30 APRIL 1967 LMSC-A847941

Study of Mission Modes and System Analysis for Lunar Exploration

MIMOSA

FINAL REPORT

MIMOSA SUMMARY TECHNICAL REPORT

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

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Prepared Under Contract NAS 8-20262
for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

FOREWORD

This document is the MIMOSA Summary Technical Report, which constitutes part of the final report on the Study of Mission Modes and Systems Analysis for Lunar Exploration (MIMOSA). This study was conducted by the LMSC MIMOSA team for the George C. Marshall Space Flight Center under contract NAS 8-20262. The entire final report covers work performed from 3 January 1966 to 3 February 1967 and comprises the following parts:

- MIMOSA Summary Digest
- MIMOSA Summary Technical Report
- MIMOSA Technical Report:
  Volume I – Lunar Exploration Equipment and Mode Definition
  Volume II – Candidate Lunar Exploration Programs
  Volume III – Recommended Lunar Exploration Plan
- MIMOSA Planning Methodology:
  Volume I – Planners' Handbook
  Volume II – Exploration Equipment Data Book
  Volume III – Scientific Programs

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- Lockheed Missiles & Space Company. Prime Contractor
- AiResearch Manufacturing Company. Environmental Control and Life Support System
- Bell Aerosystems Company. Lunar Flying Vehicles
- Bendix Corporation, Aerospace Systems Division. Lunar Roving Vehicles Definition and Contributions to Scientific Program Formulation
- General Electric Company, Missile & Space Division. Electrical Power Systems

The technical management of the study was conducted by a government team composed of several organizations and their selected representatives. The Technical Supervisor and Contracting Officers' Representative for the National Aeronautics and Space Administration was David Paul 3rd, of the Advanced Systems Office, Marshall Space Flight Center (MSFC). Contributing organizations and their representatives were as follows:

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Dr. Harold Masursky of the Astrogeology Branch, U.S. Geological Survey, was consulted regarding geological experimentation, and Dr. William G. Tifft, Steward Observatory, University of Arizona, was consulted regarding optical astronomy. In addition, Dr. Alfred H. Webber of St. Louis University provided general advice on scientitic experimentation.

The study also drew on certain previous and concurrent studies for information. The most significant of these were as follows:

- Scientific Mission Support for Extended Lunar Exploration. North American Aviation, Inc., Contract NAS 8-20258 (William McKaig, Study Leader)
- Lunar Surface Mobility Systems Comparison and Evolution Study (MOBEV). Bendix Corporation, Aerospace Systems Division, Contract NAS 8-20334 (Carmelo J. Moscolino, Study Leader)
- Early Lunar Shelter Design and Comparison Study. AiResearch Manufacturing Company, Contract NAS 8-20261 (William L. Burriss, Study Leader)

The study was aided by an independent effort on the part of Mr. Wes C. Schmill of Atomics International, a Division of North American Aviation, Inc., who contributed to the definition of nuclear power systems.

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INTRODUCTION

The objectives of the MIMOSA study were twofold – to produce a methodology for generating lunar exploration programs and to generate a recommended lunar exploration plan, using the developed methodology.

The MIMOSA study was divided into the following three phases:

- Phase I – compilation and generation of data for the later phases (these data are contained in the Exploration Equipment Data Book.)
- Phase II – development of the planning methodology that includes a computer program for the mechanization of data handling, generation of a broad spectrum of candidate programs, and comparative analysis to answer certain planning questions
- Phase III – formulation of a recommended plan of lunar exploration, generation of three selected lunar exploration programs for implementing the plan, and intensive design effort for the equipment used in these three programs

Generation of the recommended lunar exploration plan is described in the MIMOSA Technical Report. The methodology is presented in three volumes under MIMOSA Planning Methodology.

This volume is a technical summary of the MIMOSA study and describes (1) study objectives and approach, (2) the MIMOSA planning methodology, (3) the candidate exploration programs, (4) the recommended lunar exploration plan, (5) significant results from the MIMOSA study, and (6) technology implications.

Chapter 1

STUDY OBJECTIVES AND APPROACH

One of the major tasks of the National Aeronautics and Space Administration is long-range planning for the manned exploration of the Moon. Past effort has been devoted to specific system concepts and limited exploration eras; in this approach, the fulfillment of scientific goals has been limited by the potential performance of the concepts studied. Valuable data has been collected on system feasibilities and alternate approaches to lunar exploration. However, no coordinated plan for lunar exploration has emerged that gives sufficiently detailed descriptions of various program options available for achieving predetermined scientific objectives.

The MIMOSA study is an attempt to integrate existing data, with new information where applicable, into a coherent and evolutionary approach to lunar exploration between 1970 and 1990. This approach has been formulated through the use of a planning methodology, developed and exercised during the study, that recognizes the scientific objectives as a prime forcing factor.

1.1 STUDY OBJECTIVES

The two principal objectives of the MIMOSA study were to:

- Develop a planning methodology that can provide NASA management with programmatic data, describe alternate approaches to lunar exploration, resolve planning questions, and establish preferred exploration concepts and an effective course for post-Apollo lunar activities
- Analyze a broad spectrum of alternate lunar exploration program candidates and with that background, formulate an overall plan for post-Apollo lunar exploration that embodies and describes several optional and attractive programs

Supporting, subsidiary objectives were to:

- Formulate representative scientific programs achieving widely different levels of scientific effort
- Evaluate exploration equipment candidates and compile an Equipment Data Book of normalized design, cost, and performance data
- Develop a computer program for mechanizing of data in support of the planning methodology
- Generate candidate lunar exploration programs that represent a wide range of possible equipment uses
- Identify and evaluate the important decision-shaping factors that will influence lunar exploration planning
- Select, as part of the recommended plan, a minimal set of exploration equipment that is adaptable to changes in the planning environment

1.2 STUDY GROUND RULES

The MIMOSA study has the following general ground rules:

- Planning period — 1970's to 1980's
- Scientific programs to be based on established, national scientific goals
- Maximum use to be made of Apollo-developed technology and systems
- Only existing launch vehicles and their uprated versions to be considered
- Development of equipment capability must be in an evolutionary manner
- Equipment designs, cost, and schedules to be normalized
- Data on scientific experiments to be based on North American Aviation catalog developed under NASA Contract NAS 8-20258
- Continuous funding and procurement to be maintained

1.3 DEFINITION OF TERMS

Many of the terms used in MIMOSA have specific interpretations that sometimes differ from the normally accepted connotations. Some of the most frequently used terms are as follows:

- Exploration Program. A scheduled plan for Moon exploration that extends over a significant time period and that uses a particular set of exploration equipment to perform a given scientific program
- Scientific Program. A complete set of experiments that must be performed and a list of lunar locations to be visited to achieve given scientific objectives
- Exploration Equipment. All hardware and systems used in exploring the Moon
- Transportation System. A specific combination of a launch vehicle and its associated logistics or personnel spacecraft
- Mission Equipment. Major system and support hardware (other than transportation systems) used to support and aid the accomplishment of a scientific mission; includes roving and flying vehicles, shelters, and large items of scientific equipment
- Equipment Evolution. A set of exploration equipment that achieves a particular capability for lunar exploration through a logical evolution in equipment development
- Mission. Those operations and experiments specified to be performed at a particular lunar location and within a designated time
- Mode. A set of compatible exploration equipment with an associated operational procedure that can be used to perform a scientific mission

1.4 STUDY APPROACH

Figure 1-1 illustrates the approach taken in the MIMOSA study and some of the major study outputs. Example scientific programs of varying scope were formulated to satisfy basic scientific goals posed by the scientific community. These scientific programs were developed by relating specific experiments to fundamental questions regarding the Moon and are published in MIMOSA Methodology, Vol. III. Scientific missions could then be formulated for the experiments contained in a particular scientific program. The mission requirements can be satisfied by a particular set of exploration equipment (mode). Data on the candidate exploration equipment were generated independently and

