaction among the subsystems that will affect their functional performance and to verify that the integrated systems performance is not appreciably degraded by the mission environment.

Test Article Description. Three test vehicles (Figure 17) are planned to be used to accomplish the integrated systems tests. Test Vehicle T-2 will be used in the unmanned earth-orbital tests and T-4 in manned earth-orbital tests. Test Vehicle T-4 will use the propulsion module (PM) and intelligence module (IM) that comprised Test Vehicle T-2, plus the added crew module (CM). Test Vehicle T-6 will be fabricated to meet the manned lunar tug configuration and will include the cargo module and landing gear subsystems and also the tank set for design Concepts 5 and 11. These vehicles will include the structure subsystem with all other subsystems installed.

Test Description. The objectives of the integrated systems tests are to provide: data for determining vibration levels to which the components or assemblies of the subsystems will be subjected, the subsystems mechanical and electrical compatibility, and thermal-vacuum tests to demonstrate that the integrated systems functional performance is unaffected by space environment. In the qualification of the integrated system, ground simulation tests, flight tests, or a combination of both, will be used. Tradeoff analysis will be conducted to determine the most cost-effective method to accomplish these tests without affecting the adequacy and usefulness of the test data. Flight tests would be used for material, components, and subsystem qualification if it is feasible without increasing the program costs significantly or impacting program major milestones.

Acceptance Tests. All installed equipment in the vehicles will receive a series of formally documented acceptance tests prior to final delivery of the vehicles to the customer.

Components. All components delivered to the prime contractor by suppliers and subcontractors must pass an acceptance test. The exact nature of these tests and the determination of who will accomplish them will be decided on an individual basis by the prime contractor. Any tests performed away from the prime contractor's facility will be witnessed by their Quality Assurance personnel.

Subsystems. Acceptance testing of subsystems will be accomplished by using prime contractor-prepared test procedures. These tests may be conducted prior to installation.

Combined Systems. The combined systems tests will be accomplished following installation and functional checkout of each subsystem. Procedures will be developed to simulate specific mission phases.

Ground Operational Tests. Ground operational tests will be accomplished at the shuttle launch site. In addition to a receiving inspection on each delivered module or set of modules, a final checkout prior to integration with the shuttle vehicle will include an abbreviated combined systems test to verify the critical functions of subsystems. Details of these tests will be developed in Phase D and will include appropriate test and checkout requirements and procedures for the RST after its return from space for maintenance, modification, repair, or refurbishment. These requirements and procedures will be incorporated in a master test plan prepared in Phase D. That plan will include subplans for acceptance tests, in-plant checkout, launch-site checkout, and operations checkout.

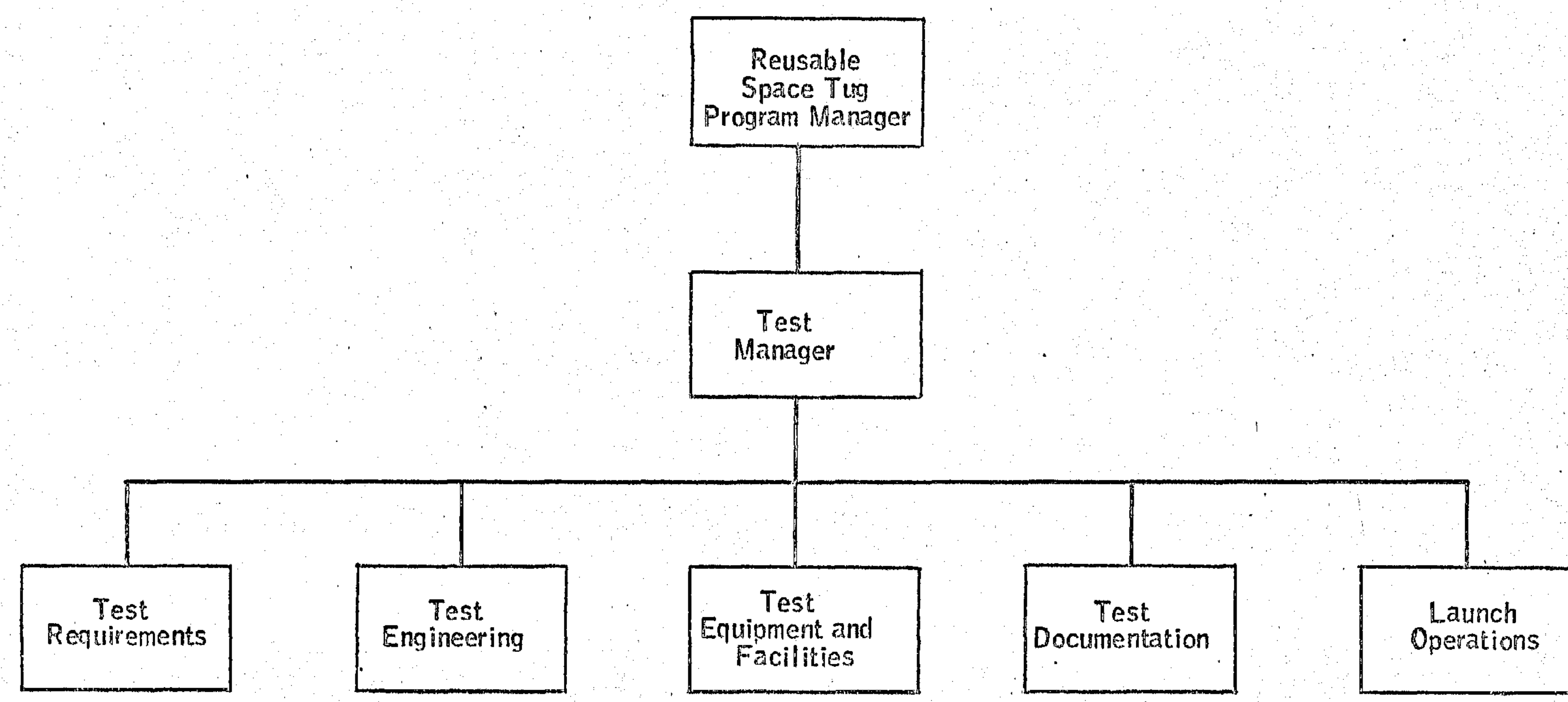

Figure 18. Test Organization Chart

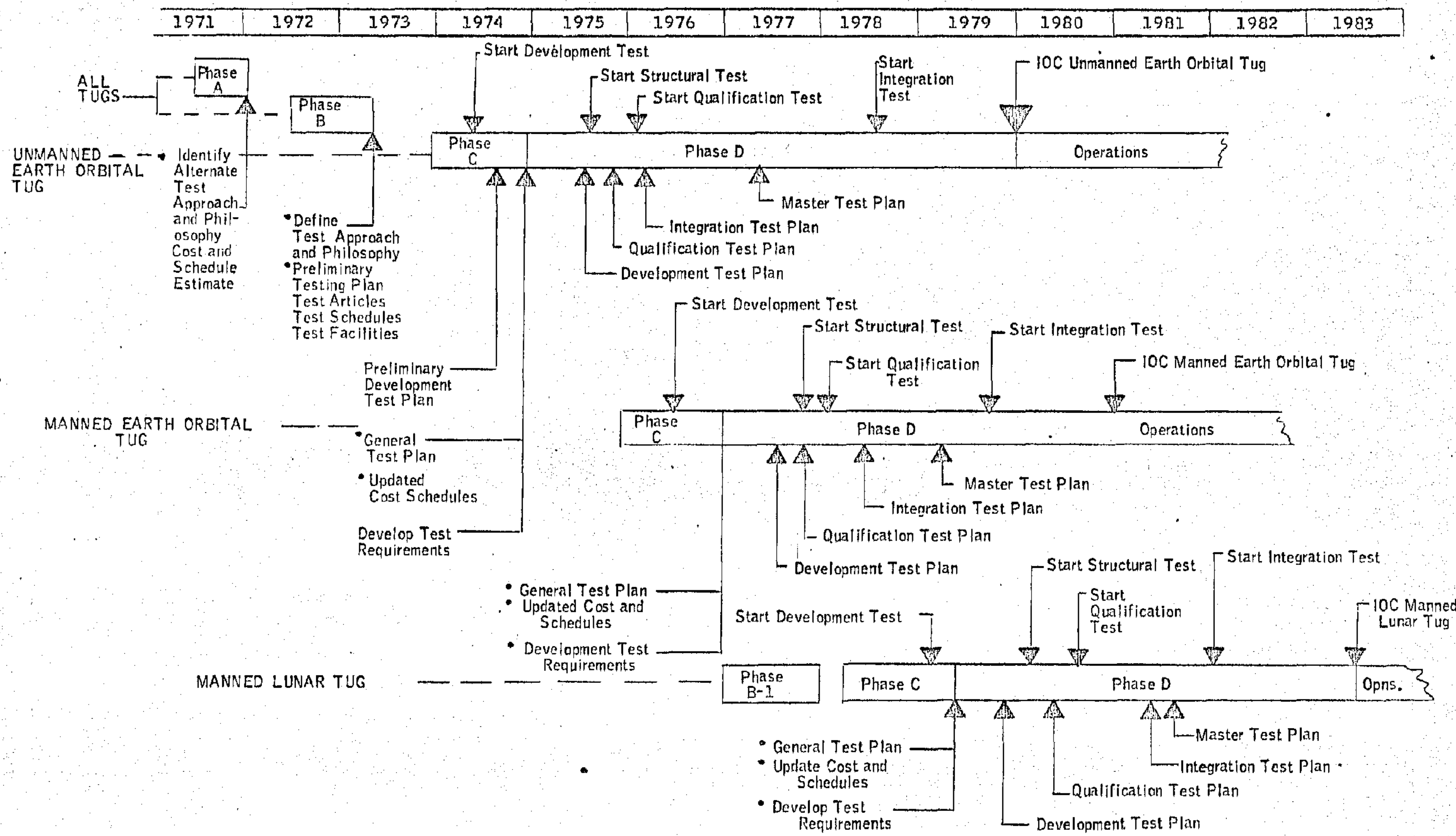

Figure 19. Preliminary Test Schedule

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3.3.4 Implementation and Management

Organization

During Phase A and Phase B the testing function will report to the Chief Program Engineer for technical direction. In subsequent phases, an organizational structure (Figure 18) will be implemented.

Schedule and Milestones

Major program testing milestones are shown in Figure 19.

Interfaces with Other Plans

The test planning interfaces with other program plans, including the main areas of mutual concern, are listed below:

Design plan. Critical test areas and development issues influence design selection.

Manufacturing plan. The identification and use of test articles defined in the testing plans are prime factors in setting the manufacturing sequence and schedules.

Ground operations plan. The test philosophy described in the testing plan for acceptance, combined systems, and operations influences the ground operations functional flow.

3.4 GROUND OPERATIONS PLAN

3.4.1 Purpose

The purpose of this plan is to define the ground operations necessary to support the reusable space tug (RST) with minimum cost and maximum safety of personnel and hardware.

3.4.2 Scope

This plan covers preliminary ground operational requirements and activities to support the RST in shipment from factory to liftoff, and in turnaround from return to earth through relaunch. Other aspects of ground operations support (e.g., ground tracking and communications) will be developed and incorporated in the plan during a subsequent phase of the program. The plan is applicable to all three selected design concepts for the unmanned earth-orbital tug, manned earth-orbital tug, and manned lunar tug. It is assumed that integration, assembly, and checkout capabilities will exist at both the factory and the launch site.

3.4.3 Ground Operations Descriptions

The ground operations requirements and activities necessary to support the space tug from factory to liftoff are shown in Figure 20, while turnaround ground operations for relaunch are shown in Figure 21. Blocks formed by dashes in Figure 20 represent factory responsibilities, while in Figure 21 they represent shuttle responsibilities.

Requirements

Module or assembled vehicle packaging must include requirements for system purging (propulsion module) and instrumentation for g-load recording and temperature and humidity controls.

Transportation of the module or assembled vehicle configurations of the RST may be by land, sea, or air. Unless specific transportation vehicles are identified, special containers may be a requirement. Future trade studies will be conducted to determine the optimum mode of transportation.

The propulsion, intelligence, crew, and cargo modules will require adjustable handling equipment to minimize assembly time, ensure proper alignment, and eliminate flight hardware damage.

The testing requirements are covered in the testing plan.

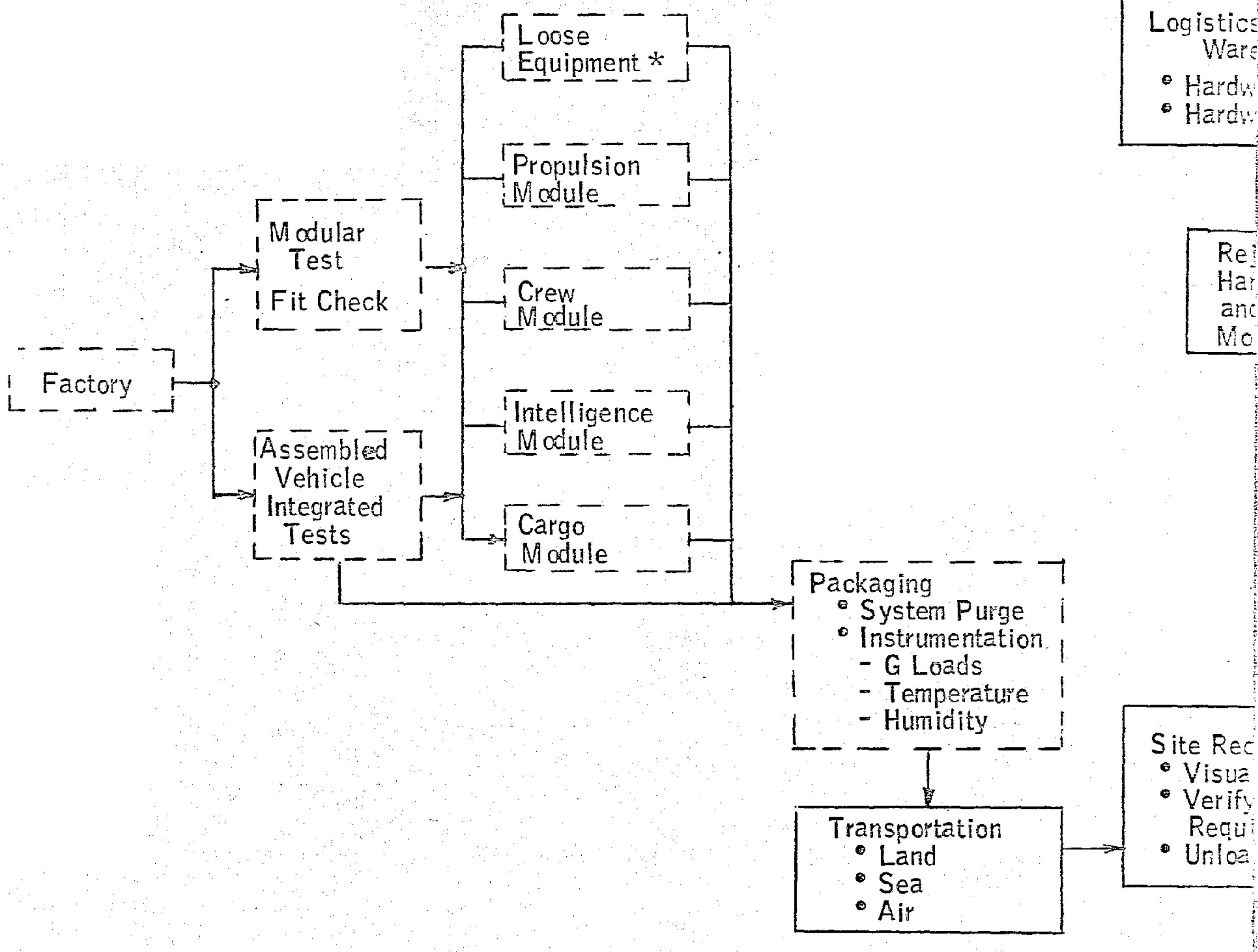
Supplies will be loaded in relation to the mission requirements.

The tug will be loaded into the shuttle in the horizontal position. The loose equipment (lunar landing gear) will not be assembled but will be loaded separately.

The space tug may be unfueled, partially fueled, or totally fueled at the launch pad, depending upon the final basing concept.

In post-flight shuttle unloading, the space tug will be unloaded from the shuttle in the horizontal position after post-flight shuttle safing. During post-flight space tug safing, the propulsion system will be purged and the vehicle or modules may require a wash down.

FOLDOUT FRAME 1



* Loose Equipment

1. Manipulator Kit
2. Lunar Landing Gear Kit

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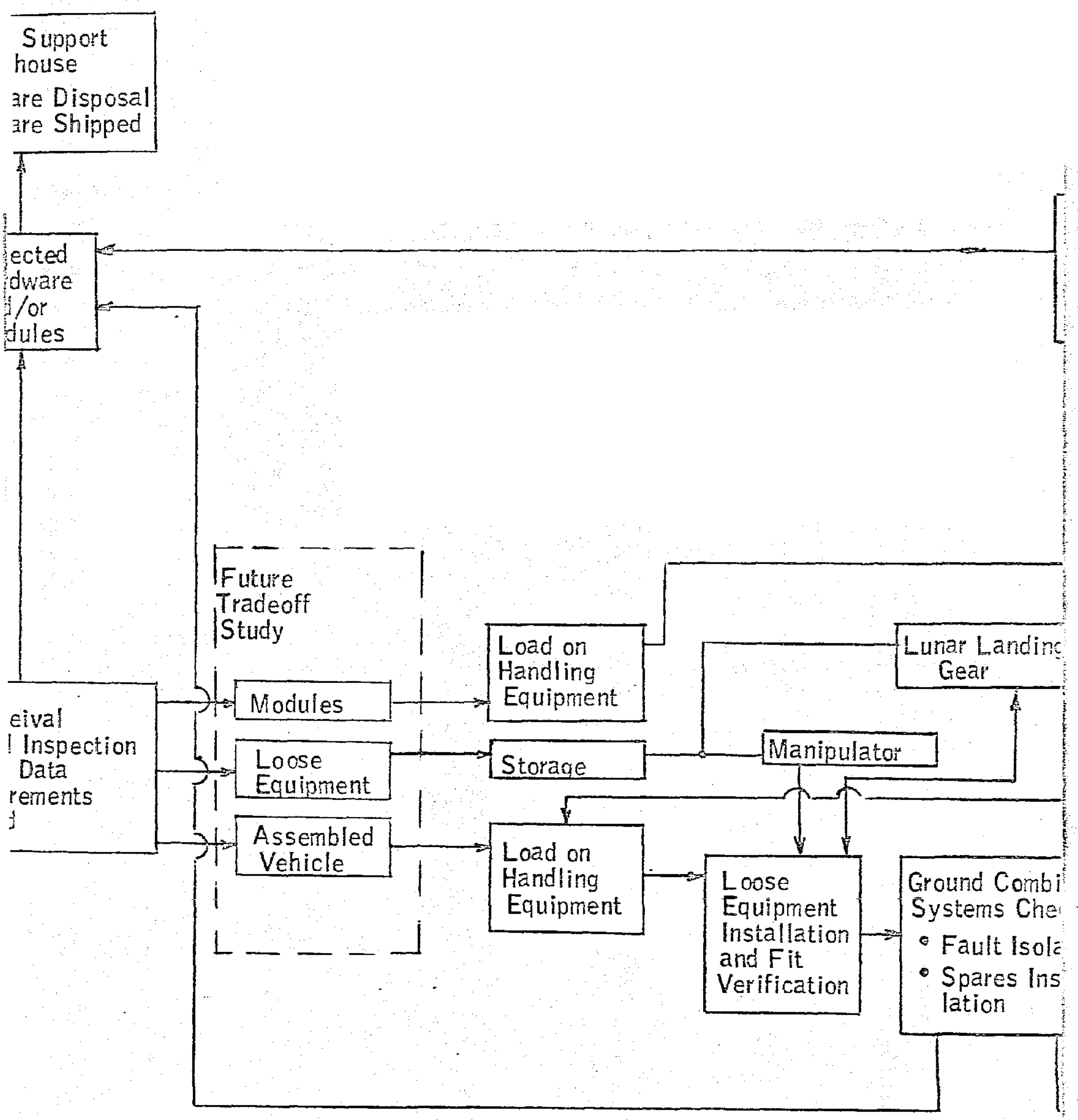