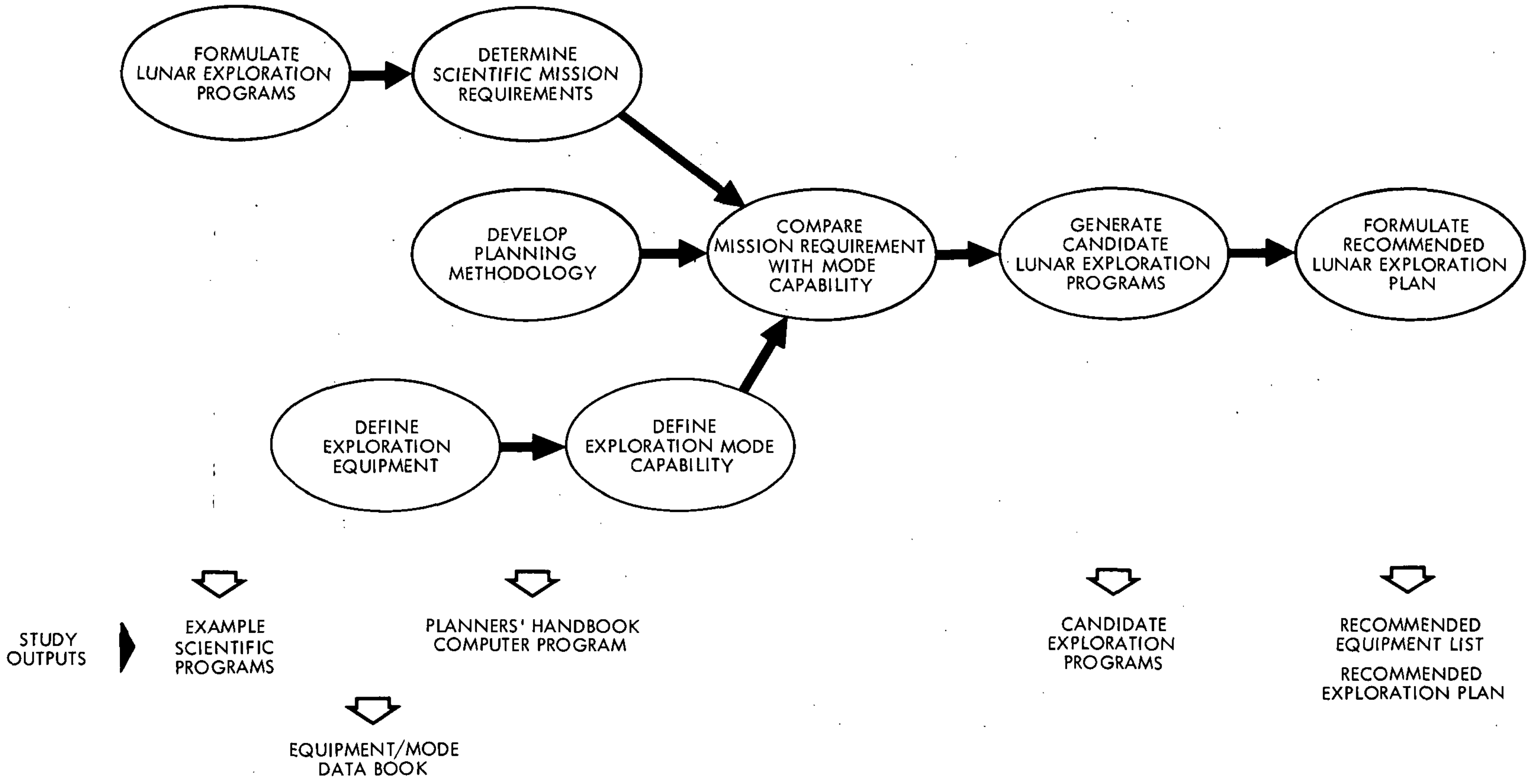

Fig. 1-1 MIMOSA Study Approach

include design, performance, schedule, and cost information. These data are contained in the MIMOSA Data Book (MIMOSA Planning Methodology, Vol. II.)

The MIMOSA planning methodology was developed to coordinate and control information and to provide the overall logic for the generation and analysis of candidate exploration programs. The methodology uses a computer program to perform routine calculations rapidly, to provide a data storage bank, and to give a comprehensive display of a variety of mission and program parameters. The methodology is fully described in MIMOSA Planning Methodology, Vol. I, and is summarized in Chapter 2 of this report.

Using the methodology developed, mission requirements and mode capabilities were matched, the missions scheduled and costed, and the characteristics of the resulting exploration program displayed in detail on the computer output. About 30 exploration programs, representing a broad spectrum of possible exploration approaches and levels of scientific activity, were generated in the study (MIMOSA Technical Report, Vol. II). Information learned during the analysis helped establish important parameters for determining the scope of some of the later candidate programs. An analysis of these programs was then performed to determine the influence of important planning variables.

The final step consisted of formulating a recommended plan for lunar exploration (MIMOSA Technical Report, Vol. III) based on the conclusions drawn from the candidate program analysis and program guidelines from NASA. This plan, summarized in Chapter 4 of this volume, identifies major decision points associated with future lunar exploration planning and describes the implications of exercising the various planning options available.

Chapter 2
MIMOSA PLANNING METHODOLOGY

An important portion of the MIMOSA study was associated with the development of a systematic method of analyzing alternate approaches to lunar exploration. The MIMOSA planning methodology provides a set of standard procedures and criteria for organizing and evaluating the large amounts of data associated with a planning exercise. This chapter outlines the overall planning methodology and describes its major elements. Complete instructions for using the methodology are contained in the MIMOSA Planners Handbook, MIMOSA Planning Methodology, Vol. I.

2.1 PLANNING QUESTIONS

Before proceeding with a lunar program analysis, a planner must define an objective. These objectives take the form of planning questions to which well-substantiated answers are sought. The MIMOSA methodology was, therefore, designed to handle a wide variety of questions in the following areas of interest:

- Scientific – e.g., how does the size of the scientific program influence exploration cost
- Equipment – e.g., what Saturn V uprating is the most cost-effective when used in the performance of a particular scientific program
- Operational – e.g., what Saturn V launch rates are required to achieve a given exploration program
- Program/Resource – e.g., when must nonrecurring investments be committed for the introduction of a new item of exploration equipment into a particular exploration program

The answers to such questions are obtained through the generation of one or more exploration programs and comparative analysis of the relevant program-dependent parameters, such as cost, schedule, and scientific accomplishments.

2.2 PLANNING METHODOLOGY

The planning methodology, summarized in Fig. 2-1, consists of five major steps:

- Selecting a set of planning assumptions (e.g., specific questions to be answered, launch constraints, funding rates, and timing of major events), the size of the scientific program, and an equipment evolution to perform against that scientific program.
- Planning the scientific missions, based on requirements for experimentation established by the selected scientific program (e.g., mission sequence, identification of experiments, shape and length of traverses, and representative sites for major scientific equipment). Mission equipment and candidate modes are then selected to accomplish scientific experiment requirements for each mission.
- Matching of mission requirements and mode capabilities. From stored equipment, mission, and mode information, the MIMOSA computer program can verify the validity of each match of equipment and experiments. Repeated iterations can be made depending on the required accuracy of matching. For the MIMOSA study, two or three iterations yielded the desired results. After successful mission-mode matching, costing and scheduling of the program by the computer will require two or three iterations depending on demands regarding smoothness of funding distribution.
- Summarizing the large amount of information generated in a standard format (Exploration Program Summary).
- Making a comparative analysis of the programs generated to find answers to the planning questions that were originally posed

2.3 MIMOSA COMPUTER PROGRAM

Because the MIMOSA methodology requires the routine handling of large amounts of technical and resource data, a special computer program was developed to assist the planner. This program performs calculations, organizes data, and provides printed output that would require many manhours of tedius labor if done by hand.

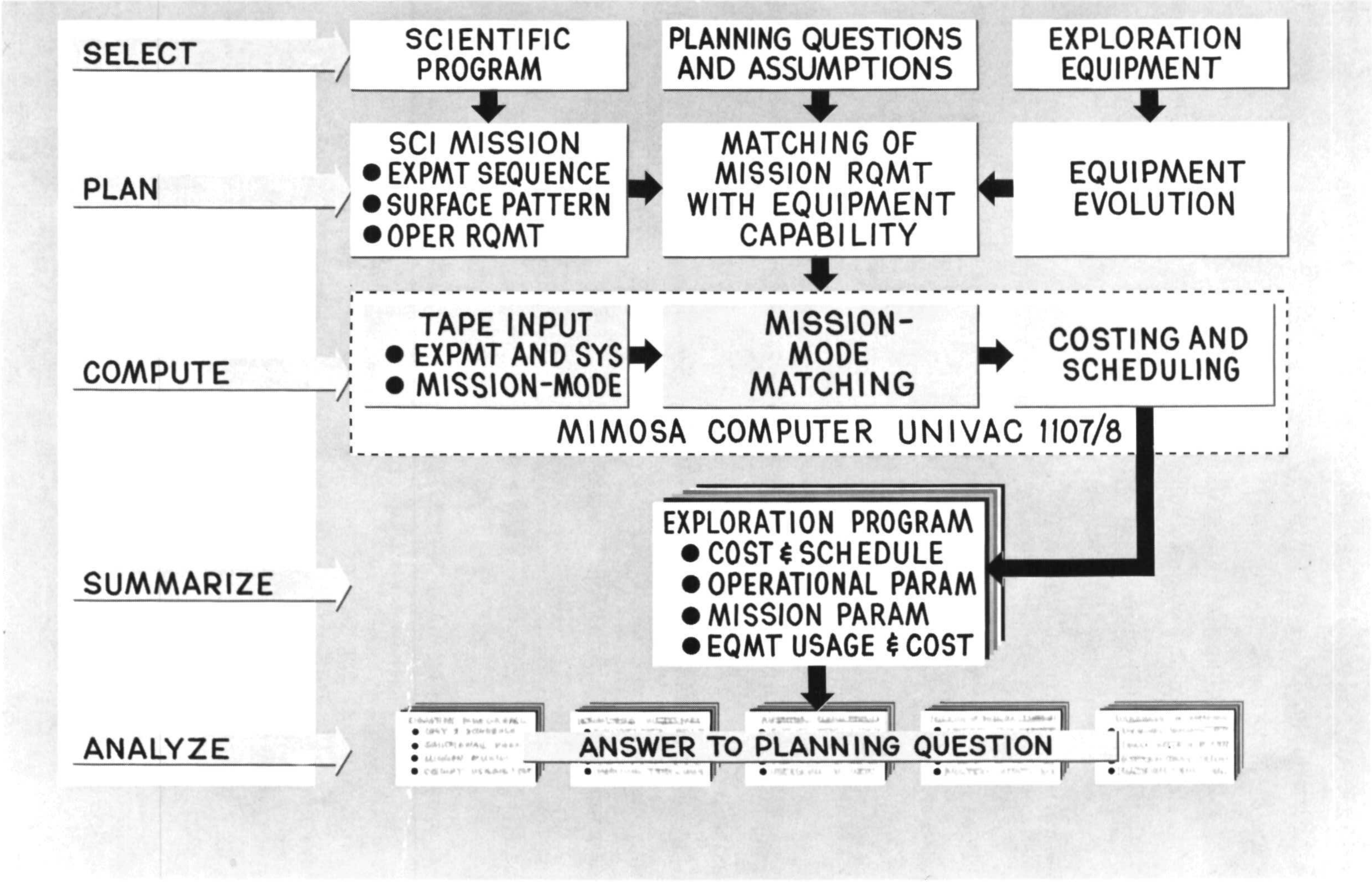

Fig. 2-1 MIMOSA Planning Methodology

The program written for the Univac 1107 and compatible with the faster 1108, consists of three major routines. The input and update routine generates magnetic tapes from card input to store all necessary calculation data, updates these tapes to allow revisions and additions, and copies and prints out all or part of the contents of any tape. The mission-mode comparison routine compares the capabilities of a specified mode with the requirements of a specified mission by making up to 45 separate tests. (Examples of typical test criteria are: do the staytime requirements exceed the mode capability, does the traverse range requirement exceed the maximum range of the roving vehicle, etc.) Any possible problems in matching the mode to the mission are printed out for the information of the planner. The integration and cost routine establishes the schedule of key events resulting from a set of mission-mode combinations, determines equipment usage versus projected time, and calculates nonrecurring and recurring costs versus time.

The program is large, being made up of about 24,000 separate Fortran IV instructions. Approximately 15 minutes of Univac 1108 machine time is required to completely analyze a 30-mission lunar program, including two mission-mode comparison iterations. The computer does not make decisions; it only performs calculations and organizes data in a manner to allow easier analysis by planners. A detailed description of the computer program and instructions for its use are included in the MIMOSA Planners Handbook, MIMOSA Planning Methodology, Vol. I.

2.4 SCIENTIFIC PROGRAM FORMULATION

Conceptual lunar scientific programs of broad scope and significantly different magnitude were needed to provide realistic requirements for developing exploration programs within the MIMOSA planning methodology. Since no detailed, long-term scientific program was available, a systematic procedure was developed for generating lunar scientific programs. Figure 2-2 is a flow diagram representing the procedure used.

2.4.1 Scientific Goals and Scientific Areas

The procedure begins with identification of scientific goals. A set of scientific goals expressed in the form of 25 basic questions was derived from the proceedings of the