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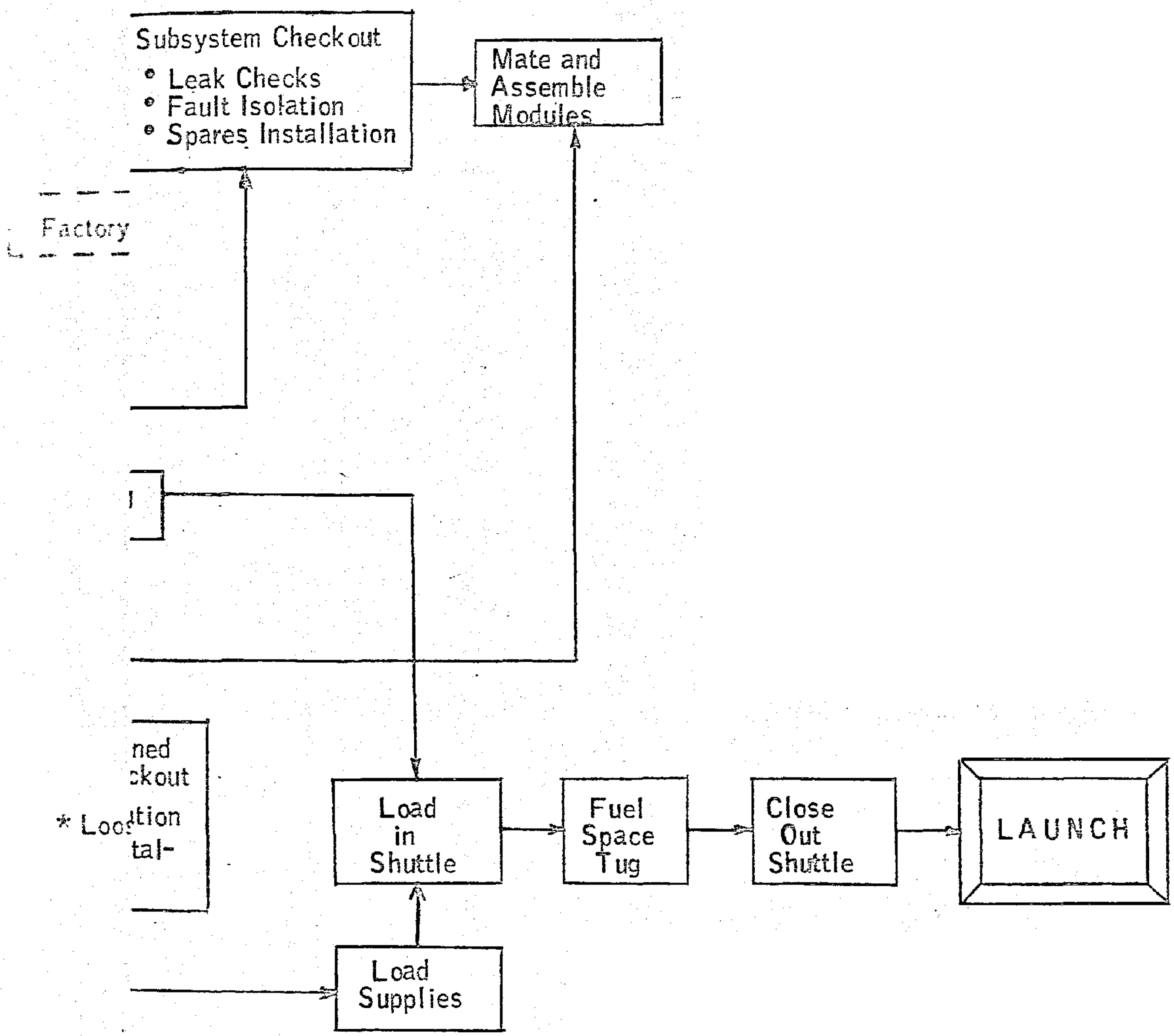

Figure 20. Factory-to-Liftoff Ground Operations

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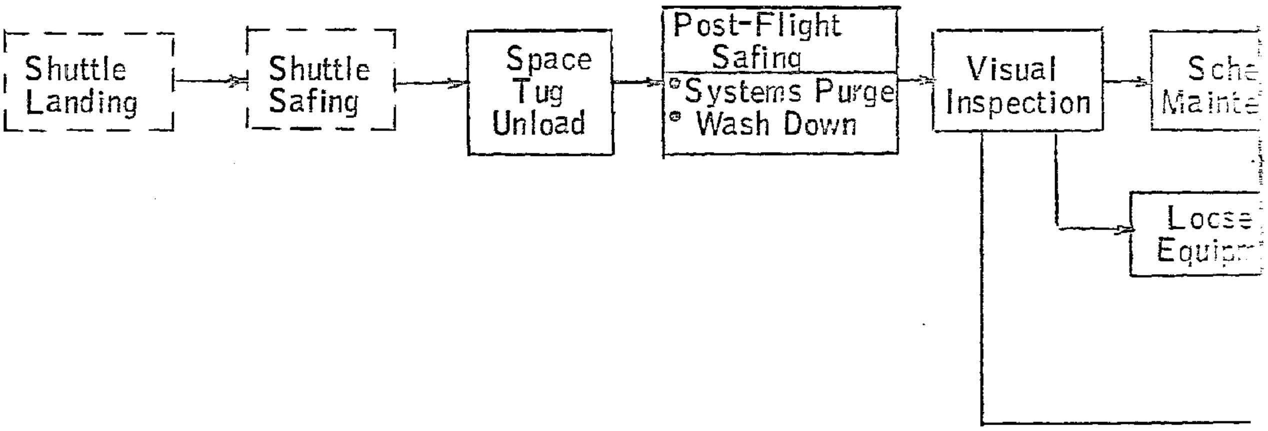

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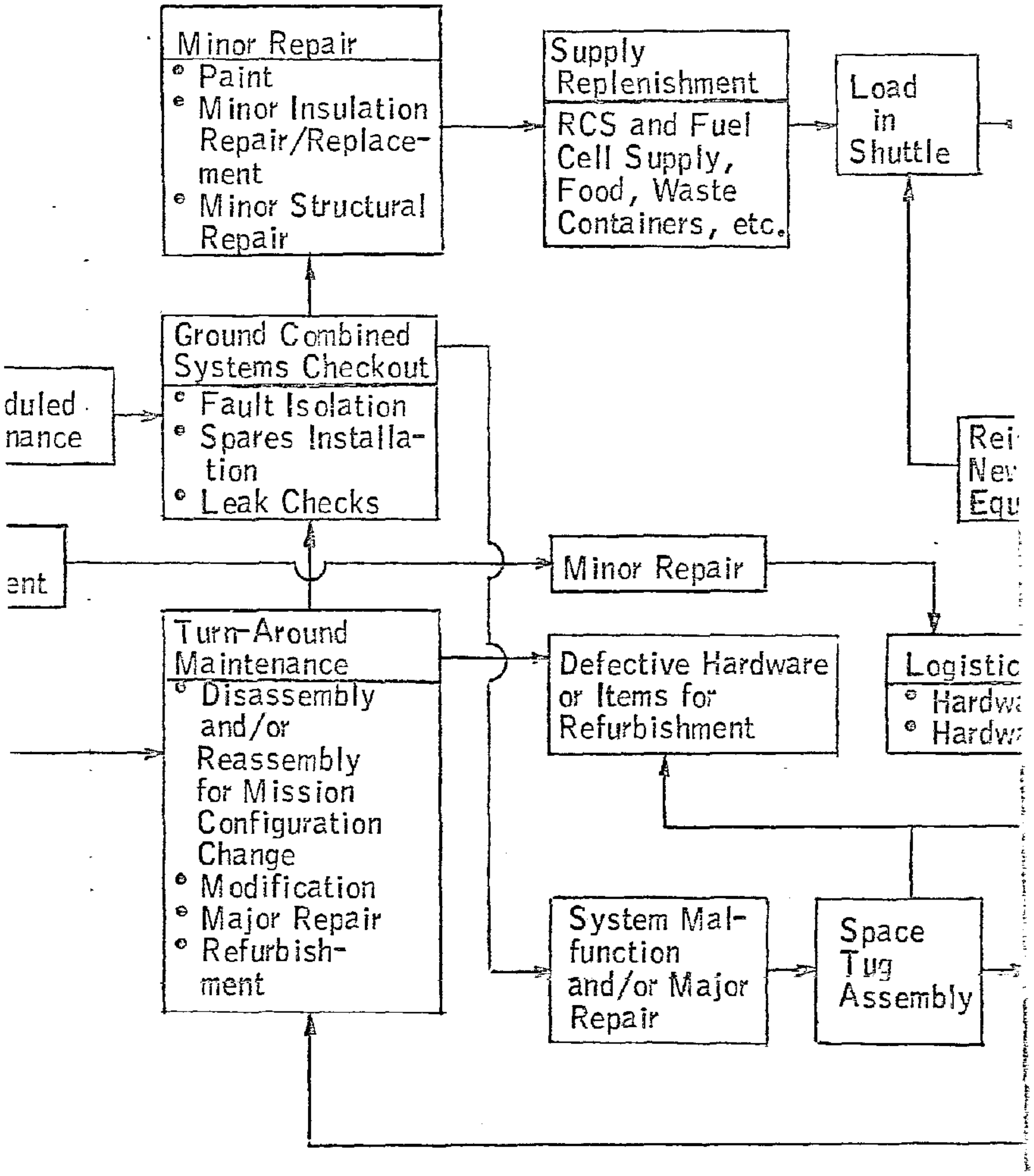

Figure 21.

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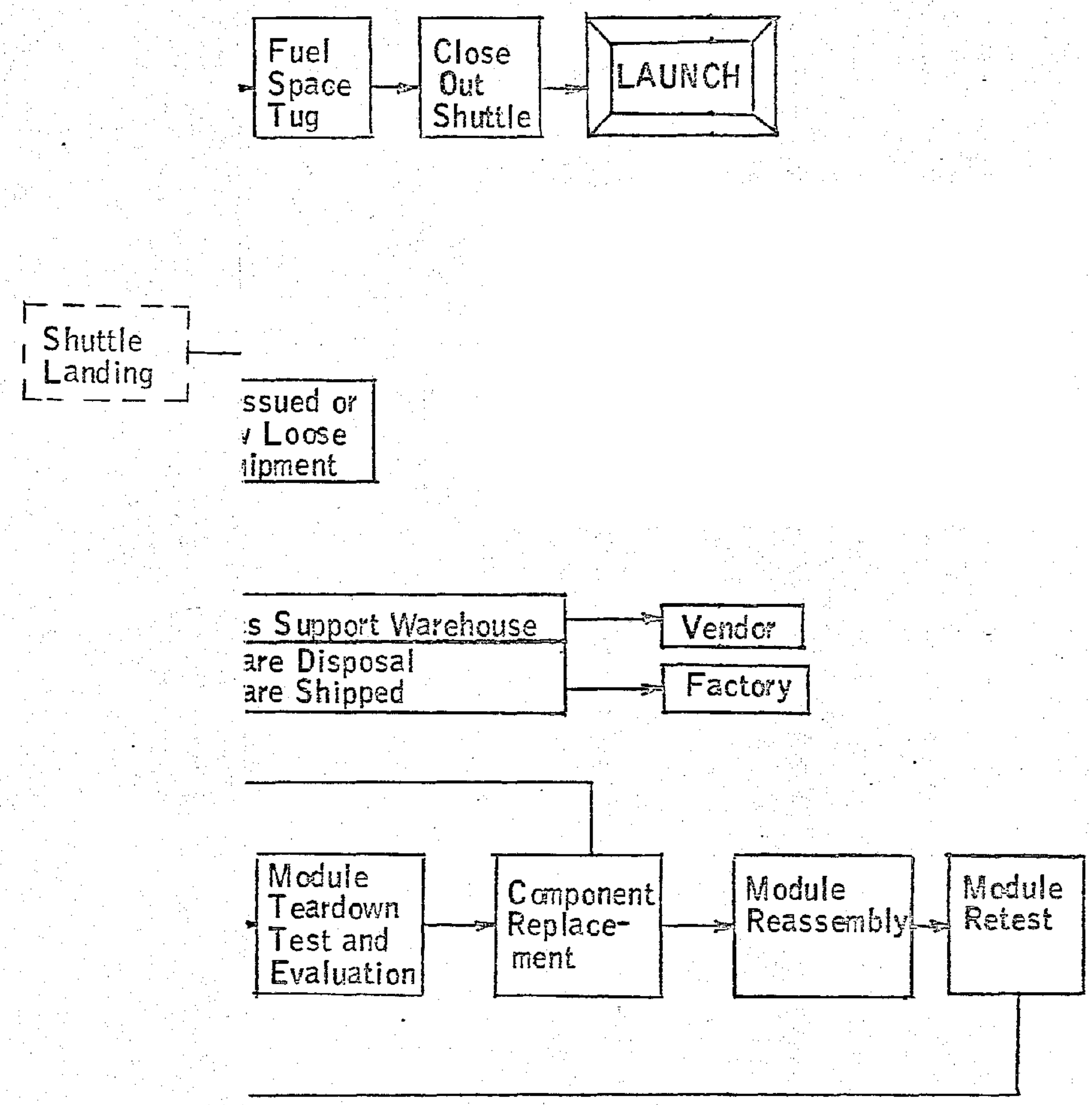


Turnaround Ground Operations for Relaunch

After visual inspection, vehicle configuration changes can be made to satisfy the requirements of the next mission. Ground combined systems checkout will be completed including the replacement of hardware. Loose equipment will be inspected, repaired, and returned to the warehouse after each flight.

Ground Operations Philosophy

Packaging requirements should be held to a minimum of new concepts by utilization of previous program experience. Existing modes of transportation will be used whenever practical. If special transportation containers become a requirement, ground support equipment and instrumentation designs should be common to other module requirements.

Module delivery to the site is assumed, while the loose equipment (manipulator and lunar lander gear) is shipped separately. This approach for shipment from the factory as opposed to an assembled vehicle and loose equipment should be the subject of a trade study to be accomplished during a subsequent phase of this program.

Assembly at the launch site will be assisted by good design practices (precision guide pins, etc.), for critical module interfaces during mating operations. All loose equipment not installed prior to launch will be fit-checked on the ground when mounting requirements are scheduled in space. The space tug will be loaded and unloaded with the shuttle in the horizontal position to minimize the need for special ground support loading equipment. The prelaunch and post-launch corrective maintenance of this vehicle will be limited to actual failed or damaged hardware replacement, unless the vehicle is scheduled for overhaul. The handling, the storage, and availability of replacement hardware and the repair of hardware at vendors or at the factory will be handled by existing logistics support practices and will be defined in the plan in a subsequent phase of this program.

Ground Operations and Facilities Requirements

Site operations will begin with the receipt of the delivered modules from the factory. Modules will be inspected visually for damage; and instrumentation records of a transportation crew, taped or charted data, will be evaluated for possible damage to the flight hardware. Loose equipment will be processed to a Logistics Support warehouse. Space tug modules will be processed to the Assembly/Maintenance area. This area should be the same area as that assigned to the shuttle or at least adjacent to the shuttle area. This requirement will minimize the need for special space tug transportation equipment at the launch site.

The Assembly/Maintenance area should have facility provisions that allow work to be accomplished on the space tug in both the horizontal and vertical positions. The launch site should have provisions to support this program with machine shop, clean room, quality control laboratory (calibration certification, nondestructive testing, etc.), and normal, as well as, environmental controlled storage facilities. In the event minor repairs to insulation, outer shell, or paint are required, adequate ventilation will be a requirement to avoid the need for an additional maintenance area to accomplish this effort.

To ensure the maximum amount of safety for hardware and personnel and to alleviate added weight problems, the space tug will be fueled at the launch pad while loaded in the shuttle. Provisions for loading, topping, and possible unloading of fuel will be a facility requirement at the launch pad. Extended periods of time at the launch pad prior to fueling may require purging equipment.

The space tug will be unloaded and post-flight safing will be accomplished in the same area in which the shuttle is safed.

Ground Support Equipment (GSE)

GSE not identified in this preliminary plan will be identified in total in a subsequent phase of this program.

Vehicle Refurbishment

Should the design life of the module be extended or when overhaul is contemplated, modules will be returned to the factory under the control of a Logistics Support system. In the event task teams are utilized for this effort, the Logistics Support function will negotiate team member requirements with the contractor facility. In either case, a Ground Operations Analysis group will define refurbishment and overhaul requirements with the concurrence of Engineering.

Further analysis in this area should be accomplished in subsequent phases of this program.

Vehicle and Module Inspection

Upon delivery of the flight hardware from the factory or from space by the shuttle, visual inspections and instrumentation records review will be performed to identify obvious discrepancies.

Ground Combined Systems Checkout

A ground combined systems checkout will be performed after initial modular assembly at the launch site or after return from a previous mission with the vehicle configuration remaining the same for the next mission. Only failed items will be replaced and discrepancies noted previously will be corrected before the space tug is routed to the launch pad.

Module Damage

In the event modules receive extensive damage because of handling in-flight conditions or loading into the shuttle, major repairs may involve complete refurbishment at the factory.

Component Discrepancies

Normal maintenance on the Space Tug will involve replacement at the component level due to failure or damage. It is anticipated that replacement hardware will be available as spares at the site.

Scheduled Maintenance

Calibration, lubrication, replacement of limited-life hardware, and replacement of age-sensitive hardware, etc., will be accomplished prior to ground combined systems checkout for relaunch.

3.4.4 Implementation and Management

Organization

The organization required for the full scope of ground operations support will be developed and incorporated in the plan during a subsequent phase of the program.

Schedules

Timelines and schedules will be developed and incorporated in the plan during a subsequent phase of the program.

Cost Avoidance

As the RST ground operations plan is subsequently developed in more detail, every effort will be made to minimize costs and still maintain the operational capability to support mission requirements. Some of the guidelines are as follows:

Utilize existing modes of transportation, facilities, and ground support equipment, wherever practical.

Evaluate each operation to avoid the necessity for new ground support equipment development.

Ensure that good maintainability characteristics are incorporated in the design of the reusable space tug (RST) in order to simplify ground operations, equipment, and technician training.

Stress commonality for support and handling equipment between modules.

Interfaces with Other Plans

Coordination with the design, manufacturing, and testing plans will continue through the follow-on phases of this program to ensure ground operations compatibility with other functional support requirements.

3.5 SUPPORTING RESEARCH AND TECHNOLOGY PLAN

3.5.1 Purpose

The supporting research and technology plan will provide NASA with information that identifies critical issues and technologies and those that require resolution for an orderly and timely tug development program. The material can be used in future tug development phase planning and in administrating the necessary supporting research activity for the tug in coordination with other NASA space programs and projects.

3.5.2 Scope

The plan encompasses the assessment of technologies appropriate to the subsystems level and is based upon a 1973-1974 technology base. It is related to the vehicle design concepts as identified in the tug Prephase A study. Emphasis is placed upon the maximum potential commonality of technologies and hardware with the earth-orbital shuttle, the earth-orbital space station, and other major NASA projects. For each important or critical item of required technology development, an identification and justification will be provided together with a brief plan that encompasses objectives, approaches considered most appropriate, and schedule considerations.

The major system and subsystem areas covered are:

Structure

Propulsion

Guidance, navigation and control

Electrical power

Environmental control and life support

Telecommunications and data

3.5.3 Approach

The general approach in creating this plan is to recognize and identify the reasonably probable technologies to be available as of 1973-1974 and to compare these with the system and subsystem tug requirements. Wherever possible, the technologies and actual hardware of EOS are utilized to save costs, because that major program will precede the tug program. Where the necessary technology required is clearly available even now, no further effort was expended except in those cases where some potential improvements are foreseen that promise substantial gains. Most important in the tug studies has been the vehicle sensitivity to inert weights, which tends to apply unusual pressure to the achievement of lightest possible systems and subsystems. Coordination with NR current studies for all major elements of the IPP ensures that the technologies from these other study projects (i.e., EOS, EOSS, OPD, CIS, RNS, etc.) are considered and related to those for tug.

Structure

Close attention to EOSS and EOS studies has been a key in the structural area. Experience with Apollo and Saturn S-II structural development also is important in considering available tug technology. These studies, currently more detailed in study phases than Tug, provide guidance and specific tradeoff and point design data. The approach taken has been to examine alternative structural philosophies, particularly related to load paths geometry, and to utilize for baseline design a simple and straightforward approach that would lead to high confidence for long space life.

Propulsion

Awareness of the first generation of O_2/H_2 engines typified by the RL-10 and J-2 engines has formed a base of knowledge concerning applications and supporting systems. A close relationship with the EOS propulsion studies has been maintained to ensure that fullest advantage of the related technology developments on that project are utilized. Particular attention is paid to the orbital maneuvering system (OMS) of the EOS, which has been studied with O_2/H_2 engines of appropriate size and type to permit not only technology transfer to the tug but, possibly, hardware applicability as well. Use of advanced engine technology of this type is necessary to ensure tug performance with reasonable size.

Likewise, the auxiliary EOS propulsion developments (studies) also are being seriously considered because of their direct applicability in principle or in fact to the tug. The extensive Phase A and Phase B studies of EOS auxiliary propulsion (RCS engines, thermal control, thermodynamic venting, cryogenic propellant insulation concepts, and auxiliary controls and mechanisms) are followed because of evident commonality for RST application. Continuous coordination with prime engine system vendors (Aerojet, Rocketdyne, and Pratt & Whitney) assures that data utilized are cross-checked and represent realistic, attainable characteristics.

Guidance, Navigation, and Control

The very sophisticated operations and equipment designed for the Apollo Program provided a strong base in this area. Contact with the later studies of the Skylab, EOS, EOSS, and other major IPP systems currently under study at NR, such as RNS, CIS, Lunar Orbit, and Surface Base, provides a substantial lead in defining required interfaces, available technology, and systems for long life with reusability. These projects have been consulted to establish reasonable interrelationships and useful fallout in both directions. This is particularly valuable in rendezvous sensors, data links, docking interfaces, etc. Sufficient redundancy is provided to ensure long life, with safe space operations under failure conditions when operating unmanned. With men aboard, additional display and control override is provided. Major support from a prime supplier (Honeywell) has been utilized to ensure a separate source of knowledge applied to the space tug G&N problem.

Electrical Power

The electrical power approach has been to build upon Apollo background and to utilize the extensive tradeoff study data generated in the Phase B EOSS and EOS studies to help in evaluating similar systems for the RST. Results of tradeoff and design studies are compared with those of other IPP systems also under concurrent study at NR. Considerations are minimum weight, reliability, and trouble-free long life with basic provisions for unmanned deep-space flight and add-ons or kits for manned applications.

Environmental Control and Life Support

The approach has been for maximum use of the experience gained on the Apollo CSM and LM programs. Subsequent and current work on the EOSS and EOS provides concurrent data on similar systems operating under similar conditions, including utilization of pertinent vendor contacts made under these other programs at NR. The advantage of this approach is that it leads to greater confidence in study results as well as to more extensive coverage of the variables present.

Different candidate systems were compared to determine which promises lowest weight with adequate safety, volume, cost, and flexibility. Unmanned automated flight is basically provided for 7 days in space with add-on kits for manned and longer-duration missions.

Telecommunications and Data

A strong background of Apollo experience again was utilized as a base. Current NR studies of EOS, EOSS, and other IPP elements provide a wide knowledge of complex interfaces, tradeoff study results, and design data. Maximum flexibility for alternate missions, manned and unmanned missions, deep and near space operations, and maximum autonomy have added complexity to the design considerations. This approach has required largely self-sufficient G&N sensors operating either automatically or on command from the nearest appropriate IPP command element such as EOS or space station.

3.5.4 Technology Summary

Table 6 summarizes the technology considerations currently anticipated for the systems and subsystems.

It should be noted that even with the emphasis on long life, autonomy, flexibility, and high performance, a reusable space tug (RST) could be built without any special new technology developments. However, they could provide greater assurance of program success or achievement of high-performance and long-life goals. In some areas, such as propulsion, the

Table 6. Supporting Research and Technology Summary

System and Subsystem Critical Functions and Components	Most Significant Baseline Requirements	Principal Source of Required Technology	Substitutes or Alternatives and Penalties	Potential Baseline Improvement Possibilities
Structure				
Tank skirt supports	High strength and weight, low heat conduction, easy fabrication	Apollo, EOS, Industry development	Use heavier titanium or glass epoxy	Develop boron-epoxy manufacturing techniques
Propulsion				
Main propellant thermal control				
Multilayer high performance insulation Propellant line and tank support heat blocks Thermodynamic vents	Adequate outgas capability Thermal performance low weight-long life serviceability Minimize boiloff Efficient propellant weight Minimum losses	EOS, RNS, CIS, others	No adequate substitute (Design problem)	Improve manufacturing methods, application, and test methods
Propellant location control				
Zero-g provisions	Efficient propellant management Thermal interaction	Apollo, EOS, others	(Design problem)	Concept testing and evaluation in space
Main propulsion				
O_2/H_2 engine	High P_c, A_e Throttling (lunar lander), childown time, I_{sp}, reliability, low cost, weight, low NPSH	EOS (OMS)	RL-10 existing engine	
Electrical power				
O_2/H_2 fuel cell power source	Long life and space maintenance, variable energy demands, low cost, low weight	EOS (also CIS, RNS, etc.)	Heavier and more external protrusions: chemical dyn. APU, solar-cell arrays, batteries	Lower cost, weight with continuing development
Power cabling	Low weight, low loss	No special source	None	Potential decrease in weight - flat conductors or tube conductors
Environmental control and life support				
Temperature and humidity control atmospheric thermal loop	Long life and space maintenance, crew size flexibility, habitability criteria, low cost, add-on kits, low weight, power	Apollo/Skylab	None	Possible refinements or new developments
Waste storage and disposal	No interior contamination, external dump constraints, storage weight and volume	Skylab	External dump or reprocessing	None known

Table 6. Supporting Research and Technology Summary (Cont)

System and Subsystem Critical Functions and Components	Most Significant Baseline Requirements	Principal Source of Required Technology	Substitutes or Alternatives and Penalties	Potential Baseline Improvement Possibilities
Auxiliary control				
O_2/H_2 throttlable engines	Long life and space maintenance, size, location, quantity, stowability, minimum pulse	EOS	Storable bipropellant - less flexibility, off-load penalty. Fixed thrust engines	Possible development for shorter minimum pulse duration
Guidance and navigation				
Strapdown gyro inert measurement unit	Long life and space maintenance, software capacity, accuracy and drift, low weight, power, low cost	EOS, other projects	Heavier and less reliable, gimbaled platform	Further advanced state-of-art strapdown electrostatic
Autonomous Navigation	Accuracy and low propellant budget, software capacity, sensor accuracy, mission constraints, low cost, independence	No special source-potential commonality with RNS, CIS.	More ground support	More advanced sensors
Communications and data management				
S-band transmitter and antennas	Long life and space maintenance, small antenna size, other vehicle cooperation	EOSS extrapolation	Delete parab ant - limit data rate, lower weight	Lower weight with higher frequencies: Ku (15-17 gHz) Ka (25-28 gHz) V (46-56 gHz) Requires major cooperation and coordination
Plated wire operational and mass memories	Autonomous navigation capacity, housekeeping capacity, long life and space maintenance, low weight, cost	EOSS extrapolation	Delete autonomous navigation. Use heavier magnet cores	Possible further advanced state-of-art improvement coming
Digital data buses	Acquire, continue and test required, redundant paths, data rates, wire weight	EOSS extrapolation	Use heavier switching, dedicated wiring, independent subsystem processing	Possible use of flat conductors or tube conductors

Table 6. Supporting Research and Technology Summary (Cont)

System and Subsystem Critical Functions and Components	Most Significant Baseline Requirements	Principal Source of Required Technology	Substitutes or Alternatives and Penalties	Potential Baseline Improvement Possibilities
Rendezvous and docking sensors				
Laser relative state vector measurement Television and vision visual aids	Passive vehicle cooperation, light conditions, link data rate, cost, power	EOSS, other projects	Heavier microwave radar, visual aids	Further improved visual aids
Landing sensors				
Microwave radar state vector measurement Landing site beacon Television and vision visual aids	Graphic display software, light conditions, link data rate, cost, power	Apollo/LM	None	Possible developments for lower cost, power
Manipulators	Reach dexterity, link data rate, vehicle and target attachment, crew controls, sensors	Industry	Crew, EVA, RMU	Compatible satellite design, docking provisions
Docking structure				
Neuter docking system	Envelop reqmts low weight, cost, reusability, crew cargo access, dynamic requirements	EOS, EOSS, Apollo, RNS, OPD, CIS, etc.	Use Apollo system, EVA/soft docking	Relax structure reqmts by precise docking Minimize number of ports Reduce size
Active thermal control				
Cooling lines and pumps	Long life and space maintenance, degree of passive thermal, complexity, weight, power	Apollo extrapolation	None (Design problem)	Possible improvements for lower cost, weight (i.e., use of heat pipe)

RST will be depending upon the EOS program for the necessary system developments. Wherever there is doubt about the direction to be taken by EOS, a plan for the necessary technology is included in Section 6.0. Another general consideration is the need (on all future space programs) to develop more knowledge and experience with long-life reusable systems and components. A separate program on this subject appears to be in order because of its diversity and broad application to all types of systems, (as proposed separately by NR).

3.5.5 Integrated Technology Development Schedule

Figure 22 shows the estimated timing requirements for the RST technology development items.

3.5.6 Supporting Research and Technology Descriptions

Each item shown on Figure 22 is discussed in this section. Many of the items, however, particularly in the subsystems area, do not present formidable or complex development problems; for these, no technical plan or schedule is given.

Structures Supporting Research and Technology

Boron-Epoxy Unpressurized Structure. Analysis has shown that use of BE composite in lieu of titanium alloy for construction of the primary structure attached to the LH_2 and LO_2 tanks will increase the payload capability of the propulsion module by 5 to 10 percent. This arises from the very high strength/weight ratio of this material and its low thermal conductance. Experimental development of aircraft structural parts has been accomplished, but construction of large diameter structures as required for the RST would require development of techniques and tooling. The development of this technology would ensure availability of additional weight margin.

The objectives of the development task will be to (1) verify by test that a flightworthy BE shell structure can be fabricated for RST application, and (2) develop fabrication techniques and specifications. The technical approach will be to:

1. Utilize existing development data on BE tubular struts and on aircraft wing panel sections and design edge fitting test articles.

2. Test and verify edge fitting design.

3. Design and test full-size BE shell subjected to loadings simulating critical flight phases for the RST.

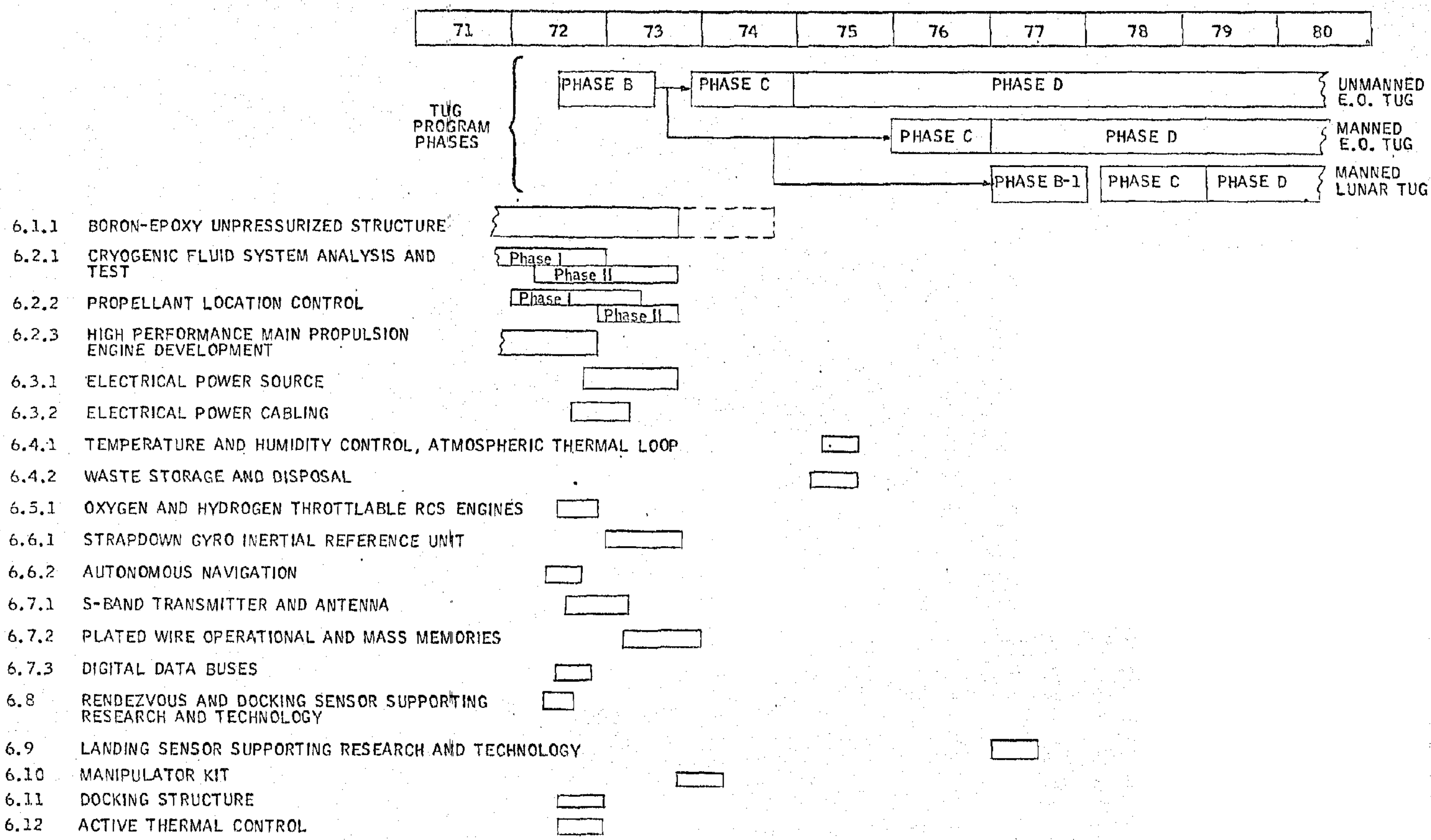


Figure 22. Integrated Technology Development Schedule

The schedule for task completion is estimated to be 2 years. It is also estimated that the time to produce flight hardware would be significantly greater than for hardware of conventional materials such as glass-epoxy and titanium. The availability of BE structures could be considered as a growth item for some future change point in the RST program. For incorporation in the RST mainstream, the research should be accomplished prior to Phase C.

Propulsion Supporting Research and Technology

Cryogenic Fluid Systems Analysis and Test. Many industry studies have been conducted for the analysis and design of high-performance cryogenic tank systems. Laboratory tests on part scale models have explored system performance but within prescribed and limited conditions, although the service life and maintainability of such systems has not been proved. While the basic RST is to be space-based, there will be pressure to operate alternatively as a ground-based or partially ground-based system. In regard to multilayer cryogenic insulation design, a space-based concept is relatively straightforward, because the insulation is always operated in deep vacuum wherein layer-to-layer gas conduction is not a problem.

A ground-based concept requires that the multilayer insulation be "bagged" and purged with dry gas (nitrogen or helium) while on the ground, be vented to space for outgassing during ascent, and must be completely evacuated to less than 10^{-4} Torr within a short time after achieving orbit. Upon mission completion, the insulation must be provided with dried (no moisture) air or gas under pressure to dive-vent the insulation during descent into the atmosphere. While the EOS has this problem and will therefore provide information applicable to the RST, their solutions may be different as a consequence of differences from the RST in their profile, timing, configurations, and weight criticality.

Thermal performance predictions of complete cryogenic thermal protection systems inclusive of multilayer insulations and their hardware attachments, conductive heat blocks for plumbing, tank supports, electrical and instrumentation cables, etc., have historically proven to be as much as 200 to 500 percent lower than has been obtained in large-scale tankage system tests. The additional potential requirements for the RST reusability and endurance of reentry environment will impose even greater technological developments. Other new subsystem provisions that will require proof of feasibility by large-scale tank tests are: (1) insulation purge and venting systems to isolate the insulation from air and moisture throughout the earth-bound cryogenic life cycle of the vehicle, providing rapid ascent pumpdown to a vacuum pressure environment of 10^{-5} mm Hg or lower; (2) insulation repressurization system to provide moisture and atmospheric separation of the insulation upon return to the earth for earth-based systems; (3) tank venting under zero-g environments by means of passive thermodynamic process; and (4) cryogenic fluid thermal destratification. The close functional interdependence of the previously mentioned subsystems make it necessary that feasibility tests be conducted on a large-scale cryogenic tankage system consisting of all the previously noted systems.

The feasibility of an RST liquid hydrogen tankage system shall be established inclusive of its cryogenic thermal protection subsystem, insulation venting and repressurizing system, thermodynamic venting system, and cryogenic destratification subsystem to satisfy the extreme performance, reusability, and long-term cryogenic storage requirements of the RST.

Technical Approach (Phase I — Component Tests). Design, construct, and test components and elements of the cryogenic tankage system to: (1) demonstrate concept structural integrity, materials compatibility, and reusability performance; (2) establish feasibilities and concept selection data; and (3) formulate detail design information for the large-scale cryogenic tankage test article. Ascent-descent cryogenic hydrogen calorimetric tests will be conducted on a small-scale tankage system (3-foot diameter by 6 feet long) inclusive of insulation, purge and venting provisions, minimum heat transfer tank supports, and plumbing shall be performed as well as combined centrifugal force and vibration (with cryo hydrogen) tests of the insulation installation concepts in a vacuum environment. Complete this phase prior to the midterm of Phase B RST studies.

Technical Approach (Phase II — Cryogenic Tankage System Test). Design and construct a large-scale model of the tug cryogenic propulsion module hydrogen tankage system with complete subsystems; formulate a test plan, and perform ascent-descent thermal and pressure environmental profile tests and simulated space thermal-vacuum tests on the large-scale tankage system. Complete all tests prior to Phase C studies.

	Schedule (Months)											
	2	4	6	8	10	12	14	16	18	20	22	24
Phase I - component tests												
Phase II - cryogenic tankage system tests												

Propellant Location Control. Consideration of the combined problems of tug cryogenic and gaseous fluid pressurization, venting, location control, line transport, and conditioning for long-term space operations in a near zero-g environment mandates the use of undeveloped and heretofore untried concepts. Sustained zero-g fluid heat transfer and thermodynamic processes require correlation with test data, most of which must be obtained in an orbital flight environment, because sustained near zero-g simulations exceed ground facility capabilities.

A design and analysis capability shall be developed for fluid subsystems used for the storage, conditioning, location control, and transport of cryogenic and gaseous fluids for the RST main propulsion, ACS, and fuel-cell systems.

Technical Approach (Phase I — Concepts and Design Analysis). Establish concepts and develop analysis tools for design of the following cryogenic and gaseous fluid subsystems and functional operations:

Pressurization

Thermal destratification

Thermodynamic venting and subcritical storage

Capillary retention and pump cryogen location control

In-orbit cryogen transfer and storage

LO_2 regenerative cooling and LH_2 vapor-cooled shields

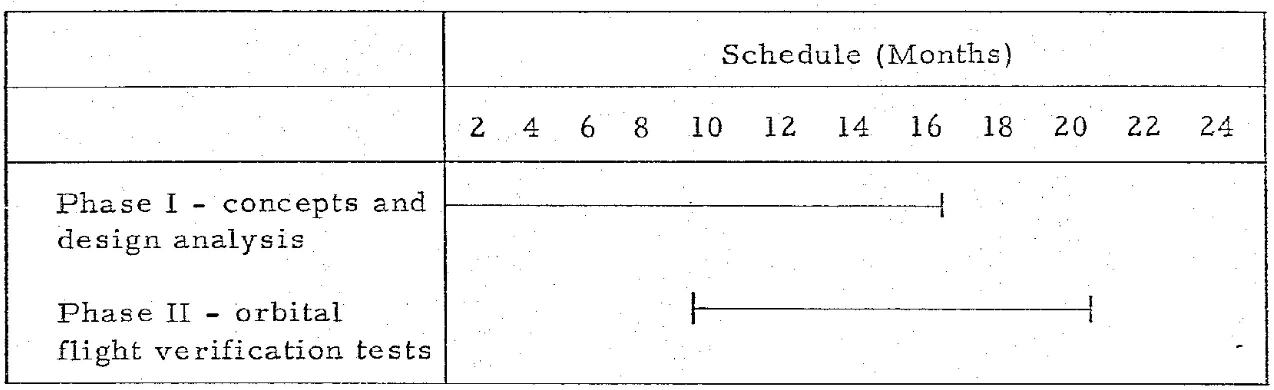
Cryogen slosh and feed out thermo-hydrodynamics

Zero-g fluid gauging techniques

Supercritical storage and fluid conditions

The analysis tools will incorporate capabilities to establish sizing, cyclic operational modes, transient responses, concept trades data, mission timeline data, and subsystem operational interface effects. Laboratory tests shall be conducted to establish empirical relationships in support of analysis capability development.

Technical Approach (Phase II — Orbital Flight Verification Tests). Subscale models of the cryogenic and gaseous fluid subsystem shall be design and constructed for orbital flight tests to be conducted as part of or in conjunction with the Skylab orbital test program. A test plan shall be formulated inclusive of instrumentation requirements; and flight test data shall be correlated with predictions and computer programs shall be upgraded as necessary to develop analytical tools for tug fluid system hardware designs. Subsystems of the tug main propulsion, ACS, and fuel-cell cryogenic tankage systems shall be included in three subscale test articles (i.e., subcritical, supercritical, and transfer tankage). Acquisition of subcritical and supercritical cryogenic storage and scaling data and fluid transfer for tankage depletion and orbital fill experimentation requires a minimum of three tankage system test articles. In addition to special experimental investigations of zero and near zero-g heat transfer and thermodynamic phenomena, simulations of the prelaunch, launch, and orbital phases of the RST mission shall be conducted. All work should be completed prior to Phase C studies.