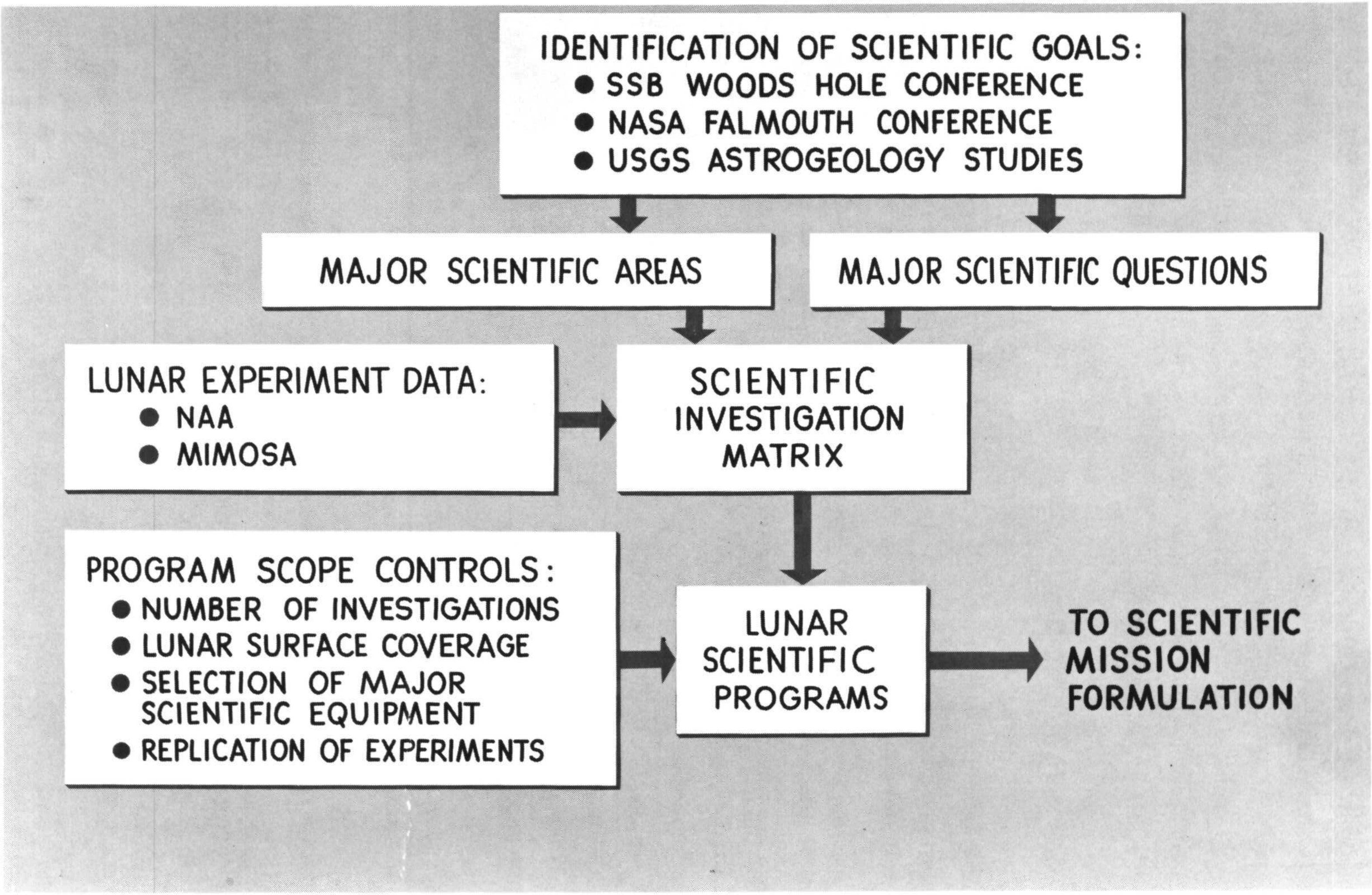

Fig. 2-2 Scientific Program Formulation

1965 Summer Conference of the National Academy of Science's Space Science Board at Woods Hole, Massachusetts, the NASA 1965 Summer Conference at Falmouth, Massachusetts, and various publications of the Astrogeology Branch of the U. S. Geological Survey. Ten major scientific areas also were identified as being of primary importance to the scientific goal. The 25 basic questions and 10 major scientific areas are listed in Tables 2-1 and 2-2, respectively

2.4.2 Scientific Investigation Matrix

The 25 basic questions and the 10 major scientific disciplines provide a framework for assembling a matrix of scientific investigations required for developing answers to the basic questions. The structure of the scientific investigation matrix is shown schematically in Fig. 2-3. The questions are arranged in order along the abscissa of the matrix and the scientific areas are listed on the ordinate. The elements of the matrix are groups of investigations, each group being pertinent to a particular basic question and scientific area. Each investigation implies one or more scientific experiments and each experiment involves one or more items of scientific equipment. Thus, the scientific investigation matrix serves to correlate scientific experiments and equipment with the goals of scientific programs. Figure 2-4 is an excerpt from the developed matrix. The location of each investigation is identified by a three-part code number. The first part corresponds to the question, the second specifies the area and the third part denotes numerical order. The symbols P and S indicate whether the investigation is considered of primary or secondary importance to the scientific question posed by the National Academy of Science (NAS).

The principal source of scientific experiment and equipment data was the NAA catalog of lunar scientific experiments compiled under a NASA-funded study.* From the catalog of more than 350 experiments, about 200 were selected as appropriate to the investigations composing the scientific investigations matrix developed and used in this study.

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*North American Aviation, Inc., Scientific Mission Support for Extended Exploration, NAA SID Report 66-957 (in preparation)

Table 2-1

BASIC SCIENTIFIC QUESTIONS

Question No.	Question*
1	Is the internal structure of the Moon radially symmetrical like the Earth and, if it is, is it differentiated? Specifically, does it have a core and does it have a crust?
2	What is the geometric shape of the Moon? How does the shape depart from fluid equilibrium? Is there a fundamental difference in morphology and history between the sub-Earth and averted faces of the Moon?
3	What is the present internal-energy regime of the Moon? Specifically, what is the present heat flow at the lunar surface and what are the sources of this heat? Is the Moon seismically active and is there active volcanism? Does the Moon have an internally produced magnetic field?
4	What is the average composition of the rocks at the surface of the Moon and how does the composition vary from place-to-place? Are volcanic rocks present on the surface of the Moon?
5	What are the principal processes responsible for the present relief of the lunar surface?
6	What is the present tectonic pattern on the Moon and how is the tectonic activity distributed?
7	What are the dominant processes of erosion, transport, and deposition of material on the lunar surface?
8	What volatile substances are present on or near the surface of the Moon or in a transitory lunar atmosphere?
9	Is there evidence of organic or proto-organic materials on or near the lunar surface? Are living organisms present beneath the surface?
10	What is the age of the Moon? What is the range of the age of the stratigraphic units on the lunar surface and what is the age of the oldest exposed material? Is a primordial surface exposed?
11	What is the history of dynamical interaction between the Earth and the Moon?
12	What is the thermal history of the Moon? What has been the distribution of tectonic and possible volcanic activity in time?
13	What has been the flux of solid objects striking the lunar surface in the past and how has it varied with time?
14	What has been the flux of cosmic radiation and high-energy solar radiation over the history of the Moon?
15	What past magnetic fields may be recorded in the rocks at the Moon's surface?
16	What are the long-term effects of reduced gravity on various life forms, including man?
17	What lunar resources are available for exploitation?
18	What lunar environmental factors are most significant to the design of proposed lunar missions?
19	Are the basic postulates of general relativity valid?
20	What is the total inventory of stars and interstellar matter in a representative volume of our galaxy?
21	What processes account for the phenomena observed in the Sun, e.g., sunspots, flares, plages, faculae, and prominences?
22	What are the structures, compositions, and energy regimes of planetary atmospheres other than that of Earth?
23	What are the structures and compositions of comets?
24	What are the precise locations of discrete x-ray sources and what is the distribution of faint x-ray sources?
25	What is the distribution of radio stars having very long wavelength?

*Questions 1 through 15, inclusive, are taken directly from proceedings of the 1965 Woods Hole Conference and are concerned with the Moon per se. The remaining questions were stated or implied at the Woods Hole and Falmouth Conferences and are motivated by the potentialities of the Moon as a base for pursuit of astronomical and other extralunar scientific goals.

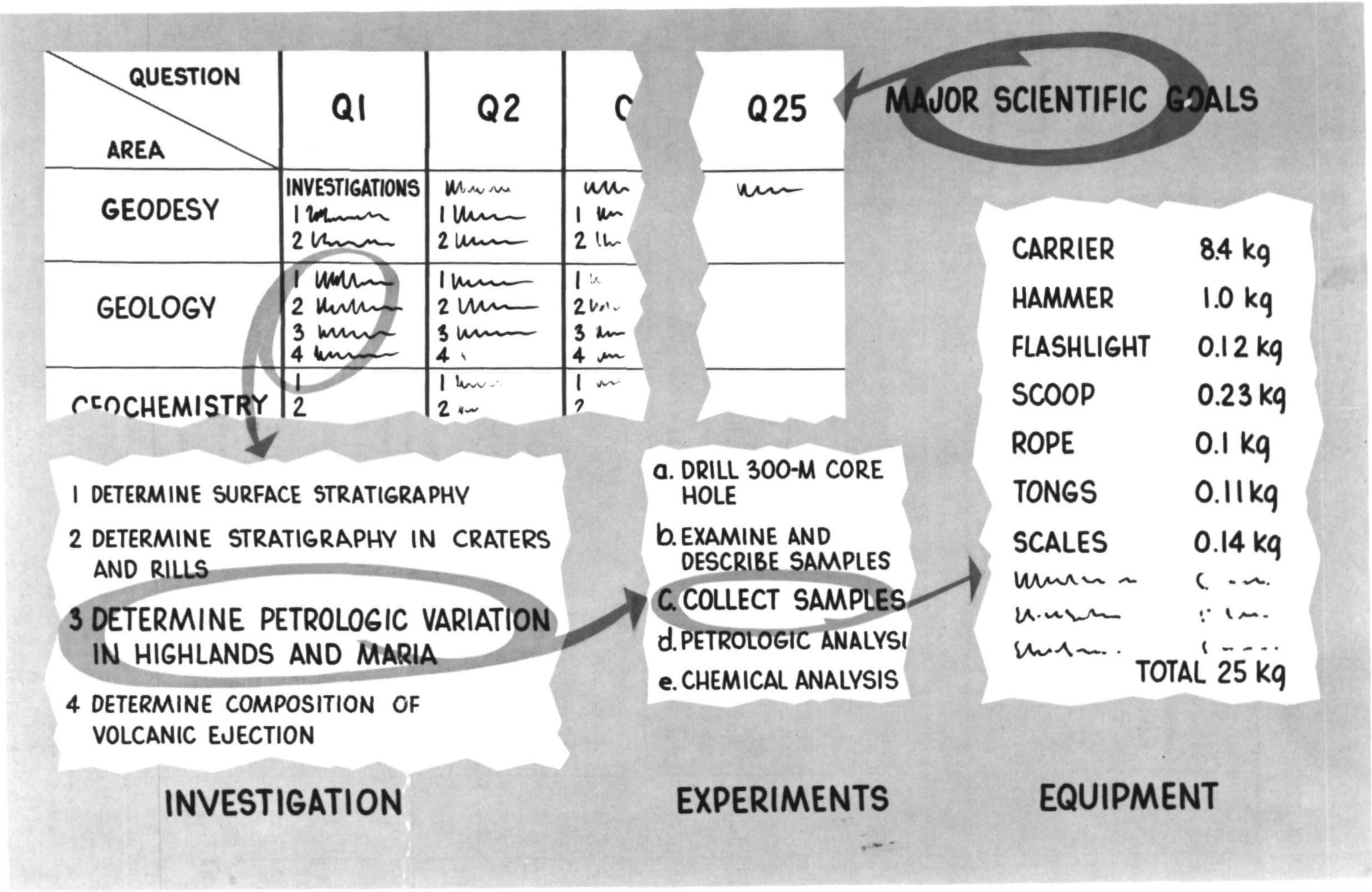
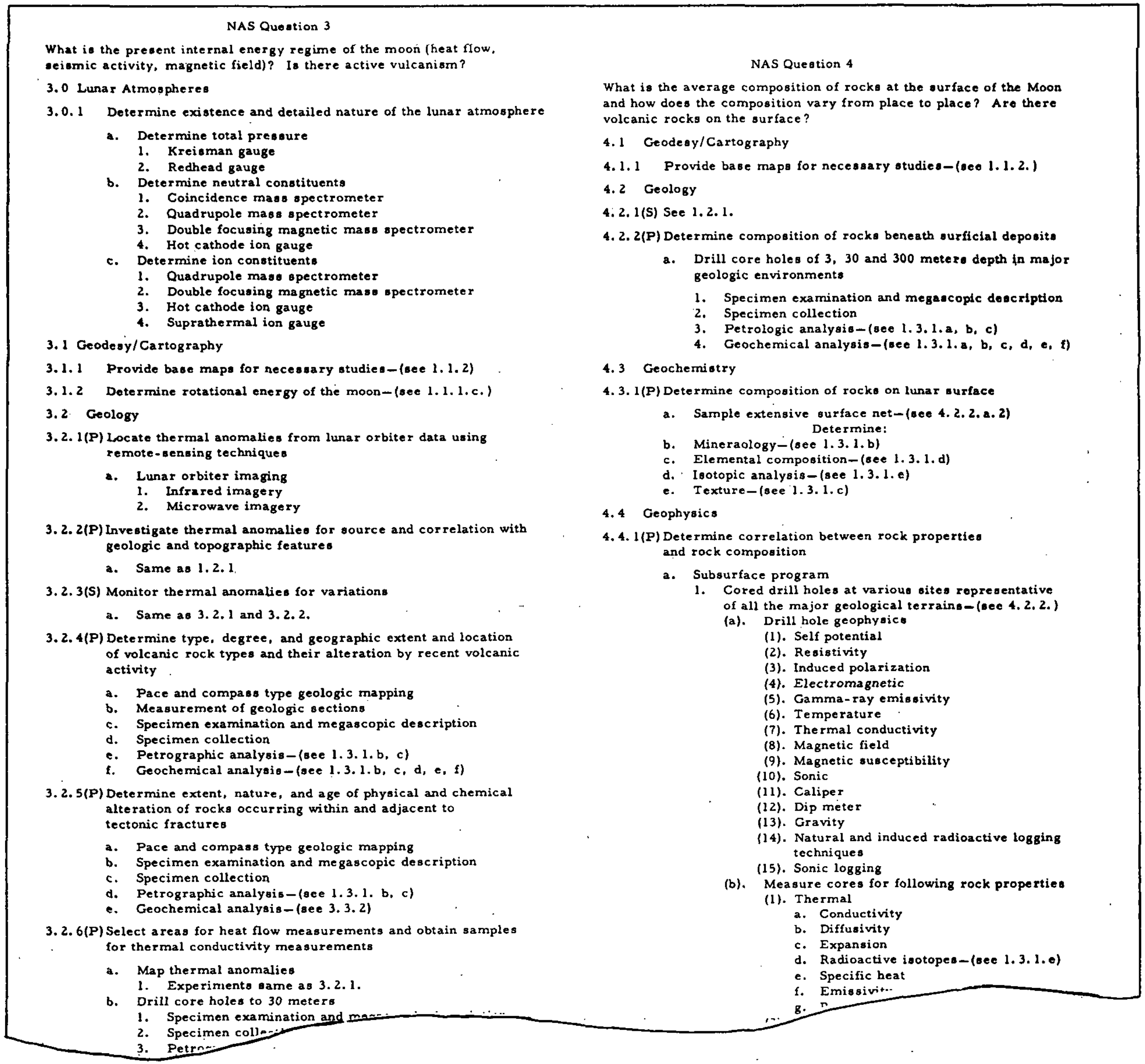


Fig. 2-3 Scientific Investigation Matrix



NAS Question 3

What is the present internal energy regime of the moon (heat flow, seismic activity, magnetic field)? Is there active vulcanism?

3.0 Lunar Atmospheres

3.0.1 Determine existence and detailed nature of the lunar atmosphere

- a. Determine total pressure
  - 1. Kreisman gauge
  - 2. Redhead gauge
- b. Determine neutral constituents
  - 1. Coincidence mass spectrometer
  - 2. Quadrupole mass spectrometer
  - 3. Double focusing magnetic mass spectrometer
  - 4. Hot cathode ion gauge
- c. Determine ion constituents
  - 1. Quadrupole mass spectrometer
  - 2. Double focusing magnetic mass spectrometer
  - 3. Hot cathode ion gauge
  - 4. Suprathermal ion gauge

3.1 Geodesy/Cartography

3.1.1 Provide base maps for necessary studies—(see 1.1.2)

3.1.2 Determine rotational energy of the moon—(see 1.1.1.c.)

3.2 Geology

3.2.1(P) Locate thermal anomalies from lunar orbiter data using remote-sensing techniques

- a. Lunar orbiter imaging
  - 1. Infrared imagery
  - 2. Microwave imagery

3.2.2(P) Investigate thermal anomalies for source and correlation with geologic and topographic features

- a. Same as 1.2.1.

3.2.3(S) Monitor thermal anomalies for variations

- a. Same as 3.2.1 and 3.2.2.