<u>High Performance Main Propulsion Engine Development</u>. O_2/H_2 engines incorporating high chamber pressure, low NPSH, high area ratio, and resulting high specific impulse are being considered currently in the EOS development studies. The EOS orbital maneuvering system (OMS) requires an advanced high-performance engine with characteristics basically similar to those required in a tug engine. Thrust levels on the two programs (RST and EOS) are not very critical and probably can be coalesced by properly clustering and adjusting requirements to match. Because performance is a critical item in the tug design mission, the highest possible propulsion performance is required. This tends to require that the area ratio be very large, on the order of 300 to 400:1, which may not be tolerable in EOS because of geometry problems. Engine throttling may be required for a lunar lander. These requirements tend to result in a special version of the basic OMS-type engine. Because OMS requirements are not well established at this time, it will be important to track this engine development to make certain that it will be developed in time for a tug, and that the tug and the EOS applications are mutually compatible.

The basic approach to propulsion for the RST requires the development of a high-performance new engine. Coordination with EOS program personnel at NR, MSC, and at the engine suppliers indicates that the EOS OMS propulsion engine is likely to be of the basic type and size required also for the RST in clusters of two to four engines. It also has been determined that the requirements for the two systems appear compatible and mutually adjustable within reasonable limits. Therefore, in the evolution of both programs, it will be important to try to maintain a flexible posture so that the one engine development will basically suffice for both requirements. The engine as modified for RST use must be available early in Phase D, and a thorough compatibility check should be accomplished earlier in mid-Phase B studies.

Electrical Power Subsystem Supporting Research and Technology

Electrical Power Source. The prime candidate power source for the RST fuel cells is being developed for the EOS program. A different-sized cell may be optimum for the RST, however. Each cell requires a system for regulating input reactants, output water, and heat removal that must be mated to the specific cell to be used. Appreciable increase in weight occurs by using nonoptimum equipment, thus, a tailored design effort is indicated.

The RST power profile shall be determined for the missions limiting the electrical power subsystem. In conjunction with suppliers, the optimum equipment shall be selected by conducting tradeoffs between performance, availability, and cost. Equipment requiring additional development shall be determined, and development funding shall be provided if necessary to ensure availability for the RST. The probable capability shall be determined by the end of Phase B.

Electrical Power Cabling. Power cabling represents a substantial RST weight item. Although no great state-of-the-art advancement is foreseen in cabling technology, the advantages of various potential techniques should be investigated because of their weight-saving potential. Appreciable weight also could be saved by ensuring that proper routing is designed into the RST harness assemblies.

Investigate flat ribbon cabling and tubular conductors for potential application. Generate wiring harness layouts that minimize wire length, and propose equipment location changes to reduce wire weight. This effort should be conducted in Phase B.

Environmental Control and Life Support Subsystems Supporting Research and Technology

Temperature and Humidity Control, Atmospheric Thermal Loop. These two functions account for a major portion of the total ECLSS weight and power consumption. Although Apollo technology is adequate, significant weight and power reductions are foreseen with further research and design.

Establish the requirements for preferable cabin temperature and humidity ranges under normal and emergency operating conditions. In cooperation with other crew module functions, establish the range of heat input rates to cabin atmosphere. Using these ranges, determine the system requirements. In conjunction with suppliers, conduct trade studies and design candidate systems. Support the development of promising concepts if necessary to ensure tug availability; provide study results by end of Phase B.

Waste Storage and Disposal. Biological and other crew-associated solid waste accumulated during a mission presents a storage problem and a potential health hazard in the confined quarters of the RST crew module; yet, the dumping of the solid waste creates a pollution and safety problem. More research and development is needed for problem solutions. Readily suggested approaches include waste compaction, combustion, and chemical reduction.

An industry survey will be conducted to determine appropriate methods for waste disposal, sterilization, and compaction. Requirements shall be set for weight, volume, power, and design of the most promising methods, which shall be recommended by end of manned tug Phase B studies.

Auxiliary Control Subsystems Supporting Research and Technology

Oxygen and Hydrogen Throttlable RCS Engines. The wide range of vehicle mass and moment of inertia encountered by the tug, together with the inherently large minimum pulse duration of gaseous oxygen and hydrogen propellant control, lead to adjustable thrust levels to meet the various tug ACS requirements. A minimum number of jets that have limited throttling capability was selected over a system using more jets of various sizes. Similar technology may be required for EOS, but the hardware size is much larger. Because no engines in the required thrust range have previously been developed with O_2/H_2 throttling capability, this development is needed.

From RST studies, requirements will be set for rated thrust level, throttling range, and feedline details. In conjunction with suppliers, development of appropriate engines shall be funded if necessary so as to be available for the tug. Design information will be provided to support Phase B studies.

Guidance and Navigation Subsystem Supporting Research and Technology

Strapdown Gyro Inertial Reference Unit. Recent technology advancements have led to the use of strapdown IRU systems in preference to the Apollo-type gimbaled platform. The result is a simpler, lighter weight system that relies on software rather than on electromechanical computation. Technology in this field is progressing so rapidly that large weight savings may be realized if advantage is taken.

The effort consists of establishing accuracy and reliability requirements and then assessing new candidates selected from existing or breadboarded systems, which could be developed in time for the tug. The possibilities for RST use of G&N systems beyond the 1973-1974 state-of-the-art (or EOS) should be assessed before the Phase C tug study begins; otherwise, it can be considered a growth item.

Autonomous Navigation. In the interest of reducing future ground installation costs, autonomous navigation is desirable. The impact of this requirement on tug systems lies in the areas of software capacity and guidance sensor accuracy. Inaccurate, less complex sensors lead to either larger midcourse corrections and greater propellant expenditures or frequent and expensive support from earth receiving stations and computer facilities.

A trade study in this area should consider the weight required for a high precision G&N system, electrical power, and reactants to compare with weight characteristics of an inexpensive, low-precision G&N system with its consequential midcourse correction propellant and ground support expense. The result is a more definitive set of G&N requirements and viable candidate systems. The data from this study should be available early in Phase B because of their influence on design weights.

Communications and Data Management Supporting Research and Technology

S-Band Transmitter and Antenna. The current selection of RST communications equipment meets the requirements for IPP element compatibility. It also is partially common with EOSS equipment. Recent technology advances show, however, that transmitters, receivers, and parabolic antennas may be reduced in weight and power demand if a higher frequency is used. Three range allocations are available for IPP element use: Ku (15 to 17 GHz), Ka (25 to 28 GHz), and V (46 to 56 GHz).

Equipment availability for use at these frequencies should be assessed for all IPP elements. This effort should be shared on a cooperative basis by all interested programs. The results of such a study should be available by late in Phase B.

Plated Wire Operational and Mass Memories. The use of plated-wire computer memories has been proposed for EOSS, although development on these components is several years from completion. Use of plated wire offers sufficient enough weight and power savings to appear to justify development funds. The unit size of EOSS memories appears to be too large for the RST, however, and would require a separate development for input and output circuits and packaging. If the funding from other programs does not materialize for plated-wire development, the RST program should either provide funds or accept the consequential weight increase from the use of an older technology.

The requirements shall be determined for simultaneous processing, computation rate, double precision, memory capacity, storage capacity, access time, and redundancy for all tug using functions. The functions include all electromechanical subsystems, but principally guidance and navigation. These requirements shall be provided to qualified vendors, and their ability shall be evaluated to produce the required equipment (providing development funds if necessary to ensure availability for the tug) by the end of Phase B.

Digital Data Buses. The selected signal distribution method for the RST uses redundant digital data buses which carry coded and addressed data to remote terminals. These terminals, the remote acquisition, control, and test units (RACU), are the only signal input and output interfaces with all subsystems equipment. The method saves an appreciable amount of wiring weight over conventional dedicated-wiring systems, but creates additional software design problems. The buses must carry high and low data rate information, and must accept priority and emergency information as established by the computer.

Further effort will be required to determine whether a single redundant set of buses will be sufficient, or whether the signal distribution task should be divided between two or more sets. These divisions may be between high and low data rate demands, between unrelated user subsystems, or between normal and priority demands. Results of this study should be available by mid-Phase B.

Rendezvous and Docking Sensor Supporting Research and Technology

Status and Justification. The primary docking sensor on the RST is the laser sensor. Data from the sensor feeds the automatic docking system and also is displayed to the pilot. Manual override by the pilot is necessary for safety. To control the operation the pilot requires separate visual indications of docking parameters. To make the RST a versatile vehicle, docking operations should become a commonplace procedure. These operations would be severely constrained if limited to certain sun angle conditions.

The optimum sun angles produce an illuminated target with no shadows that confuse the pilot. Sunlight on the active vehicle sensors may cause an approach abort. Docking operations should not be encumbered by these constraints. To circumvent the problems, better docking visual aids must be developed. These would work in conjunction with lasers but would give the pilot all of the information he needs to perform a manual docking operation. The problem applies to unmanned as well as manned tugs, because both use pilot backup either directly or remotely.

Technical Objectives. Docking visual aids shall be devised and developed for use with either direct pilot vision or television (remote pilot). The aids would provide unambiguous range, angle, and rate data to the pilot under any sun angle conditions.

Approach. Requirements shall be set for allowable errors in range, angle, and rate visual measurements within the docking structural requirement limits. Postulate Candidate aids shall be postulated that potentially meet the requirements. Visual simulations shall be conducted under predicted lighting conditions to test and select candidates. The study should be carried out in coordination with all tug potential targets. To permit the generation of mission and system requirements for the RST, the docking aids and the resulting docking philosophy should be resolved by no later than mid-Phase B.

Landing Sensor Supporting Research and Technology

Status and Justification. To avoid the cost of waiting for narrow lunar landing windows and to permit landing under any sunlight conditions, improved visual aids are necessary. These aids also should alleviate the problems of surface obscuration by dust and obstacle identification. If these problems are solved, then landings may be conducted on a safe and regular basis. The visual aids are partly a data source backing up the landing radar and partly the primary means of identifying the predetermined landing site and avoiding large obstacles. A television graphical display system has been proposed for this purpose but has an uncertain capability under poor lighting circumstances similar to natural vision.

Technical Objectives. The technical objectives are established to devise and develop landing visual aids necessary for safe and precise lunar landings under any lighting conditions.

Approach. Requirements shall be set for obstacle size resolution, dust penetration, and touchdown velocity and angle and angular rate errors. Landing shall be simulated using realistic lighting and dust obscurance conditions, and studies shall be conducted to assess vision, television, and television graphics limitations and their potentials as candidate visual aids using basic simulator facilities at Langley or MSC.

To permit mission planning and lunar landing propellant budgeting, the system should be defined by lander mid-Phase B-1.

Manipulator Kit Supporting Research and Technology

Status. One of the potential RST functions is to physically contact satellites, modules, or parts for maintenance, assembly, or retrieval purposes. This may be accomplished by either normal docking operations (if the satellite has docking provisions) or by grappling with manipulator arms. (In general, docking should be considered the normal mode in the future for satellites.) The weight, complexity, and constraints of a manipulator dictate that it be developed as an add-on kit to avoid substantial scar weight on the tug. Several contractors in the industry, including NR, have developed manipulators that could (with modifications) be used in an early or interim kit. No significant problem is foreseen in RST development for kit use, although the impact on satellite design is obviously major. It is believed that satellite servicing or retrieval should be accomplished by hard docking. While this feature adds weight to the satellite, the advent of the EOS tends to remove former tight payload weight constraints encountered with the expendable booster systems.

Objectives. RST interface and design requirements shall be developed for use of manipulator kits. These should be completed by mid-Phase C.

Docking Structure Supporting Research and Technology

Status and Justification. One candidate choice of docking systems for all IPP elements is the neuter docking concept of the EOSS, which allows either vehicle to be active or passive. The structure incorporates a center passage large enough (5-foot diameter) for ready crew or cargo transfer and may have pressurization sealing provisions. While the docking system is versatile, it represents a very large weight increment (up to 750 pounds). This is a significant fraction of the tug inert weight, particularly if more than one is used per vehicle. For vehicles such as the tug that undergoes large delta-V maneuvers and for which propellant resupply is a problem, this weight increment is costly. Furthermore, many docking interfaces do not require pressurized transfer, and a simpler, smaller mechanical docking device will suffice. The Apollo docking system is lighter and appears to be structurally sufficient for use with the tug (except for crew module pressurized transfer). A possible solution to the weight problem (and one which reduces cost) is to use a combination of neuter and Apollo docking systems where requirements demand.

Technical Objectives. Requirements shall be examined for docking with all IPP elements. A best configuration shall be determined for mechanical connections with minimum weight penalty to the maneuvering vehicles. It shall be determined if the EOSS concept for pressurized transfer should be modified to reduce weight. This matter should be resolved before mid-Phase B.

Active Thermal Control Supporting Research and Technology

Status and Justification. All RST avionics components will have temperature requirements that can be met by use of an active thermal control system. The system uses circulating fluid (coldplate) interfaces to remove heat from these components. The fluid system eventually carries the heat to external space radiators. Redundant fluid lines and coldplates are necessary, because their failure could damage all electronics equipment on the line. The design of this system and the investigation of alternative approaches (heat pipes, boilers, etc), could have a significant influence on vehicle inert weight and the probability of mission success.

Technical Objectives. The active thermal control subsystem definition is a design and analysis problem that should receive additional attention in order to influence RST design by mid-Phase B.

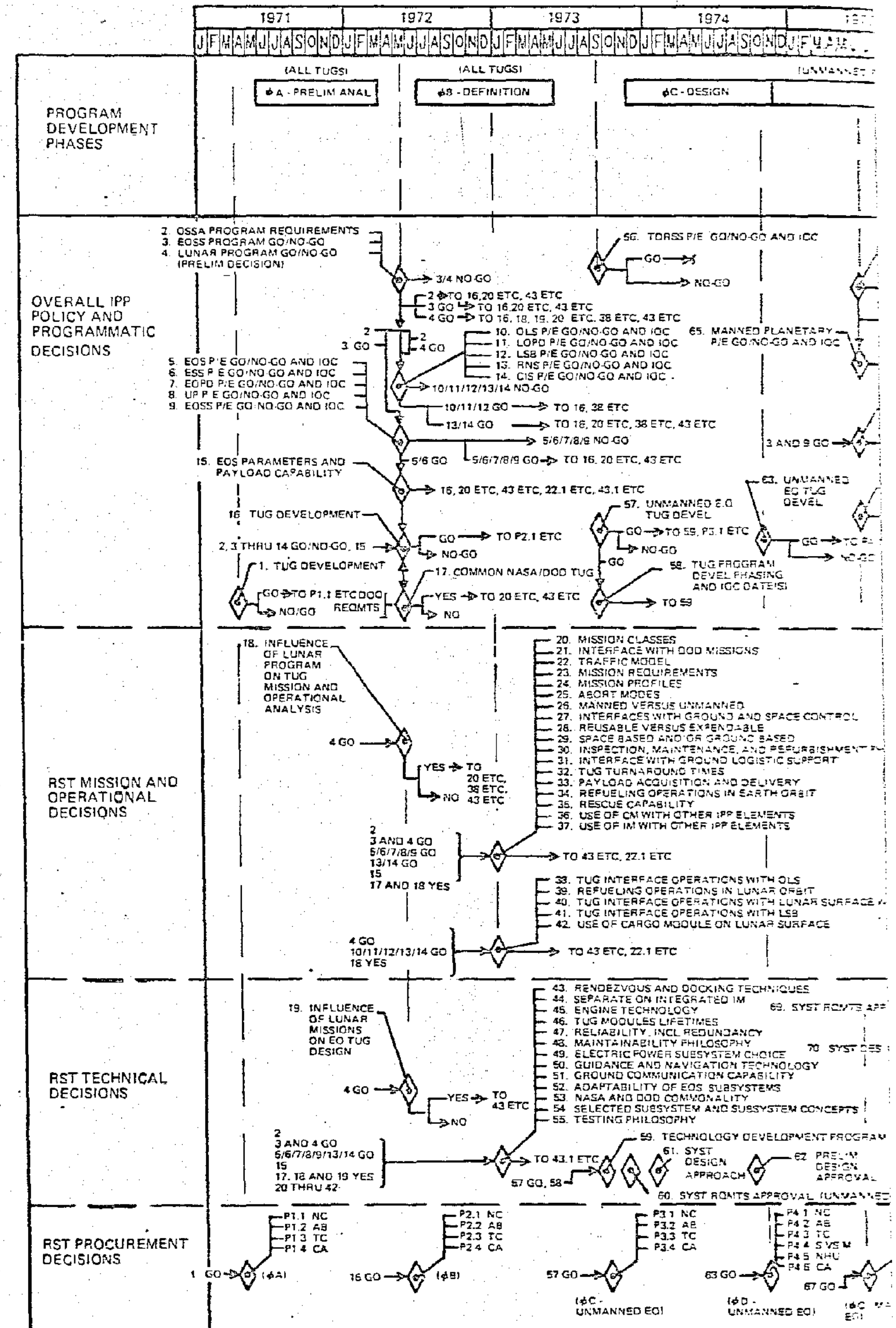
4.0 DECISION MATRIX

A decision matrix (Figure 23) includes NASA key decisions and decision points established in regard to the reusable space tug study. The matrix was derived from an analysis of the work breakdown structure (Figure 2), the requirements of Phase Project Planning Guidelines (NASA NHB 7121.2) and consideration of the results of mission, operational, and technical studies conducted during Contract NAS9-10925. The matrix is consistent with the program development schedule (Figure 3).

It will be noted that the matrix covers four decision categories: (1) overall NASA integrated program plan policy and programmatic decisions, (2) reusable space tug (RST) mission and operational decisions, (3) RST technical decisions, and (4) RST procurement decisions. The matrix also covers the three major development categories: (1) unmanned earth-orbital tug, (2) manned earth-orbital tug, and (3) manned lunar tug. The time period will extend from prior to the start of Phase A to the IOC dates for all three major development categories. The decision points are identified with respect to both the program development phases and calendar dates.

The matrix depicts the anticipated sequence of decisions, go and no-go aspects, decision dependencies, and interfaces. The matrix provides for traceability within and between decision categories. This decision matrix could be incorporated into a computer program if desired.