3.2.4(P) Determine type, degree, and geographic extent and location of volcanic rock types and their alteration by recent volcanic activity

- a. Pace and compass type geologic mapping
- b. Measurement of geologic sections
- c. Specimen examination and megascopic description
- d. Specimen collection
- e. Petrographic analysis—(see 1.3.1.b, c)
- f. Geochemical analysis—(see 1.3.1.b, c, d, e, f)

3.2.5(P) Determine extent, nature, and age of physical and chemical alteration of rocks occurring within and adjacent to tectonic fractures

- a. Pace and compass type geologic mapping
- b. Specimen examination and megascopic description
- c. Specimen collection
- d. Petrographic analysis—(see 1.3.1. b, c)
- e. Geochemical analysis—(see 3.3.2)

3.2.6(P) Select areas for heat flow measurements and obtain samples for thermal conductivity measurements

- a. Map thermal anomalies
  - 1. Experiments same as 3.2.1.
- b. Drill core holes to 30 meters
  - 1. Specimen examination and
  - 2. Specimen coll
  - 3. Petr

NAS Question 4

What is the average composition of rocks at the surface of the Moon and how does the composition vary from place to place? Are there volcanic rocks on the surface?

4.1 Geodesy/Cartography

4.1.1 Provide base maps for necessary studies—(see 1.1.2.)

4.2 Geology

4.2.1(S) See 1.2.1.

4.2.2(P) Determine composition of rocks beneath surficial deposits

- a. Drill core holes of 3, 30 and 300 meters depth in major geologic environments
  - 1. Specimen examination and megascopic description
  - 2. Specimen collection
  - 3. Petrologic analysis—(see 1.3.1.a, b, c)
  - 4. Geochemical analysis—(see 1.3.1.a, b, c, d, e, f)

4.3 Geochemistry

4.3.1(P) Determine composition of rocks on lunar surface

- a. Sample extensive surface net—(see 4.2.2.a.2)

Determine:

- b. Mineraology—(see 1.3.1.b)
- c. Elemental composition—(see 1.3.1.d)
- d. Isotopic analysis—(see 1.3.1.e)
- e. Texture—(see 1.3.1.c)

4.4 Geophysics

4.4.1(P) Determine correlation between rock properties and rock composition

- a. Subsurface program
  - 1. Cored drill holes at various sites representative of all the major geological terrains—(see 4.2.2.)
    - (a). Drill hole geophysics
      - (1). Self potential
      - (2). Resistivity
      - (3). Induced polarization
      - (4). *Electromagnetic*
      - (5). Gamma-ray emissivity
      - (6). Temperature
      - (7). Thermal conductivity
      - (8). Magnetic field
      - (9). Magnetic susceptibility
      - (10). Sonic
      - (11). Caliper
      - (12). Dip meter
      - (13). Gravity
      - (14). Natural and induced radioactive logging techniques
      - (15). Sonic logging
    - (b). Measure cores for following rock properties
      - (1). Thermal
        - a. Conductivity
        - b. Diffusivity
        - c. Expansion
        - d. Radioactive isotopes—(see 1.3.1.e)
        - e. Specific heat
        - f. Emissiv
        - g.

Fig. 2-4 Excerpt From Scientific Investigation Matrix

Table 2-2

MAJOR SCIENTIFIC AREAS

Code	Title
0	Lunar Atmosphere
1	Geodesy/Cartography
2	Geology
3	Geochemistry
4	Geophysics
5	Particles and Fields
6	Biology
7	Astronomy
8	Mission Support/Engineering
9	Applied Science

2.4.3 Program Scope Controls

By applying the following program scope controls to the investigation matrix and to the array of scientific experiments selected in relation to the matrix, lunar scientific programs of any desired scope and scientific emphasis can be derived.

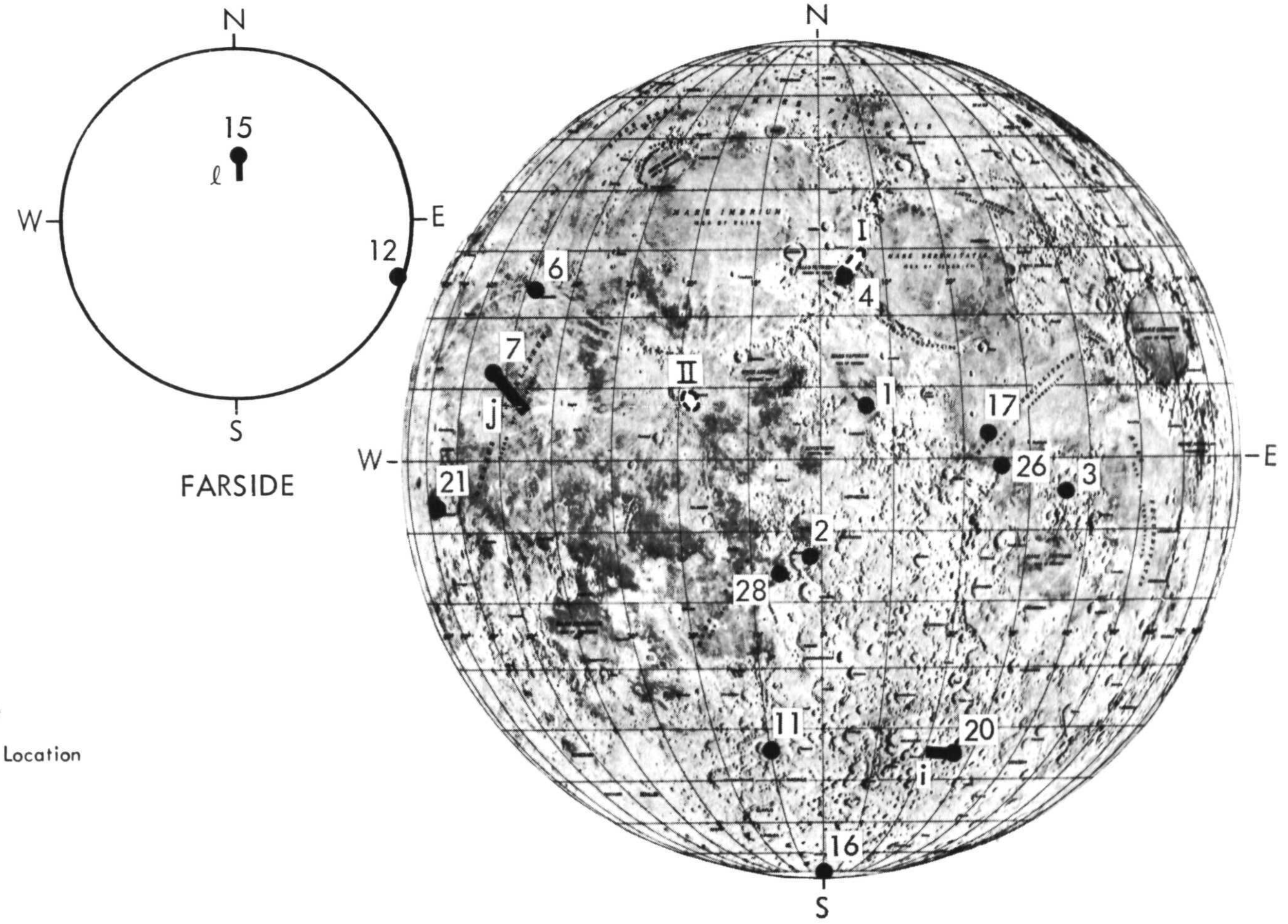
Scope Control by Investigations. Broad variation in program scope was achieved by selectively specifying the scope of investigations within each scientific area that is relevant to each basic question. Emphasis upon geoscientific questions by the National Academy of Science resulted in a large number of investigations in the geoscience areas. A minimal emphasis on lunar bioscience resulted in a small number of investigations in this area. By omission of all investigations under the last 10 basic questions, the smallest lunar scientific programs are restricted to pursuit of goals concerned only with the Moon. The larger scientific programs include investigations under all 25 basic questions and, therefore, embrace extralunar goals in astronomy, planetology, solar physics, etc.