FOLDOUT FRAME 1



LEGEND

- ◊ – NUMBER AND NAME OF DECISION
- ◊ – NASA KEY DECISIONS, NUMBERED SEQUENTIALLY
- φ – PHASE
- AB – APPROVED BIDDERS
- CA – CONTRACT AWARD
- CIS – CHEMICAL INTERORBITAL SHUTTLE
- CM – CREW MODULE
- EO – EARTH ORBITAL
- EOPD – EARTH ORBITAL PROPELLANT DEPOT
- EOS – EARTH ORBITAL SHUTTLE (TWO STAGE REUSABLE)
- EOSS – EARTH ORBITAL SPACE STATION
- ESS – EXPENDABLE SECOND STAGE (OF EO SHUTTLE)
- IM – INTELLIGENCE MODULES
- IOC – INITIAL OPERATIONAL CAPABILITY DATE
- IPP – NASA INTEGRATED PROGRAM PLAN
- LOPD – LUNAR ORBITAL PROPELLANT DEPOT
- LSB – LUNAR SURFACE BASE
- NC – NUMBER OF CONTRACTS
- NHU – NUMBER OF HARDWARE UNITS TO BE PROCURED
- OLS – ORBITING LUNAR STATION
- OSSA – OFFICE OF SPACE SCIENCE AND APPLICATIONS
- P –
- P/E –
- PM –
- RNS –
- RST –
- S VS M –
- TC –
- TDRSS –
- UP –

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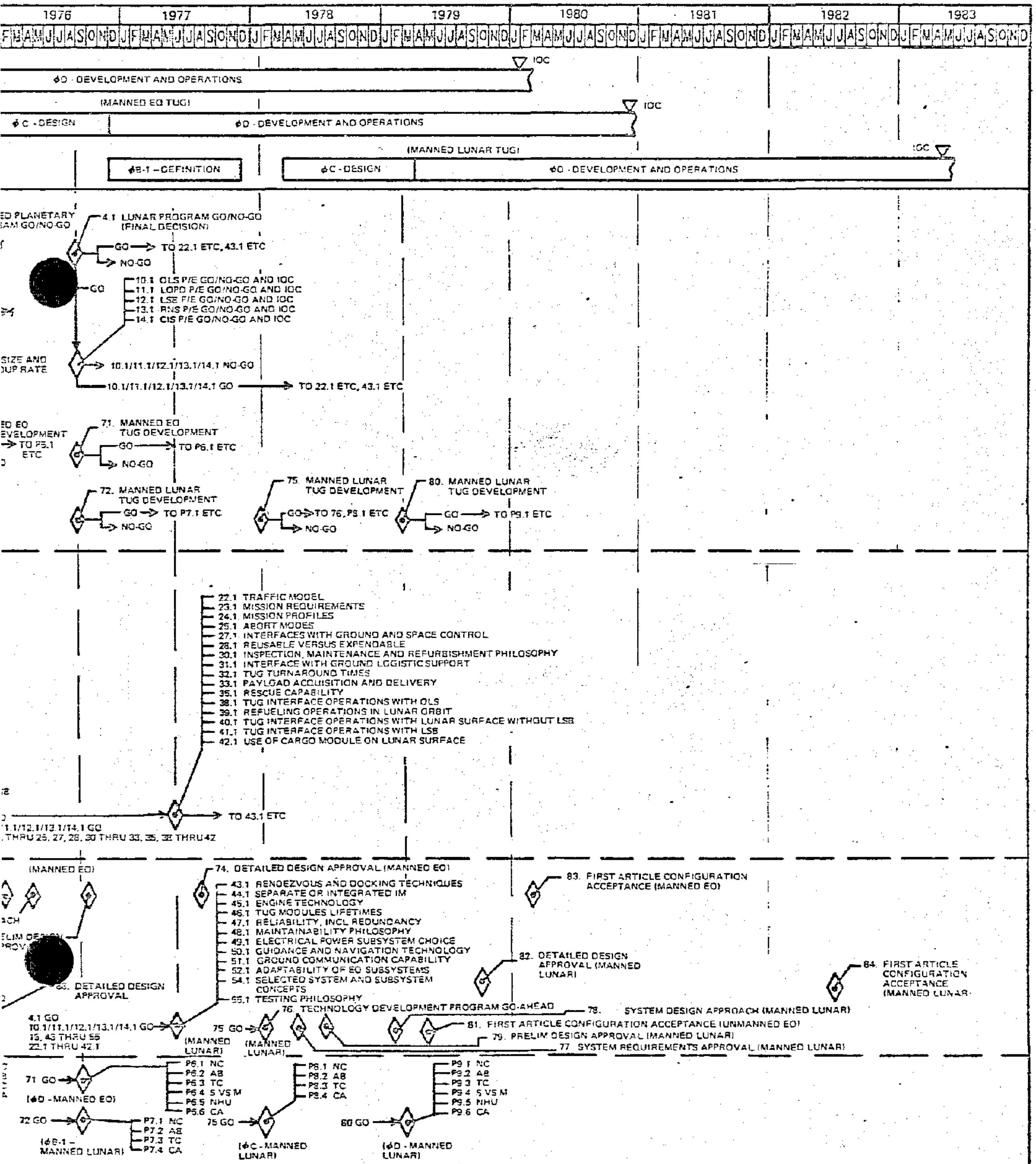

IREMENT DECISIONS OCCURRING
TED BY DECIMALS, OVER A

*4.1, 10.1 ETC, 22.1 ETC AND 43.1, ETC., INDICATE FINALIZATION OF PREVIOUS PRELIMINARY DECISIONS AFFECTING THE MANNED LUNAR TUG.

ENT
OULE
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TUG
STEM VERSUS MODULE PROCUREMENT
ACT
DATA RELAY SATELLITE SYSTEM
LOADS

Figure 23. Decision Matrix (RST - NASA Key Decisions and Decision Points)

5.0 SYSTEM DESCRIPTION

5.1 PURPOSE

To determine the estimated costs and schedules for developing the reusable space tug (RST), it is necessary to describe in generic terms the subsystems and major items comprising the selected design concepts and to indicate the development status of these subsystems (Table 7). All item descriptions in the table apply to the equipment in any module in which the equipment is located (e.g., Structure describes the type of structure used in all modules).

5.2 DEFINITION OF DEVELOPMENT STATE CATEGORIES

The information in the Table 7 column "as Is" refers to a subsystem currently (1973-1974) in production and in use in another application. There may be a requirement for a delta qualification test to meet the new mission requirements. The column headed "Modification of Existing" refers to a subsystem or item currently in production and which may be made to meet the new mission requirements by redesign and replacement of some (less than 50 percent of the detail parts). Requalification of the changed parts is mandatory, and delta qualification test of the complete subsystem or item may be required. The table column headed "New" refers to a subsystem or item in which more than 50 percent of the detail parts must be redesigned and remanufactured. There are two levels (A and B) of redesign involved. Level A includes the technology within the present state-of-the-art, and Level B includes supporting research and technology that is required to advance the state-of-the-art to a point where the design may be accomplished. A complete qualification test program for the subsystem or item is required at Level B.

Table 7. Reusable Space Tug System Description

Item	Item Descriptions and Potential Suppliers	Development State: Existing: As-Is	Development State: Existing: Modification	Development State: New	Remarks
Structure					
Module - primary	Integrally stiffened skin, mechanically attached frames and longerons - NR			A	Utilizes presently available technology
Tank	Cone-supported - aluminum shell cryogenic tanks - NR			A	Utilizes presently available technology
Docking mechanism	Passive or active system		X		Utilizes Apollo or EOSS components
Insulation	Aluminum-Mylar super insulation - NR			B	Will require extension of present state-of-the-art
Propellant feed system					
Fill and drain	Lines, Valves, etc. - NR			A	Custom design for tug
Pressurization and venting	Gas storage, valves, etc. -NR			B	Requires extension of state-of-art
Measurement system	Point sensors and PVG gauge - Bendix, Simmonds			A	Utilizes technology developed for EOS
Zero-g retention	Screens and baffles, NR			B	Requires extension of state-of-art
Attitude control					
Tanks	Filament wound - Aerojet, Lockheed			B	Data for gaseous O_2 and H_2 long-term storage in space environment must be developed
Engines	Gaseous O_2/H_2 pentads - Rocketdyne, TRW, Bell			A	Utilizes technology developed for EOS
Fill and drain	Valves, lines, etc.			A	Utilizes presently available technology

Table 7. Reusable Space Tug System Description (Cont)

Item	Item Descriptions and Potential Suppliers	Development State: Existing: As-Is	Development State: Existing: Modification	Development State: New	Remarks
Attitude control					
Conditioning	Propellant gases preheating Unit - Rocketdyne, TRW, Bell			A	Utilizes technology developed for EOS
Thrust mount and gimbals					
Thrust structure	Aluminum or steel tube truss-NR			A	Utilizes presently available technology
Gimbal actuator	Electric or hydraulic actuators-NR			A	Utilizes presently available technology
Main propulsion engines	High-performance, LOX/ LH_2-Rocketdyne, Aerojet			A	Utilizes technology developed for EOS
Guidance, navigation and control					
Inertial measuring unit	Pentad and hexad - HI		X		Modified EOS or EOSS subsystem
Attitude reference and navigation sensors	Star tracker, sun sensors, Earth horizon tracker-ITT Hughes, Quantic, Kollsman	X			Suitable sensors presently available
Controls activation	ACS driver and main engine Gimbal amplifiers - HI			A	Utilizes presently available technology
Manual controls	Rotation and translational-HI		X		Modified Apollo subsystem
Backup inertial sensors	Rate gyros, integrating Accelerometer-HI, A/N, general precision			A	Utilizes presently available technology
Manual telescope	Kollsman, ITT			A	Utilizes presently available technology
Docking equipment	Laser radar - ITT Television camera-LSI, RCA, GE	X	X		Subsystem presently available Modification of existing subsystem

Space Division
North American Rockwell

Table 7. Reusable Space Tug System Description (Cont)

Item	Item Descriptions and Potential Suppliers	Development State: Existing: As-Is	Development State: Existing: Modification	Development State: New	Remarks
Lunar landing equipment	Landing radar - Ryan		X		Modification of Apollo LM or Viking subsystem
	Gimballed TV camera and TV			A	Utilizes presently available technology
	Graphics memory - LSI, RCA, GE				
Electrical power					
Source: Primary	H_2/O_2 fuel cells-P&WA, GE			A	Utilizes technology developed for EOS
Secondary	rechargeable batteries Eagle-Picher, ESB, Gulton			A	Utilizes technology developed for EOS
Distribution	Wiring, buses, etc. -NR			A	Utilizes technology developed for EOS
Conditioning	Inverters, rectifiers, etc. - G. E., Westinghouse, Gulton			A	Utilizes technology developed for EOS and EOSS
Controls and protection	Voltage Regulator, Circuit Breakers, Switches, etc. - Gulton, Bendix, Westinghouse Teledyne, Texas Inst., HI			A	Utilizes technology developed for EOS & EOSS
Environmental control and life support	Hamilton Standard, Garrett				
Atmospheric control	Cat. Ox/sorption, LiOH, Fans, Heat Exchangers, Gas Storage		X		Modified EOSS subsystem
Life support	High Pressure Gas, Back Packs, etc.		X		Modified Apollo subsystem
Waste management	Waste storage			A	Utilizes presently available technology
Water and feed management	Food Preparation, drink guns, etc.		X		Modified Apollo subsystem
Crew support	Desks, seats, couches, etc.		X		Modified Apollo subsystem

Table 7. Reusable Space Tug System Description (Cont)

Item	Item Descriptions and Potential Suppliers	Development State			Remarks
		Existing			
		As-Is	Modification	New	
Housekeeping	Filters, Trash Bags, etc.		X		Modified Apollo subsystem
Active thermal control					
Radiators	Water, Freon-Ham Std, Garrett		X		Space Sta. hardware modified for Tug application
Fluid loop	Lines, Pumps, Valves, cold plates, heat exchangers-NR				Space Sta. hardware modified for Tug application
Communications and data management					
Communications equipment	S-Band Transceiver-HRL, A/N Motorola, GE, RCA			A	Utilizes technology developed for EOSS
	VHF Transceiver - RCA, Collins		X		Modification of Apollo subsystem
	Video Unit			A	Utilizes technology developed for EOSS
Antennas	VHF - Collins, RCA		X		Modification of Apollo antenna
	Omni-Amecom		X		Modification of Apollo antenna
	Steerable parabolic-HRL, AVCO Aerojet General			A	Utilizes presently available technology
Computer and peripherals	Communications switching and checkout control, premodulation processor, MOS-LSI Input/output controller and processor, operational and mass storage memory - A/N, ITT, HI, IBM			A	Utilizes technology developed for EOSS
Archival storage	Tape unit - Leach, Fairchild, General Dynamics			A	Utilizes presently available technology
Central Timing unit	Ceseum beam - General Time, Motorola			A	Utilizes technology developed for EOSS

Table 7. Reusable Space Tug System Description (Cont)

Item	Item Descriptions and Potential Suppliers	Development State			Remarks
		Existing			
		As-Is	Modifications	New	
Controls and displays	Color TV, audio, I/O keyboard, Status lights, alphanumeric display, remote acquisition, and control units - MI, A/N, ITT, Westinghouse			A	Utilizes technology developed for EOSS
Landing gear					
Structure	Aluminum or steel Tube Truss - NR			A	Utilizes presently available technology
Attenuation system	Hydraulic shock absorber - NR			A	Utilizes presently available technology
Manipulator kit	Remotely controlled Arms and fingers - NR			A	Utilizes presently available technology

LEGEND:

NR - North American Rockwell Corporation
ITT - International Telephone and Telegraph
HI - Honeywell Industries
A/N - Autonetics
LSI - Lear Siegler
ESB - Electric storage battery
HRL - Hughes Research Laboratory
EOS - Earth-orbit shuttle
EOSS - Earth-orbit space station
A - Redesign Level A
B - Redesign Level B

6.0 PROGRAM COST ESTIMATES

This section contains estimates for nonrecurring development costs and recurring production costs of the Reusable Space Tug Project. These costs are presented for each of the three selected design concepts, 1, 5, and 11, and include three major development categories indicating sequential development as follows: Unmanned earth orbital tug, manned earth orbital tug, and manned lunar tug. The selected design concepts are described in the technical volumes of the tug final report. For comparison purposes, cost estimates also have been made for stages with expendable modules. The time period covered by the cost estimates begins with Phase C and continues through ten years after the initial operational capability (IOC) date for the category developed first.

6.1 COST ESTIMATING GROUND RULES, COVERAGE, AND DATA FORMATS

Significant ground rules, coverage, and data formats associated with the preparation of the cost estimates were as follows:

6.1.1 Ground Rules

1. One set of cost data will be prepared for each of the three selected design concepts, covering all three development categories for each design concept.

2. Parametric estimating techniques will be employed based upon cost estimating relationships (CER's).

3. Costs reflect 1970 dollars for budgetary and planning purposes.

4. No fee or profit will be included in costs.

5. DDT and E (nonrecurring) and production (recurring) will be identified.

6. Only costs that would be incurred by a contractor will be identified.

7. Costs will be reported at level 4; and available for review at next lower level for flight hardware (1XX-01-00-00-00 through 1XX-07-00-00-00) and test hardware (1XX-08-00-00-00) only (Figure 2.)

8. NR cost estimating effort will end with a summary for the Reusable Space Tug program element (1XX-00-00-00-00) at level 3. It is assumed that NASA will add any other level 3 cost data and summarize at levels 2 or 1, as desired.

9. Flight hardware costs will encompass, but not specifically identify, design/engineering, production, materials, Q&RA, packaging, costs for deliverable software, tooling and special test equipment, captive and ground test, and test and operations; but will exclude test hardware.

10. Test hardware costs will encompass costs on same basis as the flight hardware.

11. Operations support costs will encompass, but not specifically identify, site activation and site maintenance, maintenance and refurbishment of flight hardware previously delivered to NASA, facilities and GSE maintenance, and site support services such as management/planning, documentation, etc.

12. Facilities costs will encompass, but not specifically identify, site exploration, design and construction, modifications to existing facilities, and leased facilities. Facilities include contractor R&D facilities for production, deployment, tests, maintenance, or operation; that is, buildings, structures, and real property installed equipment (RPIE).

13. Cost estimates will be consistent with the system description, Program Development Schedule, Operational Flight Vehicles Production Schedule, and Operational Schedule.

14. The cost estimates are consistent with current subsystem weight estimates, including a 5 percent allowance for growth.

15. A comparison will be made of the differences in costs between the three selected design concepts.

16. For each design concept, the cost estimates for a particular module will reflect any differences in hardware for different major development categories. It is assumed that each concept will be developed progressively in the following sequence: unmanned earth orbital tug, manned earth orbital tug, and manned lunar tug.

17. Cost estimates of expendable stages will be less detailed, but will generally follow the ground rules above, so as to permit comparison with the selected concepts.

6.1.2 Coverage

The areas covered by the cost estimates will include:

1. Hardware, software, services and other work tasks.

2. Items covered by blocks 1XX-01-00-00-00 through 1XX-15-00-00-00 of the WBS (Level 4).

3. Test articles and operational flight vehicles.

4. Period covered—Phase C's and D's for three major development categories—from the start of Phase C for the unmanned earth orbital tug (12-1-73) through 12-31-89, which includes 10 years of RST operations.

5. Does not include costs of supporting research and technology.

6. Does not include costs of propellant, personnel provisions, or crew consumables.

7. Does not include costs of flight operations.

6.1.3 Data Formats

1. Data form A: Total program cost estimate data by work breakdown structure items—one set of data for each of the three selected design concepts, showing the increment in cost for each of the three major development categories. Such detail is not included for stages with expendable modules.

2. Data form D: Total program funding schedules—one set of data for each of the three selected design concepts, covering all three major development categories.

3. Graph, depicting annual funding requirements, by Government fiscal year—covering each of the three selected design concepts and showing differences in costs among the concepts.

4. Graph, depicting cumulative funding requirements, with respect to Government fiscal years—covering each of the three selected design concepts and showing differences in costs among the concepts.

6.2 COST ESTIMATING METHODOLOGY

The basic building block in generating DDT&E (nonrecurring) costs is the design and development (D&D) effort associated with each subsystem in a module of flight hardware. In generating production (recurring) costs, the basic building block is the recurring theoretical first unit (TFU) fabrication and assembly cost for each subsystem in a given module. All costs associated with subdivisions of work in support of the D&D and production activities are derived from these basic building blocks. The costs of the selected design concepts of the tug were built up from various combinations, in quantity and configuration, of the modules 1XX-01-00-00-00 through 1XX-07-00-00-00 of the Work Breakdown Structure, Figure 2. All cost estimates are in accordance with the ground rules enumerated in Section 6.1.

6.2.1 Basic Building Blocks

The costs of the basic D&D and TFU building blocks were derived parametrically using cost estimating relationships (CER's), expressed in terms of 1970 dollar values as indicated by the ground rules. These CER's are based primarily upon the 1968 Apollo CSM and Saturn S-II cost studies, but also include other cost data from industry. In particular, the Apollo CSM D&D CER's have been adjusted to remove certain redesign effort peculiar to the CSM program. The resulting D&D and TFU CER's are plotted as straight lines on log-log paper for each subsystem, with dollars per pound measured along the ordinate and weight along the abscissa. To arrive at the cost of each tug subsystem, these CER data are adjusted for weight, complexity, and know-how differences between the tug subsystem and that for which CER data are available, which we term the "comparative" subsystem.

Weight scaling of costs for a given subsystem and type of cost is accomplished by moving along the applicable line until the abscissa location corresponding to the subsystem weight is reached. The point reached in this fashion determined the dollar per pound applicable to a subsystem of the same weight as that of the tug and of the same complexity and know-how as that of the comparative subsystem.

Differences in complexity and know-how between the tug and the CER source data were significant in determining the final costs and had to be quantified. The complexity is defined as a measure of the intrinsic features of a subsystem which specifies the effort needed to design and develop that subsystem. It is expressed in terms of a percentage of a known comparative subsystem represented by the D&D CER data, assuming the know-how, as described in Table 8, is the same for both subsystems. The complexity for the tug was determined by interviewing the responsible subsystem engineers and, to a first approximation, was assumed to apply also to the TFU costs.

Differences in know-how level between the tug and the CER data were also determined by interviewing the responsible subsystem engineers. Know-how level ratings, based on a composite of the state of the art, production experience, specification status, and operating program characteristics (Table 8) were established for both what the tug subsystem will be, and what the CER comparative subsystem was, at the inception of the development phases of the respective programs. Assumptions as to how much development on programs such as shuttle, for example, will contribute directly to space tug also were included. Each know-how level has an amount of effort assigned to it which increases as the know-how level rating number decreases. Unlike the complexity factor effort, this effort applies only to the design and development and not to production. The rationale here is that know-how sufficient to produce the item will have been developed during the design phase, and that both the CER data and the tug will be at the same level of know-how at the start of production.

The factors developed for relative complexity and relative know-how between the tug and the CER source data were multiplied by the D&D value derived by the weight scaling process to obtain dollars per pound for design and development. The complexity factor above was applied to the TFU value obtained by weight scaling to arrive at dollars per pound for first unit recurring costs.

Costs of multiple recurring flight hardware items were derived from TFU costs by the use of learning curves. A 90 percent curve was used in each instance. To be conservative, possible commonality of components between development categories was ignored. TFU's were derived as though each category represented an entirely new production line, and learning curve factors were treated accordingly. The quantitites of flight articles used in the estimates for each concept are summarized in Table 9.

6.2.2 Supporting Effort

To get the complete nonrecurring DDT&E and first unit production recurring costs also required the addition of effort that supports the basic

Table 8. Subsystem Know-How Status*

Know-How Level	State of the Art	Production Experience	Specification Status	Operating Program Characteristics
1	The item is substantially beyond the current state of the art. Major development work is required.	No production of any kind has been started.	No work on a specification has started.	None of the OPC for using the items has been formulated.
2	The item is slightly beyond the current state of the art. Some development work is required.	Experimental laboratory fabrication of a similar item is in process.	Work on a specification is in an early stage and only general requirements are identified.	The general outline of OPC under which the item will be used has been only tentatively defined and many specific details are lacking.
3	The item is within the state of the art but no commercial counterpart exists.	A prototype of the item has been produced.	A specification for the item has not been completed but a specification on a similar item is applicable.	The general outline of OPC has been formulated but many specific details are lacking.
4	The item will involve a minor modification of commercial or standard aerospace issue items.	The item has been produced in limited quantity.	A specification for the item has been prepared but is under review or revision.	The OPC have been substantially defined, but are under review or revision.
5	The item will require no modification.	The item has been produced in production quantities.	The specification is for the item as produced.	The OPC have been defined and are met by the item.

*Adapted from AFSCM 173-1.

Table 9. Summary of Flight Hardware Items

Module and Development Category	Concept 1	Concept 5	Concept 11
Intelligence module:			
Unmanned earth orbital	9	18	9
Manned earth orbital	19	20	19
Manned lunar	6	6	6
Propulsion Module:			
Unmanned earth orbital	9	18	9
Manned earth orbital	19	20	19
Manned lunar	6	6	6
Tank Set:			
Unmanned earth orbital	N/A	N/A	167
Manned lunar	N/A	6	6
Crew module:			
Manned earth orbital	12	12	12
Manned lunar	4	4	4
Manipulator kit:			
Manned earth orbital	10	10	10
Landing Gear:			
Manned lunar	6	6	6
Cargo Modules:			
Manned lunar	12	12	12

effort derived by using CER's. The subdivisions of work for the supporting effort are as follows:

Nonrecurring (included with design and development subsystem costs)

Major test hardware (MTH)
Captive and ground tests
Ground support equipment (GSE)
Tooling and special test equipment (STE)
Test and operations
Trainers
System support - system engineering and integration
Program management
Facilities

Recurring (included with first unit costs)

Test and test operations
Sustaining tooling and STE
System support - system engineering and integration
Sustaining GSE
Spares
Program management

The sequence in which these costs are listed depends upon the manner in which they are derived, as illustrated in Table 10 and 11. Facilities costs are based on fairly detailed studies on the Phase B space station study, the assumption being that similar facility costs as a percentage of design and development will be incurred since both programs rely on the space shuttle or other systems to deliver their respective modules to orbit. Accordingly, a 9.9 percent factor equal to that used for space station is used here. The quantities of test items used in estimating major test hardware (MTH) and captive and ground test costs for each of the modules, concepts, and development categories are listed in Table 12.

6.2.3 Costs as a Function of Time

In estimating costs as a function of time for nonrecurring costs, use was made of a schedule of engineering and manufacturing effort presented in Figure 14 of the Manufacturing Plan. For recurring costs, the scheduled fabrication starts in Tables 13, 14, and 15 were used. Note that the total quantities in Tables 13 - 15 match those in Table 12.

Table 10. Nonrecurring Costs, Subdivisions of Work in Support of Design and Development

	Factor (%)	Cost Base to which Percent is Applied	Rationale
1. Major Test hardware (MTH) Captive and ground test	--		Estimate is made of equivalent TFU articles
2. Tooling and STE	13.5	D&D + 1	Same as Apollo CSM
3. Ground support equipment	10.0	D&D + 1	Same as Apollo CSM
4. Test operations	7.2	D&D + 1	Same as Apollo CSM
5. Trainers and simulators	3.0	D&D + 1	Far less ambitious than Apollo CSM
6. System engineering	6.0	D&D + 1 through 5	Cost avoidance versus Apollo through advanced management techniques
7. Program management	6.0	D&D + 1 through 5	Cost avoidance versus Apollo through advanced management techniques

Table 11. Recurring Costs, Subdivisions of Work in Support of Theoretical First Unit (TFU) Fabrication and Assembly Costs

	Factor (%)	Cost Base to which Percent is Applied	Rationale
1. Test and test operations	19.8	1st Unit recurring	Same as Apollo CSM
2. Sustaining tooling and STE	4.6	1st Unit recurring	Same as Apollo CSM
3. System engineering	4.0	1st Unit recurring	Cost avoidance versus Apollo through advanced management techniques
4. Program management	4.5	1st Unit recurring	Cost avoidance versus Apollo through advanced management techniques
5. Flight spares	4.7	1st Unit recurring	Similar to Apollo CSM
6. Sustaining GSE	2.5	1st Unit recurring	Significantly less ambitious than Apollo CSM

At this stage of the program, many parts of the developmental effort have been scheduled only to WBS Level 3. Accordingly, a time duration was assumed for costs aggregated to WBS Level 3 for each design concept and the effort associated with each developmental category. Experience on other space programs to date would indicate a curve approximating an idealized cost curve with 40 percent cost expended at 50 percent of the time duration (40/60 ogive); contributing to this cost behavior is the large amount of testing in the latter phases of the development phase. In this program,

Table 12. Major Test Vehicle Requirements, All Concepts Expressed in "Equivalent TFU Articles"

Test Vehicles	IM	PM	CM	MK	CAM	LG	TS
<u>Unmanned</u>							
T^1	1.0	1.0					1.0
T^2	1.0	1.0					1.0
Laboratory (estimated)	0.7	0.4					
Total	2.7	2.4					2.0**
<u>Manned</u>							
T^3	1.0	1.0	1.0				
T^4	1.0*	1.0*	1.0	1.0			1.0
Laboratory (estimated)			0.1				
Total	1.0	1.0	2.1	1.0			
<u>Lunar</u>							
T^4	1.0	1.0	1.0		1.0	1.0	1.0
T^6	1.0	1.0	1.0		1.0	1.0	1.0
Laboratory (estimated)	0.1	0.1	0.1		0.1	0.25	
Total	2.1	2.1	2.1		2.1	2.25	2.0***

*Reuse
**Design Concept No. 11 only
***Design Concept No. 5 and No. 11 only

Table 13. Schedule of Flight Article Production Starts by Fiscal Year, Design Concept 1

Module and Development Category	Fiscal Year												Total through 1988*
	77	78	79	80	81	82	83	84	85	86	87	88	
Intelligence module:													
Unmanned earth orbital	1	2	2	2	1	-	-	1					9
Manned earth orbital			2	3	1	2	2	1	2	2	2	2	19
Manned lunar					1	1	1	1	1	1			6
Propulsion module:													
Unmanned earth orbital	1	2	2	2	-	1	-	1					9
Manned earth orbital			2	3	1	1	2	1	2	2	3	2	19
Manned lunar					1	1	1	1	1	1			6
Crew module:													
Manned earth orbital			1	2	2	2	2	2	1				12
Manned lunar					1	1	1	1					4

*Deliveries through 1989

Table 14. Schedule of Flight Article Production Starts by Fiscal Year, Design Concept 5

Module and Development Category	Fiscal Year												Total through 1988*
	77	78	79	80	81	82	83	84	85	86	87	88	
Intelligence module:													
Unmanned earth orbital	1	2	2	2	2	2	2	1	1	1	1	1	18
Manned earth orbital			2	3	2	3	3	1	1	1	2	2	20
Manned lunar					1	1	1	1	1	1			6
Propulsion module:													
Unmanned earth orbital	1	3	3	3	2	1	1	1	1	1	1		18
Manned earth orbital			2	2	2	2	1	1	2	2	4	2	20
Manned lunar					1	1	1	1	1	1			6
Tank set:													
Manned lunar					1	1	1	1	1	1			6
Crew module:													
Manned earth orbital			1	2	2	2	2	2	1				12
Manned lunar					1	1	1	1					4

*Deliveries through 1989.

Table 15. Schedule of Flight Article Production Starts by Fiscal Year, Design Concept 11

Module and Development Category	Fiscal Year												Total through 1988*
	77	78	79	80	81	82	83	84	85	86	87	88	
Intelligence module													
Unmanned earth orbital	1	2	2	2	-	1	-	1					9
Manned earth orbital			2	3	1	1	2	1	2	2	3	2	19
Manned lunar					1	1	1	1	1	1			6
Propulsion module:													
Unmanned earth orbital	1	1	2	1	-	1	1	-	1	-	1		9
Manned earth orbital			1	2	2	2	2	2	2	3	3		19
Manned lunar					1	1	1	1	1	1			6
Tank set:													
Unmanned earth orbital	1	9	12	14	15	15	15	15	17	17	18	19	167
Manned lunar					1	1	1	1	1	1			6
Crew module													
Manned earth orbital		1	2	2	2	2	2	1					12
Manned lunar				1	1	1	1						4

*Deliveries through 1989

however, more front-loading is anticipated due to the requirement for interface with shuttle at the earliest possible time. Accordingly, a 50/50 ogive was used to spread nonrecurring costs as a function of time.

In the case of recurring costs, the ground rule to show costs through 12-31-89 must be explained further. Three interpretations of the original ground rules are possible: (1) costs expended through 1989 for all items started into production through 1989, (2) costs committed through 1989 for all hardware items entering production through 1989 or (3) costs for all items delivered through 1989. The third interpretation has been used herein. As indicated in the Form D's which follow, the lead time to produce and deliver the first flight article is three years. For purposes of establishing a cutoff date, it is assumed that this lead time is reduced to two years for items delivered by 12-31-89. Accordingly, the items in Tables 13 to 15 end with starts in 1988, and it is assumed that the starts in 1988 are at the beginning of the year.

To minimize the calculation load, approximations to the recurring costs were devised which are deemed sufficiently accurate at this phase of the program. Using a constant lead-time of three years from start to delivery, the costs per each year's starts in Tables 13 to 15 were derived by module from learning curve tables and spread over the lead-time period using a 50/50 ogive. This degree of detail was followed for Design Concept 1, unmanned earth orbital tug, Concept 1, manned earth orbital tug, Concept 5, manned lunar tug, and Concept 11, unmanned earth orbital tug. The funding was aggregated at the WBS Level 3 for comparability with nonrecurring costs, and an overall ogive through the 1989 period was derived. Noting similarities with other concepts and developmental categories, and that Concept 5 earth orbital unmanned has more deliveries in later years than the same developmental category in Concept 1, ogives for the other cases were derived by inspection of the schedules in Tables 13 to 15. The following ogives have been used to approximate the recurring funding:

Design Concept	Development Categories: E.O. Unmanned	E.O. Manned	Manned Lunar
1	80/20	60/40	60/40
5	70/30	60/40	60/40
11	50/50	60/40	60/40

6.3 COST ESTIMATES SUMMARY

Several significant features of the cost estimates are noted in order to provide the proper perspective for the present estimates and possible developments in future estimates. These features are discussed under the headings of cost drivers, effects of progressive development, inflation factors, and design and weight factors.

6.3.1 Cost Drivers

The major subsystem cost drivers, that is, the highest contributors to total costs, in the various modules are as follows:

Intelligence module

- Data management
- Communications
- Guidance, navigation, and control

Propulsion module

- Engines
- Structure

Crew module

- Communications
- Structure
- Guidance, navigation, and control

Of the subsystems listed above, data management was judged more complex than the comparative CER subsystem, engines and structure equally complex, and the others less complex. Generally, subsystems that were not major cost drivers were also judged less complex than comparative subsystems with few exceptions.

The know-how ratings on the cost-driving subsystems are generally higher (see Table 8) than the comparative systems, indicating a cost benefit due to knowledge generated on past programs.

6.3.2 Effects of Progressive Development

There are two primary sources of cost reduction due to developmental fallout which raise the know-how level for the space tug and consequently lower development costs. One source is the knowledge and state-of-the-art fallout from the shuttle and/or space station programs. In the cost-driving subsystems, this source affects the guidance, navigation, and control subsystem; also the engines in the propulsion module are assumed to be an adaptation of the orbit maneuvering system (OMS) engine of the shuttle.

The second source of cost benefits in the space tug program accrue from the design progression within each concept, with each development category building upon previous development. Each succeeding development category results in a higher know-how rating by virtue of familiarity gained in prior activity on a previous development category. This effect is generally true with the notable exceptions of guidance, navigation, and control, which requires significant modification to go from an earth orbital to a lunar mission, and the engine of the propulsion module, which requires a throttleable capability for the lunar mission.

6.3.3 Inflation Factors

The use of a 1970 cost index must be continually borne in mind when interpreting the cost figures summarized herein. Assuming a 5 percent annual inflation factor, a simplified constant level funding curve, and a mid-point of the program in 1983, costs in then-year dollars would be approximately $(1.05)^{13}$ or about 190 percent of the 1970 dollars listed herein!

6.3.4 Weight and Design

As stated previously, the costs are based upon the latest weight estimates including a 5 percent growth factor. Design concepts now envisage most subsystems as less complex than comparable Apollo and S-II subsystems. Weight growths in excess of 5 percent have not been uncommon on past programs. Costs will vary in approximately the same percentage ratio as weight. Accordingly, cost accuracy is only as good as the accuracy of the weight estimates.

As technical concepts are developed further in later phases of the program, complexity and know-how relationships should become clearer. To the extent that these estimates change, so will the cost estimates.

6.3.5 Cost Differences Among Design Concepts

The costs of the various concepts are summarized in Table 16, and broken down further in Tables 17, 18, and 19. The recurring costs in these tables are based on the quantities in Table 9 and the theoretical first unit (TFU) costs summarized in Table 20. Another summary of such costs is presented in Table 21. The least costly is Concept 1, in both nonrecurring costs and recurring costs. Although the cost of developing the propulsion module is less in Concept 5 than in Concept 1, the cost of developing the tank set offsets that saving. In addition, the requirement for larger numbers

Table 16. Reusable Space Tug Cost Summary (1970 Cost Index)

(12-1-73 thru 12-31-89)

		$ MILLIONS
Design Concept 1		
Nonrecurring		$ 1518
Recurring		1470
	Total	$ 2988
Design Concept 5		
Nonrecurring		$ 1544
Recurring		1746
	Total	$ 3290
Design Concept 11		
Nonrecurring		$ 1542
Recurring		1915
	Total	$ 3457

of intelligence and propulsion modules in Concept 5 (see Table 9) and the need for tank set units makes recurring costs about $276 million larger than in Concept 1. While Concept 11 offers slight development cost improvements over Concept 5 by virtue of weight savings in the propulsion module, this is more than offset by recurring cost increases stemming from the large number of tank set units required in the unmanned missions. Concept 11 is thus the most expensive of all over the operational time period studied.

6.3.6 Funding Requirements

Cumulative funding requirements for nonrecurring, recurring, and total program costs are summarized in Figure 24. Corresponding annual requirements are shown in Figure 25. The cumulative funding requirements

Table 17. Cost Summary, Design Concept 1
($ Million, 1970 Cost Index)

Module	Unmanned E.O.		Manned E.O.		Manned Lunar	
	Non-recurring	Recurring	Non-recurring	Recurring	Non-recurring	Recurring
Intelligence module	$433	$256	$ 433	$ 256	$ 433	$ 256
			144	465	144	465
					223	197
	433	256	577	721	800	919
Propulsion module	131	85	131	85	131	85
			49	160	49	160
					121	60
	131	85	180	245	301	305
Crew module	-	-	194	162	194	162
					127	78
			194	162	321	240
Manipulator kit	-	-	2	2	-	-
Landing gear	-	-	-	-	13	4
Cargo module	-	-	-	-	7	2
Facilities	33	-	33	-	33	-
	-	-	21	-	21	-
					22	-
	33	-	54	-	76	-
Total	$597	$341	$1,007	$1,130	$1,518	$1,470

Table 18. Cost Summary, Design Concept 5
($ Million, 1970 Cost Index)

Module	Unmanned E.O.		Manned E.O.		Manned Lunar	
	Non-recurring	Recurring	Non-recurring	Recurring	Non-recurring	Recurring
Intelligence module	$433	$460	$433	$ 460	$ 433	$ 460
			144	486	144	486
					223	197
	433	460	577	946	800	1,143
Propulsion module	116	131	116	131	116	131
			43	143	43	143
					113	52
	116	131	159	274	272	326
Tank set	-	-	-	-	57	31
Crew module	-	-	194	162	194	162
					127	78
	-	-	194	162	321	240
Manipulator kit	-	-	2	2	-	-
Landing gear	-	-	-	-	13	4
Cargo module	-	-	-	-	7	2
Facilities	29	-	29	-	29	-
			20	-	20	-
					25	-
	29	-	51	2	74	6
Total	$578	$591	$981	$1,384	$1,544	$1,746

Tabe 19. Cost Summary, Design Concept 11
($ Million, 1970 Cost Index)

Module	Unmanned E.O.		Manned E.O.		Manned Lunar	
	Non-recurring	Recurring	Non-recurring	Recurring	Non-recurring	Recurring
Intelligence module	$433	$256	$ 433	$ 256	$ 433	$ 256
			144	465	144	465
					223	197
	433	256	577	721	800	919
Propulsion module	99	57	99	57	99	57
			35	108	35	108
					102	40
	99	57	134	165	236	205
Tank set	57	514	57	514	57	514
			-	-	34	31
	57	514	57	514	91	545
Crew module	-	-	194	162	194	162
		-	-	-	127	78
	-	-	194	162	321	240
Manipulator kit	-	-	2	2	-	
Landing gear	-	-	-	-	13	4
Cargo module	-	-	-	-	7	2
	-	-	2	2	20	6
Facilities	31	-	31	-	31	-
	-	-	20	-	20	-
	-	-	-	-	23	-
	31	-	51	-	74	-
Total	$620	$827	$1,015	$1,564	$1,542	$1,915

Table 20. Summary of Theoretical First Unit (TFU) Costs ($ Million)

Module and Development Category	Concept		
	1	5	11
Intelligence module:			
Unmanned earth orbital	$39.7	$39.7	$39.7
Manned earth orbital	38.3	38.3	38.3
Manned lunar	43.1	43.1	43.1
Propulsion module:			
Unmanned earth orbital	13.2	11.3	8.9
Manned earth orbital	13.2	11.3	8.9
Manned lunar	13.2	11.3	8.9
Tank set:			
Unmanned earth orbital	N/A	N/A	6.7
Manned lunar	N/A	6.7	6.7
Crew module:			
Manned earth orbital	19.7	19.7	19.7
Manned lunar	24.0	24.0	24.0
Manipulator kit:			
Manned earth orbital	0.3	0.3	0.3
Landing gear:			
Manned lunar	0.8	0.8	0.8
Cargo module:			
Manned lunar	0.2	0.2	0.2

Table 21. Reusable Space Tug Cost Summary by Module
($ Million, 1970 Cost Index)

Module	Unmanned Earth Orbital RDT&E	Unmanned Earth Orbital 1st Unit	Manned Earth Orbital RDT&E	Manned Earth Orbital 1st Unit	Manned Lunar Tug RDT&E	Manned Lunar Tug 1st Unit	Total RDT&E
Intelligence							
(All Concepts)	$433	$39.7	$144	$38.3	$223	$43.1	$800
Propulsion							
Concept 1	131	13.2	49	13.2	121	13.2	301
Concept 5	116	11.3	43	11.3	113	11.3	272
Concept 11	99	8.9	35	8.9	102	8.9	236
Tank Set							
Concept 5	N/A	N/A	N/A	N/A	57	6.7	57
Concept 11	57	6.7	N/A	N/A	34	6.7	91
Crew							
(All Concepts)	N/A	N/A	194	19.7	127	24.0	321
Manipulator kit							
(All Concepts)	N/A	N/A	2	0.3	N/A	N/A	2
Landing gear							
(All Concepts)	N/A	N/A	N/A	N/A	13	0.8	13
Cargo							
(All Concepts)	N/A	N/A	N/A	N/A	7	0.2	7
Facilities							
Concept 1	33	N/A	21	N/A	22	N/A	76
Concept 5	29	N/A	20	N/A	25	N/A	74
Concept 11	31	N/A	20	N/A	23	N/A	74
Total RDT&E							
Concept 1	$597	N/A	$410	N/A	$511	N/A	$1,518
Concept 5	578	N/A	403	N/A	563	N/A	1,544
Concept 11	620	N/A	395	N/A	527	N/A	1,542

NOTE: N/A means non-applicable.

for RDT&E are so similar among the various concepts as to be within the plotting accuracy and calculating accuracy described in Section 6.2. Thus only one line is shown in Figure 24. The total cumulatives for these vary by less than 2 percent, between $1518 million and $1542 million. The annual funding curves in Figures 25 through 28 also illustrate that variations are minor. Annual nonrecurring funding by development categories and total funding are shown in Figures 26, 27, and 28.

On the other hand, significant differences in both cumulative and annual costs are evident when recurring costs are considered. The requirements for Concept 5 are larger than for Concept 1, and those for Concept 11 are the largest, for the same reasons cited in Section 6.3.5. The annual funding is higher in the years following 1979 for Concept 5 because of the significant increase in production starts of the intelligence module and the propulsion module in 1979 and later years (Tables 13 and 14). In Concept 11, the increases in tank set requirements, evident in Table 15, account for the large funding in that case. Small variations in annual funding in the early years in Figure 25 are as much as function of the calculation procedures described in subsection 6.2 as of differences in requirements attributable to the various concepts. Hence they are not considered significant.