Scope Control by Lunar Surface Coverage. The number and sizes of areas and paths to be explored on the lunar surface are major factors affecting the magnitude of scientific programs. Two different types of lunar surface exploration patterns have been examined for purposes of mode comparison. The first type, called the locale approach, emphasizes observations in the immediate neighborhood (within about 10 km) of isolated landing points, supplemented by broader investigation of larger areas termed regions (dimensions of the order of 100 km). The other type, called the path approach, concentrates on the distribution of scientific observations along paths joining salient features of interest.

The influences of the two approaches in determining the nature of the lunar surface exploration patterns are shown in Figs. 2-5 and 2-6 which correspond, respectively, to the locale and the path approaches. Both surface exploration patterns are intended to accomplish generally the same level of scientific penetration; essentially the same places of major interest are visited in both approaches.

The two approaches differ mainly in the required number of launchings from Earth. With the locale approach, each major target of interest on the Moon requires a separate mission. The path approach (assuming adequate mobility is available) permits visiting a number of major targets in one mission and therefore requires fewer launchings from Earth for a given scientific program. Program parameters resulting from each of these philosophies can be compared in the MIMOSA Technical Report, Vol. II

Scope Control by Major Scientific Equipment. Major scientific equipment consists of those items of scientific equipment whose size and complexity are dominant enough to merit special treatment in their delivery to and deployment on the lunar surface. Examples of major scientific equipment are deep drills, large radio and optical telescopes, and geochemical or biomedical laboratories of major competence. Operationally, for the purposes of MIMOSA, major scientific equipment is treated in the same manner as major hardware systems.



Legend:

Locales

1	Hyginus Rille
2	Alphonsus
3	Capella M
4	Hadley's Rille
6	Aristarchus
7	Marius Hills
11	Tycho
12	Mare Orientale
15	Farside
16	South Pole
17	Ranger VIII Landing Site
20	Southern Highlands
21	Grimaldi, Astronomical Location
26	Moltke B
28	Mare Nubium

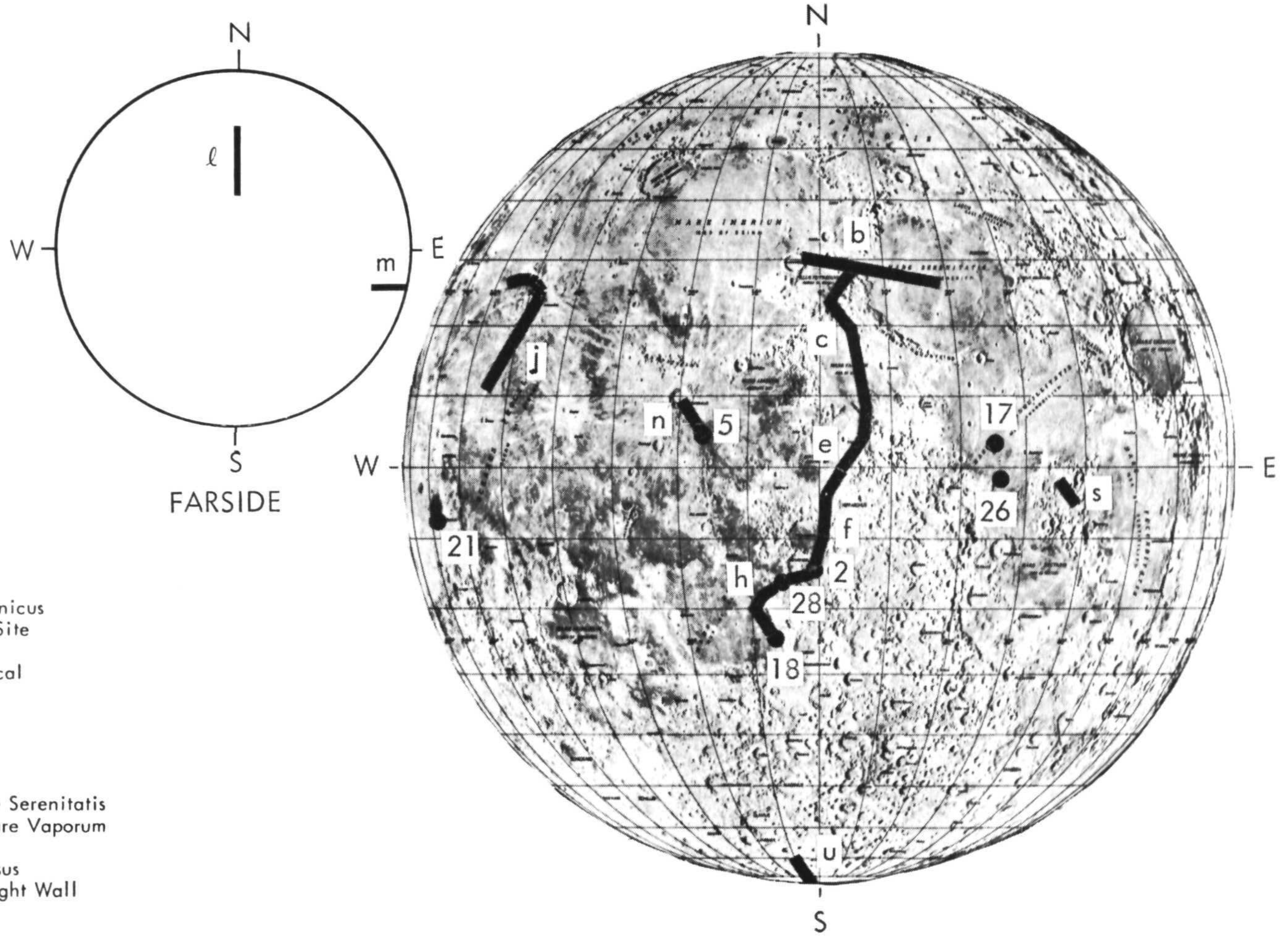
Paths

i	Southern Highlands
j	Marius Hills
ℓ	Central Farside

Regions

I	Palus Putredinis
II	Copernicus

Fig. 2-5 Surface-Exploration Pattern – Locale Approach



Legend:

Locales

2 Alphonsus
5 Dark Halo Craters Southeast of Copernicus
17 Ranger VIII Landing Site
18 Straight Wall
21 Grimaldi, Astronomical Location
26 Moltke B
23 Mare Nubium

Paths

b Mare Imbrium – Mare Serenitatis
c Palus Putredinis – Mare Vaporum
e Sinus Medii
f Ptolemaeus – Alphonsus
h Mare Nubium – Straight Wall
j Marius Hills
ℓ Central Farside
m Mare Orientale
n Copernicus
s Capella M
u South Pole

Fig. 2-6 Surface-Exploration Pattern – Path Approach

Extensive scientific investigations and experiments are generally associated with major scientific equipment and usually considerable support operations are involved. Thus, the inclusion or omission of various items of major scientific equipment significantly affects the scope of a scientific program.

Scope Control by Replication of Experiments. Many experiments gain significance through replication. For example, determination of the average composition of the lunar surface depends upon sampling the surface at many places. Similarly, the gravitational configuration of the Moon requires observations at many widely separated places on the Moon. Varying the specifications for replication of experiments of this kind is another means for varying the aggressiveness of a program and, in turn, its demands for total manhours of scientific effort. Obviously, a cut in the number of replications reduces the confidence of the resulting scientific judgements and reduction beyond some point will completely negate the experiment's worth.

2.4.4 Presentation of Lunar Scientific Programs

The final step in scientific program formulation is to present the contents of a program in a form in which the data can be used readily by the mission planner, who organizes experiments into missions. The contents of the program specification package consists of lunar maps describing the lunar surface exploration pattern, a list of the locales, regions and paths to be explored, a list of the major scientific equipment to be used in the program, and a list of scientific experiments with instructions specifying distribution of the experiments in location and time and specifying the number and frequency of replications of each experiment.