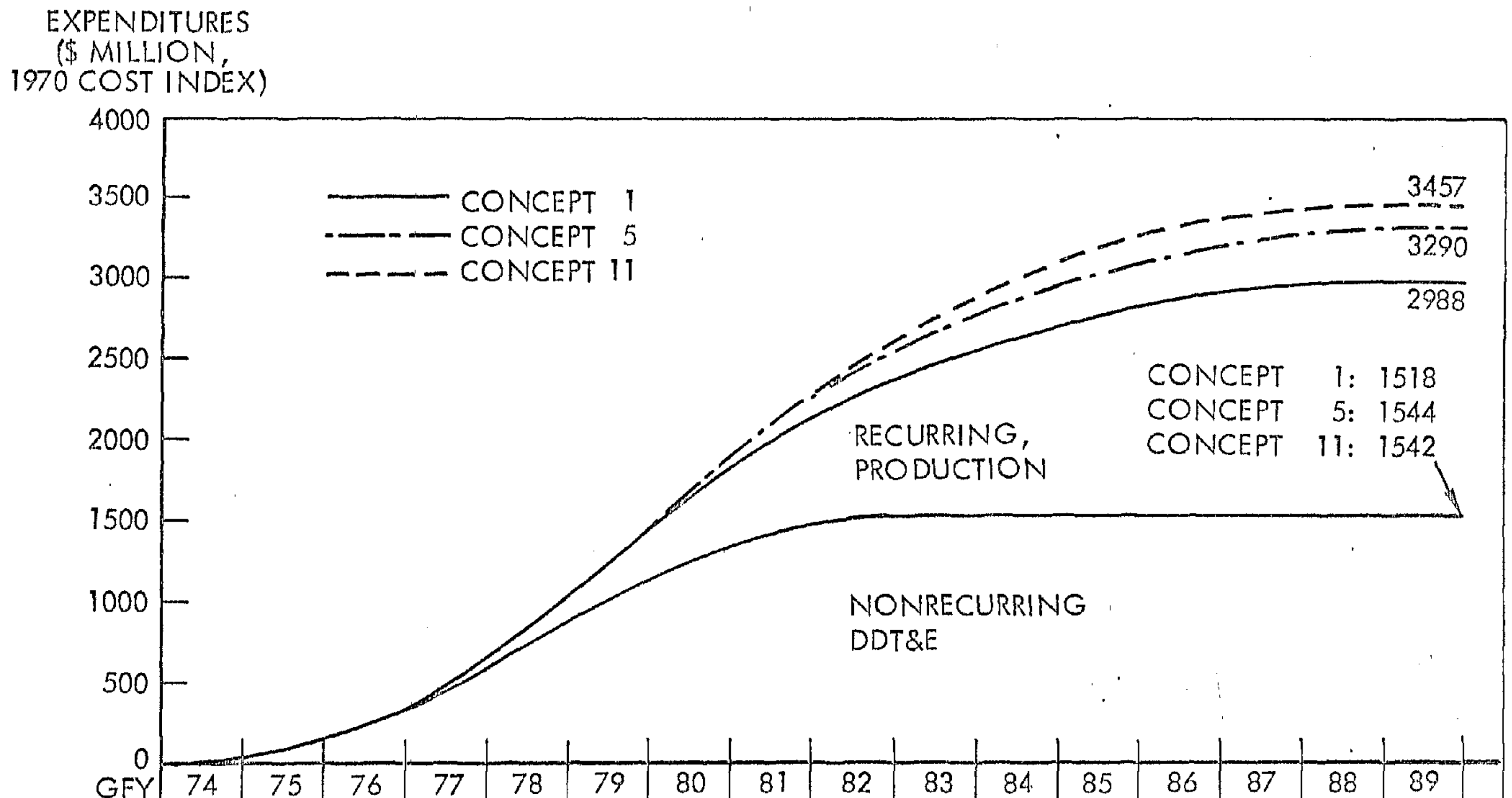
It should be noted that annual funding does not exceed $450 million in any of the concepts considered.

It should also be noted that, to the extent that consumable costs, particularly propellant costs, are significant in the various concepts, the behavior shown in Figures 24 and 25 would be altered to some extent.

6.4 COST ESTIMATES FOR DESIGN CONCEPT 1

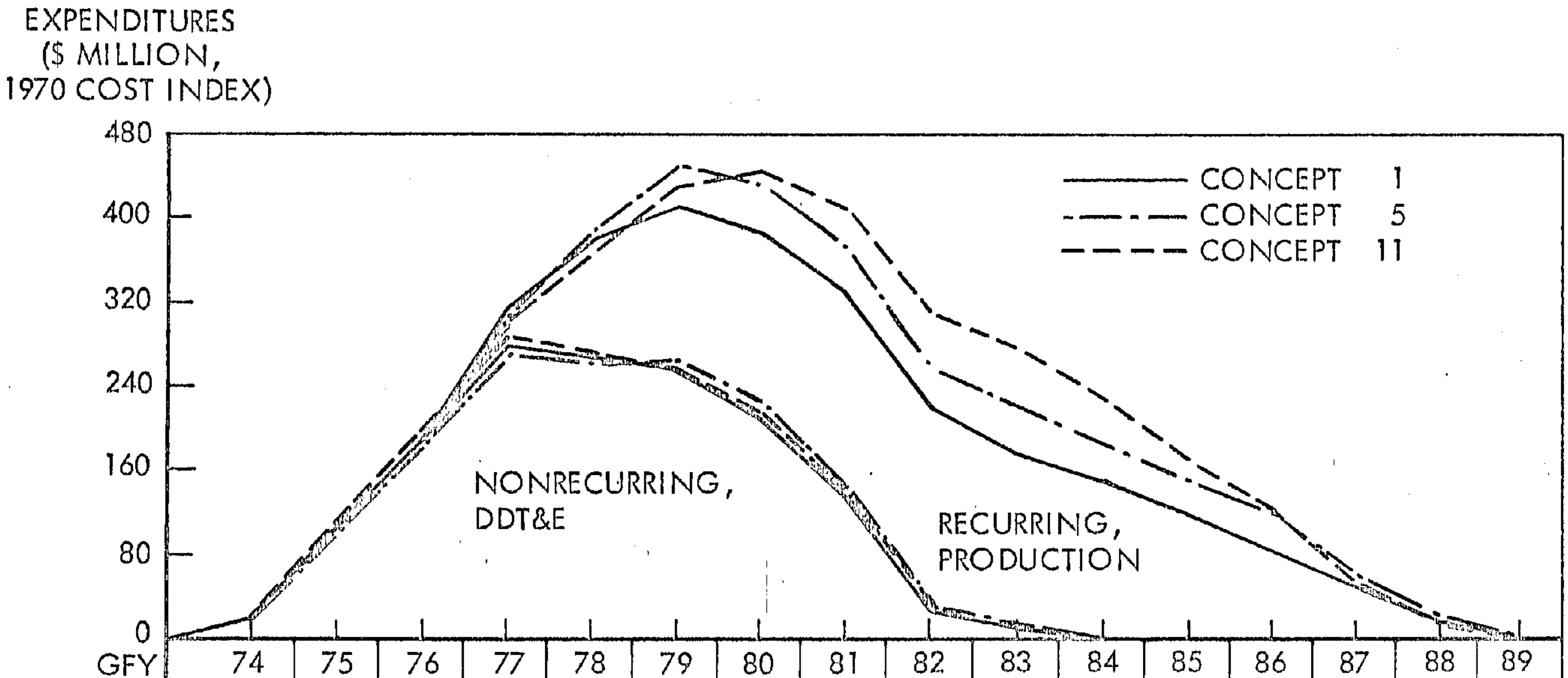
Cost estimates, in 1970 dollars, are presented in Data Forms A and D using terminology as defined in NASA Data Requirements Description Number MF 003M dated 22 May 1970. As indicated in Subsection 6.2, a 50/50 ogive was used at WBS Level 3 to spread the nonrecurring costs as a function of time. The nonrecurring costs for each of the development categories are tabulated in Table 22. T_d, the duration of cost accrual and T_s, the lead time to the launch milestone for each category, are in accordance with the schedule in the manufacturing plan.

The recurring costs, tabulated in Table 23, are based on a 90 percent learning curve, a three-year lead time, and a 50/50 ogive. Supporting activity and program management are time-phased in the same fashion as the aggregate flight hardware effort.



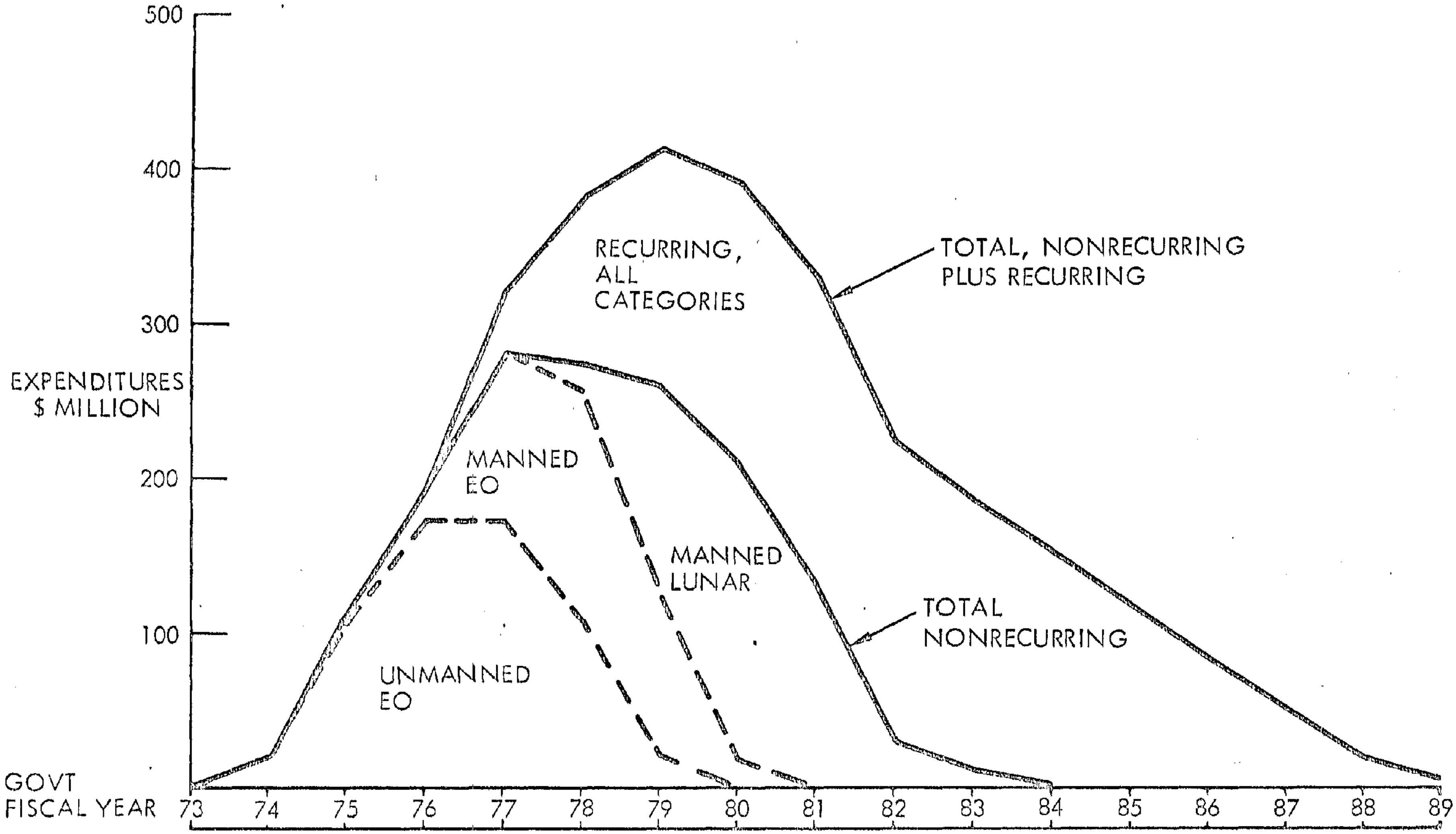
TOTALS	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
CONCEPT 1	22	130	323	641	1018	1429	1818	2145	2368	2554	2708	2829	2913	2965	2985	2988
CONCEPT 5	20	124	313	627	1014	1461	1897	2270	2532	2757	2944	3092	3197	3260	3286	3290
CONCEPT 11	22	133	333	642	1007	1433	1876	2283	2598	2877	3108	3279	3385	3437	3454	3457

Figure 24. Cumulative Funding Requirements - Three Selected Concepts



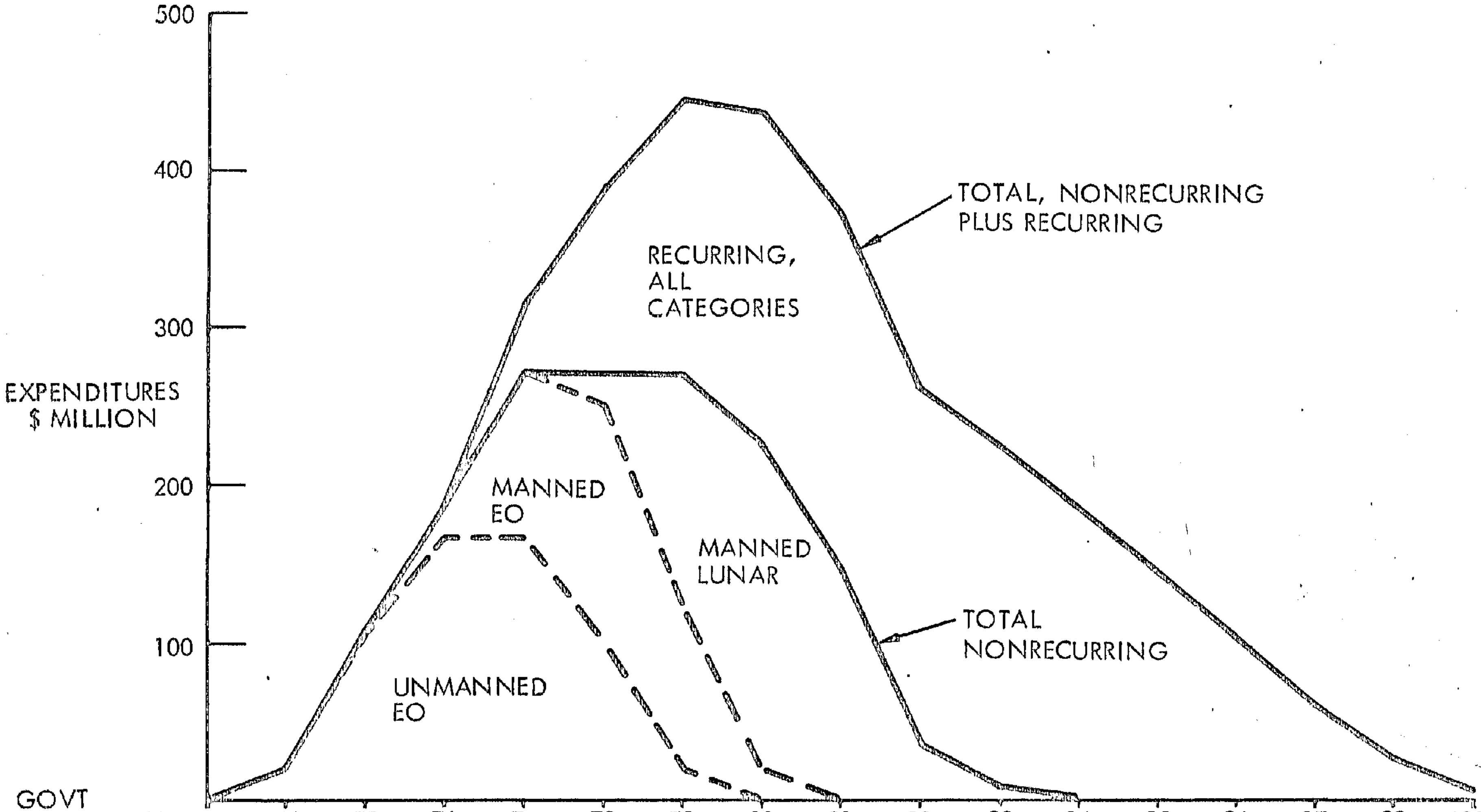
TOTALS	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
CONCEPT 1	22	108	193	318	377	411	389	327	223	186	154	121	84	52	50	3
CONCEPT 5	20	104	189	314	387	447	436	373	262	225	187	148	105	63	26	4
CONCEPT 11	22	111	200	309	365	426	443	407	315	279	231	171	106	52	17	3

Figure 25. Annual Funding Requirements - Three Selected Concepts



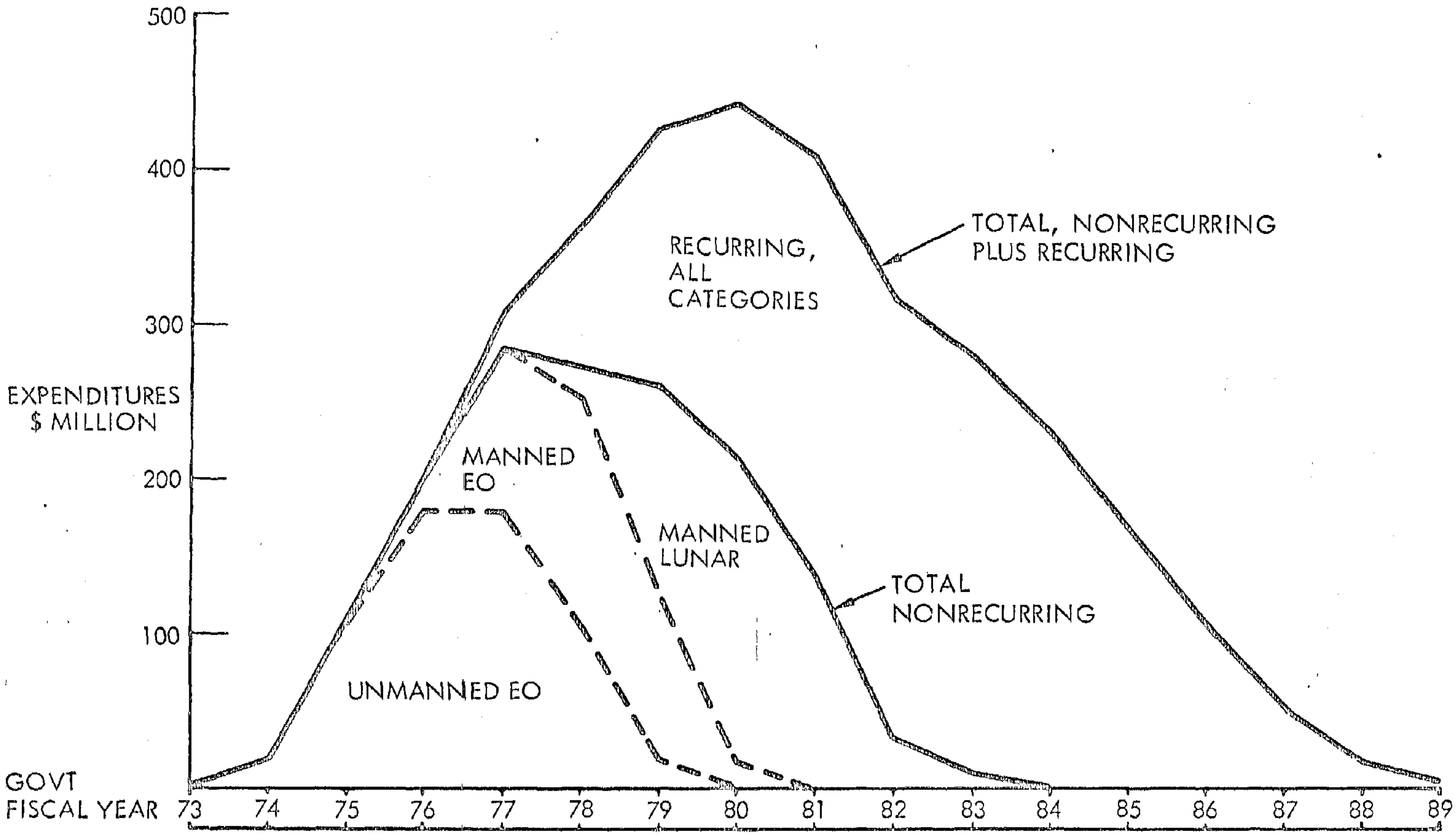
GOVT FISCAL YEAR	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
NON-REC	0	22	108	193	280	274	261	209	133	30	8	-					
REC	0	0	0	0	38	103	150	180	194	193	178	154	121	84	52	20	3
TOTAL	0	22	108	193	318	377	411	389	327	223	186	154	121	84	52	20	3

Figure 26. Design Concept 1 - Annual Funding Requirements



GOVT FISCAL YEAR	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
NON-REC	0	20	104	189	273	272	271	227	146	33	9	-					
REC	0	0	0	0	41	115	176	209	227	229	216	187	148	105	63	26	4
TOTAL	0	20	104	189	314	387	447	436	373	262	225	187	148	105	63	26	4

Figure 27. Design Concept 5 - Annual Funding Requirements



GOVT FISCAL YEAR	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
NON-REC	0	22	111	200	283	273	262	215	137	30	9						
REC	0	0	0	0	26	92	164	228	270	285	270	231	171	106	52	17	3
TOTAL	0	22	111	200	309	365	426	443	407	315	279	231	171	106	52	17	3

Figure 28. Design Concept 11 - Annual Funding Requirements

Space Division
North American Rockwell

Table 22. Nonrecurring (DDT&E) Cost Estimate Data — Form A Design Concept 1

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-earth orbital, unmanned	597	54	60	50/50	January 1980
4	1XX-01-00-00-00	Propulsion module	77				
4	1XX-02-00-00-00	Intelligence module	252				
4	1XX-08-00-00-00	Test hardware	100				
4	1XX-10-00-00-00	Operations support	27				
4	1XX-11-00-00-00	Facilities	33				
4	1XX-12-00-00-00	Ground support equipment	38				
4	1XX-13-00-00-00	Training equipment	11				
4	1XX-14-00-00-00	Systems support	30				
4	1XX-15-00-00-00	Program management	29				
3	1XX-00-00-00-00	Reusable space tug-earth orbital, manned	410	40	48	50/50	December 1980
4	1XX-01-00-00-00	Propulsion module	27				
4	1XX-02-00-00-00	Intelligence module	82				

Table 22. Nonrecurring (DDT&E) Cost Estimate Data — Form A Design Concept 1 (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
4	1XX-03-00-00-00	Crew module	119				
4	1XX-07-00-00-00	Manipulator kit	1				
4	1XX-08-00-00-00	Test hardware	66				
4	1XX-10-00-00-00	Operations support	19				
4	1XX-11-00-00-00	Facilities	21				
4	1XX-12-00-00-00	Ground support equipment	26				
4	1XX-13-00-00-00	Training equipment	8				
4	1XX-14-00-00-00	Systems support	21				
4	1XX-15-00-00-00	Program management	20				
3	1XX-00-00-00-00	Reusable space tug-lunar lander, manned	511	41	49	50/50	April 1983
4	1XX-01-00-00-00	Propulsion module	71				
4	1XX-02-00-00-00	Intelligence module	104				
4	1XX-03-00-00-00	Crew module	60				

Table 22. Nonrecurring (DDT&E) Cost Estimate Data — Form A Design Concept 1 (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
4	1XX-05-00-00-00	Landing gear kit	9				
4	1XX-06-00-00-00	Cargo module	5				
4	1XX-08-00-00-00	Test hardware	122				
4	1XX-10-00-00-00	Operations support	24				
4	1XX-11-00-00-00	Facilities	22				
4	1XX-12-00-00-00	Ground support equipment	33				
4	1XX-13-00-00-00	Training equipment	10				
4	1XX-14-00-00-00	Systems support	26				
4	1XX-15-00-00-00	Program management	25				

Table 23. Recurring (Production) Cost Estimate Data — Form A Design Concept 1

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($ Millions)	Number of Units	Reference Units	Learning Index	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-earth orbital, unmanned	341	-	1	90%	36	36	50/50	January 1980
4	1XX-01-00-00-00	Propulsion module	64	9	1	90%				
4	1XX-02-00-00-00	Intelligence module	191	9	1	90%				
4	1XX-9-00-00-00	Logistics support	11							
4	1XX-10-00-00-00	Operations support	48							
4	1XX-12-00-00-00	Ground support equipment	6							
4	1XX-14-00-00-00	Systems support	10							
4	1XX-15-00-00-00	Program management	11							
3	1XX-00-00-00-00	Reusable space tug-earth orbital-manned	789	-	1	90%	36	36	50/50	December 1980
4	1XX-01-00-00-00	Propulsion module	120	19	1	90%				
4	1XX-02-00-00-00	Intelligence module	347	19	1	90%				
4	1XX-03-00-00-00	Crew module	120	12	1	90%				
4	1XX-07-00-00-00	Manipulator kit	1	10	1	90%				
4	1XX-09-00-00-00	Logistics support	26							
4	1XX-10-00-00-00	Operations support	112							
4	1XX-12-00-00-00	Ground support equipment	14							
4	1XX-14-00-00-00	Systems support	24							
4	1XX-15-00-00-00	Program management	25							

Table 23. Recurring (Production) Cost Estimate Data — Form A Design Concept 1 (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($ Millions)	Number of Units	Reference Units	Learning Index	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-lunar lander-manned	340		1	90%	36	36	50/50	April 1983
4	1XX-01-00-00-00	Propulsion module	45	6	1	90%				
4	1XX-02-00-00-00	Intelligence module	147	6	1	90%				
4	1XX-03-00-00-00	Crew module	58	4	1	90%				
4	1XX-05-00-00-00	Landing gear kit	3	6	1	90%				
4	1XX-06-00-00-00	Cargo module	2	12	1	90%				
4	1XX-09-00-00-00	Logistics support	11							
4	1XX-10-00-00-00	Operations support	48							
4	1XX-12-00-00-00	Ground support equipment	5							
4	1XX-14-00-00-00	Systems support	10							
4	1XX-15-00-00-00	Program management	11							

Total nonrecurring costs amount to $1518 million and total recurring costs to $1470 million, for a total of $2988, in agreement with Table 13.

Nonrecurring funding is summarized in Table 24, Form D, this funding reaches a maximum of $274 million in 1978. Recurring funding is presented in Table 25, Form D, this funding reaches a maximum of $194 million in 1981. Peak total funding of $411 million occurs in 1979.

6.5 COST ESTIMATES FOR DESIGN CONCEPT 5

Cost estimates for Concept 5 in 1970 dollars are presented in Forms A and D in the same manner as for Concept 1. Nonrecurring and recurring costs total $1544 million and $1746 million, respectively, for a total program cost of $3290 million. These costs are presented in Table 26 and 27, respectively.

Tables 28 and 29 show funding requirements. Nonrecurring funding peaks at $273 million in 1977, while recurring peaks at $229 million in 1982. Peak total funding of $447 would occur in 1979.

6.6 COST ESTIMATES FOR DESIGN CONCEPT 11

Cost estimates for Concept 11 in 1970 dollars are presented in Tables 30 and 31 in Form A format. Nonrecurring costs total $1542 million, and recurring costs total $1915 million for a total of $3457 million.

In Tables 32 and 33, it is seen that nonrecurring funding peaks at $283 million in 1977 and recurring funding peaks at $285 million in 1982. Peak total funding of $443 million would occur in 1980.

6.7 UNMANNED EARTH-ORBITAL EXPENDABLE SPACE TUG

This section covers the costing of unmanned earth-orbital expendable space tugs, which consist of a vehicle encompassing the capabilities of a propulsion module and intelligence module. Payload and consumables are not included.

Costs covering the development, design, test, and engineering (DDT&E) nonrecurring costs and production theoretical first unit (TFU) recurring costs are summarized in Table 34. The cost estimating methodology is described in Paragraph 6.2. The cost presentation is not as detailed for Concepts 1, 5, and 11, because it is intended only for rough comparison purposes. Hence, neither Form A nor Form D is included.

The reductions in RDT&E and first unit costs are evident when comparing Table 34 with Tables 17 through 20. The main reasons for these economies are the reduced weight and complexity in key cost-driving subsystems, which result from simplified mission requirements when expendable rather than recoverable stages are used. This factor is most significant in the guidance/navigation and control, communications, and data management subsystems of the intelligence module. Savings in the propulsion module are primarily due to weight savings and to the absence of docking and docking instrumentation requirements. Engine development in the expendable stage is predicted on modifications to the RL-10 engine and is estimated to be as expensive as the shuttle OMS modification on the propulsion module in the first pertinent development category in Concepts 1, 5, and 11.

Table 24. Cost Estimate Data—Form D, Nonrecurring Costs (DDT&E)— Design Concept 1

Project WBS Items	GFY										Total
	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	
Reusable space tug—earth-orbital-unmanned	22	104	173	173	104	21					597
Reusable space tug—earth-orbital-manned		4	20	107	150	107	22				410
Reusable space tug—lunar lander-manned					20	133	187	133	30	8	511
Total Cost ($ millions)	22	108	193	280	274	261	209	133	30	8	1,518

Table 25. Cost Estimate Data—Form D
Recurring Costs (Production)—
Design Concept 1

Project WBS Items	GFY													Total
	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	
Reusable space Tug—earth-orbital-unmanned	17	40	51	54	50	43	33	24	15	8	6			341
Reusable space tug—earth-orbital-manned	15	44	69	88	101	105	101	91	74	53	32	14	2	789
Reusable space tug—lunar lander-manned	6	19	30	38	43	45	44	39	32	23	14	6	1	340
Total cost ($ Millions)	38	103	150	180	194	193	178	154	121	84	52	20	3	1,470

Table 26. Cost Estimate Data — Form A Nonrecurring (DDT&E) — Design Concept 5

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-earth orbital, unmanned	578	53	61	50/50	January 1980
4	1XX-01-00-00-00	Propulsion module	69				
4	1XX-02-00-00-00	Intelligence module	252				
4	1XX-08-00-00-00	Test hardware	96				
4	1XX-10-00-00-00	Operations support	26				
4	1XX-11-00-00-00	Facilities	29				
4	1XX-12-00-00-00	Ground support equipment	37				
4	1XX-13-00-00-00	Training equipment	11				
4	1XX-14-00-00-00	Systems support	29				
4	1XX-15-00-00-00	Program management	29				
3	1XX-00-00-00-00	Reusable space tug tug-earth-orbital-manned	403	40	48	50/50	December 1980
4	1XX-01-00-00-00	Propulsion module	25				
4	1XX-02-00-00-00	Intelligence module	82				
4	1XX-03-00-00-00	Crew module	119				

Table 26. Cost Estimate Data — Form A Nonrecurring (DDT&E) — Design Concept 5 (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
4	1XX-07-00-00-00	Manipulator kit	1				
4	1XX-08-00-00-00	Test hardware	64				
4	1XX-10-00-00-00	Operations support	18				
4	1XX-11-00-00-00	Facilities	20				
4	1XX-12-00-00-00	Ground support equipment	26				
4	1XX-13-00-00-00	Training equipment	8				
4	1XX-14-00-00-00	Systems support	21				
4	1XX-15-00-00-00	Program management	19				
3	1XX-00-00-00-00	Reusable space tug-lunar lander-manned	563	41	49	50/50	April 1983
4	1XX-01-00-00-00	Propulsion module	69				
4	1XX-02-00-00-00	Intelligence module	104				
4	1XX-03-00-00-00	Crew module	60				
4	1XX-04-00-00-00	Tank set	34				
4	1XX-05-00-00-00	Landing gear kit	9				

Table 26. Cost Estimate Data — Form A Nonrecurring (DDT&E) — Design Concept 5 (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
4	1XX-06-00-00-00	Cargo module	5				
4	1XX-08-00-00-00	Test hardware	129				
4	1XX-10-00-00-00	Operations support	26				
4	1XX-11-00-00-00	Facilities	25				
4	1XX-12-00-00-00	Ground support equipment	36				
4	1XX-13-00-00-00	Training equipment	10				
4	1XX-14-00-00-00	Systems support	29				
4	1XX-15-00-00-00	Program management	27				

Table 27. Cost Estimate Data — Form A Design Concept 5

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($ Millions)	Number of Units	Reference Units	Learning Index	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-earth-orbital, unmanned	592	-	1	90%	36	36	50/50	January 1980
4	1XX-01-00-00-00	Propulsion module	99	18	1	90%				
4	1XX-02-00-00-00	Intelligence module	345	18	1	90%				
4	1XX-9-00-00-00	Logistics support	20							
4	1XX-10-00-00-00	Operations support	84							
4	1XX-12-00-00-00	Ground support equipment	10							
4	1XX-14-00-00-00	Systems support	16							
4	1XX-15-00-00-00	Program management	18							
3	1XX-00-00-00-00	Reusable space tug-earth-orbital-manned	793	-	1	90%	36	36	50/50	December 1980
4	1XX-01-00-00-00	Propulsion module	108	20	1	90%				
4	1XX-02-00-00-00	Intelligence module	363	20	1	90%				
4	1XX-03-00-00-00	Crew module	120	12	1	90%				
4	1XX-07-00-00-00	Manipulator kit	1	10	1	90%				
4	1XX-09-00-00-00	Logistics support	27							
4	1XX-10-00-00-00	Operations support	113							
4	1XX-12-00-00-00	Ground support equipment	14							
4	1XX-14-00-00-00	Systems support	23							
4	1XX-15-00-00-00	Program management	24							

Table 27. Cost Estimate Data — Form A Design Concept 5 (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($ Millions)	Number of Units	Reference Units	Learning Index	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-lunar lander-manned	362	-	1	90%	36	36	50/50	April 1983
4	1XX-01-00-00-00	Propulsion module	39	6	1	90%				
4	1XX-02-00-00-00	Intelligence module	147	6	1	90%				
4	1XX-03-00-00-00	Crew module	58	4	1	90%				
4	1XX-04-00-00-00	Tank set	23	6	1	90%				
4	1XX-05-00-00-00	Landing gear kit	3	6	1	90%				
4	1XX-06-00-00-00	Cargo module	2	12	1	90%				
4	1XX-09-00-00-00	Logistics support	12							
4	1XX-10-00-00-00	Operations support	51							
4	1XX-12-00-00-00	Ground support equipment	6							
4	1XX-14-00-00-00	Systems support	10							
4	1XX-15-00-00-00	Program management	11							

Table 28. Cost Estimate Data—Form D
Nonrecurring Costs (DDT&E)—
Design Concept 5

Project WBS Items	GFY										Total
	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	
Reusable space tug—earth-orbital-unmanned	20	101	168	168	101	20					578
Reusable space tug—earth-orbital-manned		3	21	105	148	105	21				403
Reusable space tug—lunar lander-manned					23	146	206	146	33	9	563
Total cost ($ millions)	20	104	189	273	272	271	227	146	33	9	1,544

Table 29. Cost Estimate Data—Form D
Recurring Costs (Production)—
Design Concept 5

Project WBS Items	GFY													Total
	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	
Reusable space tug—earth-orbital-unmanned	19	51	76	79	80	75	67	54	40	27	16	6	1	591
Reusable space tug—earth-orbital-manned	15	44	69	89	101	106	102	91	74	54	32	14	2	793
Reusable space tug—lunar lander-manned	7	20	31	41	46	48	47	42	34	24	15	6	1	362
Total cost ($ millions)	41	115	176	209	227	229	216	187	148	105	63	26	4	1,746

Table 30. Cost Estimate Data — Form A Nonrecurring (DDT&E) — Design Concept II

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-earth orbital, unmanned	620	53	61	50/50	January 1980
4	1XX-01-00-00-00	Propulsion module	60				
4	1XX-02-00-00-00	Intelligence module	252				
4	1XX-04-00-00-00	Tank set	34				
4	1XX-08-00-00-00	Test hardware	101				
4	1XX-10-00-00-00	Operations support	28				
4	1XX-11-00-00-00	Facilities	31				
4	1XX-12-00-00-00	Ground support equipment	39				
4	1XX-13-00-00-00	Training equipment	12				
4	1XX-14-00-00-00	Systems support	32				
4	1XX-15-00-00-00	Program management	31				
3	1XX-00-00-00-00	Reusable space tug-earth-orbital-manned	395	40	48	50/50	December 1980
4	1XX-01-00-00-00	Propulsion module	21				
4	1XX-02-00-00-00	Intelligence module	82				

Table 30. Cost Estimate Data — Form A Nonrecurring (DDT&E) — Design Concept 11 (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
4	1XX-03-00-00-00	Crew module	119				
4	1XX-07-00-00-00	Manipulator kit	1				
4	1XX-08-00-00-00	Test hardware	62				
4	1XX-10-00-00-00	Operations support	18				
4	1XX-11-00-00-00	Facilities	20				
4	1XX-12-00-00-00	Ground support equipment	25				
4	1XX-13-00-00-00	Training equipment	8				
4	1XX-14-00-00-00	Systems support	20				
4	1XX-15-00-00-00	Program management	19				
3	1XX-00-00-00-00	Reusable space tug-lunar lander-manned	527	41	49	50/50	April 1983
4	1XX-01-00-00-00	Propulsion module	64				
4	1XX-02-00-00-00	Intelligence module	104				
4	1XX-03-00-00-00	Crew module	60				
4	1XX-04-00-00-00	Tank set	16				

Table 30. Cost Estimate Data — Form A Nonrecurring (DDT&E) — Design Concept II (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($Millions)	T/D	T/S	Spread Function	Milestone Date
4	1XX-05-00-00-00	Landing gear kit	9				
4	1XX-06-00-00-00	Cargo module	5				
4	1XX-08-00-00-00	Test hardware	125				
4	1XX-10-00-00-00	Operations support	24				
4	1XX-11-00-00-00	Facilities	23				
4	1XX-12-00-00-00	Ground support equipment	34				
4	1XX-13-00-00-00	Training equipment	10				
4	1XX-14-00-00-00	Systems support	27				
4	1XX-15-00-00-00	Program management	26				

Table 31. Cost Estimate Data — Form A Recurring (Production) — Design Concept 11

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($ Millions)	Number of Units	Reference Units	Learning Index	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-earth-orbital, unmanned	827	-	1	90%	36	36	50/50	January 1980
4	1XX-01-00-00-00	Propulsion module	43	9	1	90%				
4	1XX-02-00-00-00	Intelligence module	191	9	1	90%				
4	1XX-04-00-00-00	Tank set	384	167	1	90%				
4	1XX-9-00-00-00	Logistics support	26							
4	1XX-10-00-00-00	Operations support	121							
4	1XX-12-00-00-00	Ground support equipment	14							
4	1XX-14-00-00-00	Systems support	23							
4	1XX-15-00-00-00	Program management	25							
3	1XX-00-00-00-00	Reusable space tug-earth-orbital-manned	737	-	1	90%	36	36	50/50	December 1980
4	1XX-01-00-00-00	Propulsion module	80	19	1	90%				
4	1XX-02-00-00-00	Intelligence module	347	19	1	90%				
4	1XX-03-00-00-00	Crew module	120	12	1	90%				
4	1XX-07-00-00-00	Manipulator kit	1	10	1	90%				
4	1XX-09-00-00-00	Logistics support	25							
4	1XX-10-00-00-00	Operations support	105							
4	1XX-12-00-00-00	Ground support equipment	14							
4	1XX-14-00-00-00	Systems support	22							
4	1XX-15-00-00-00	Program management	23							

Table 31. Cost Estimate Data — Form A Recurring (Production) — Design Concept 11 (Cont)

WBS Level	WBS Identification Number	WBS Item Name	WBS Item Cost ($ Millions)	Number of Units	Reference Units	Learning Index	T/D	T/S	Spread Function	Milestone Date
3	1XX-00-00-00-00	Reusable space tug-lunar lander-manned	351	-	1	90%	36	36	50/50	April 1983
4	1XX-01-00-00-00	Propulsion module	30	6	1	90%				
4	1XX-02-00-00-00	Intelligence module	147	6	1	90%				
4	1XX-03-00-00-00	Crew module	58	4	1	90%				
4	1XX-04-00-00-00	Tank set	23	6	1	90%				
4	1XX-05-00-00-00	Landing gear kit	3	6	1	90%				
4	1XX-06-00-00-00	Cargo module	2	12	1	90%				
4	1XX-09-00-00-00	Logistics support	11							
4	1XX-10-00-00-00	Operations support	49							
4	1XX-12-00-00-00	Ground support equipment	6							
4	1XX-14-00-00-00	Systems support	10							
4	1XX-15-00-00-00	Program management	12							

Table 32. Cost Estimate Data—Form D
Nonrecurring Costs (DDT&E)—
Design Concept 11

Project WBS Items	GFY										Total
	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	
Reusable space tug—earth-orbital-unmanned	22	108	180	180	108	22					620
Reusable space tug—earth-orbital-manned		3	30	103	144	93	22				395
Reusable space tug—lunar lander-manned					21	137	193	137	30	9	527
Total cost ($ millions)	22	111	210	283	273	252	215	137	30	9	1,542

Table 33. Cost Estimate Data—Form D
Recurring Costs (Production)—
Design Concept 11

Project WBS Items	GFY													Total
	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	
Reusable space tug—earth-orbital-unmanned	5	32	69	106	131	140	131	106	69	32	6			827
Reusable space tug—earth-orbital-manned	15	41	64	83	94	98	94	85	69	50	31	11	2	737
Reusable space tug—lunar lander-manned	6	19	31	39	45	47	45	40	33	24	15	6	1	351
Total cost ($ millions)	26	92	164	228	270	285	270	231	171	106	52	17	3	1,915

Table 34. Cost Estimates for Unmanned Earth Orbital Expendable Space Tug

Item	Model 1 (a) Single-Stage Expended (Cryogenic LOX/LH_2)	Model 1 (b) Single-Stage Expendable (N_2O_4/A50) Storable
Intelligence module		
Dry weight	(1,459 lb)	(1,459 lb)
Nonrecurring cost	\$85 $\overline{M}$	\$85 $\overline{M}$
Recurring cost (1st unit)	\$11.3 $\overline{M}$	\$11.3 $\overline{M}$
Propulsion module		
Dry weight	(3,980 lb)	(3,300 lb)
Nonrecurring cost	\$81 $\overline{M}$	\$73 $\overline{M}$
Recurring cost (1st unit)	\$4.8 $\overline{M}$	\$3.1 $\overline{M}$
Total—expendable vehicle		
Dry weight	(5,439 lb)	(4,759 lb)
Nonrecurring cost	\$166 $\overline{M}$	\$158 $\overline{M}$
Recurring cost (1st unit)	\$16.1 $\overline{M}$	\$14.4 $\overline{M}$