In this study, scientific programs of three different levels of ambitiousness were generated. Lunar surface exploration patterns were prescribed in accordance with the locale and the path approach for each program size, thus creating six program situations. The parameters of these six programs are summarized in Fig. 2-7 and are presented in full in MIMOSA Scientific Programs, MIMOSA Planning Methodology, Vol. III.

	PATH APPROACH			LOCALE APPROACH		
SCIENTIFIC PROGRAM	A	B	C	A'	B'	C'
NO. OF LOCALES	8	7	6	21	15	13
NO. OF PATHS	20	11	6	4	3	2
TOTAL PATH LENGTH, KM	8500	4800	2400	1700	600	200
NO. OF REGIONS	-	-	-	4	2	1
TOTAL REGION AREA, SQ KM	-	-	-	54,000	1800	1500
NO. OF EXPERIMENTS	198	177	113	188	165	121
SCIENTIFIC MANHOURS	54,000	30,000	7,000	54,000	30,000	9,000
MINOR SCI EQMT MASS, KG	45,000	30,000	17,000	33,000	23,000	15,000
MAJOR SCI EQMT MASS, KG	110,000	50,000	14,000	110,000	50,000	14,000
MASS OF EXPLOSIVES, KG	156,000	94,000	42,000	48,000	18,000	2,600
EARTH RETURN MASS, KG	12,000	6,200	3,100	10,000	5,300	2,600

Fig. 2-7 Summary of MIMOSA Scientific Programs

2.5 EXPLORATION EQUIPMENT DEFINITION

One of the major tasks of the MIMOSA study was to survey the existing information on exploration equipment concepts and designs and to normalize these to a common set of groundrules and assumptions. It was essential that all equipment be defined in terms of the same groundrules and assumptions to permit a valid comparative analysis. The existing concepts were supplemented by new concepts where required. The resulting information is an important constituent of the MIMOSA planning tool and is presented in the MIMOSA Exploration Equipment Data Book, Vol. II of the MIMOSA Planning Methodology. The analysis procedure, as well as the contents of the data sheets, are summarized in Fig. 2-8.

2.5.1 Ground Rules and Assumptions

The ground rules and assumptions used in the equipment definition are given below.

Transportation Systems

- The number of personnel to be delivered to the lunar surface in one launch will be two, three, or six.
- Accessibility will be provided to any site on the lunar surface.
- No consideration will be given to reusable launch vehicles and spacecraft.
- No dependence to be assumed on lunar-stored propellants for ascent and Earth return stages.
- Maximum utilization will be made of Apollo systems.
- Propellants considered will be limited to Apollo storables (N_2O_4 and 50/50 hydrazine/UDMH) and Saturn cryogenics (LOX and LH_2).
- Continuous abort capability will not be required.

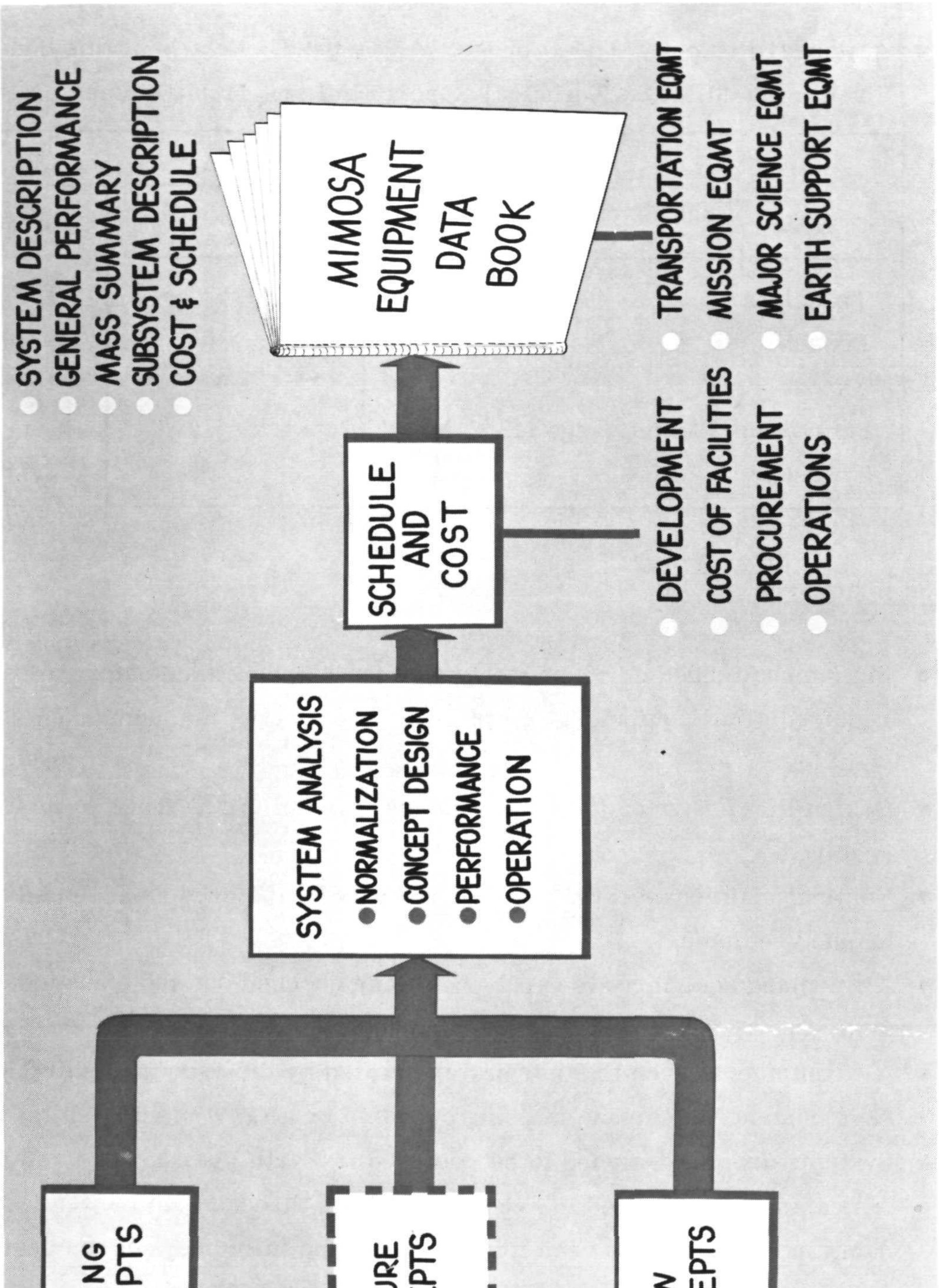


Fig. 2-8 Exploration Equipment Definition

- A standard velocity (ΔV) budget will be used. Details of this budget are given in the MIMOSA Technical Report, Vol. I. Major elements are:

Flight Maneuver	ΔV (m/sec)	
	Lunar Orbit Rendezvous	Direct
Translunar	1,074	1,074
Descent	2,100	2,100
Ascent	2,018	1,870
SM Orbital Plane Change (13.2 deg)	370	—
Transearth	1,186	1,186

Mission Equipment

- Six-mo unattended dormant storage on the lunar surface before activation is required of all equipment except probes, orbiters, and unmanned surface vehicles.
- Design life of 1 yr on the lunar surface with unlimited reuse in this period is required.
- Nominal maintenance and repair capability by the crew is assumed for all manned equipment.
- All manned equipment is capable of being checked out and operated by one man.
- All equipment, even that normally operated by the crew in a shirtsleeve environment, is capable of being operated by a crew in spacesuits.
- Systems are not designed to be returned to Earth.
- All cabins are designed to accommodate 5th through 95th percentile astronauts in shirtsleeves, vented spacesuits, and fully pressurized spacesuits.
- Usable volume requirements for cabins are:

  Up to 14 days: 3.1 m^3/man

  Beyond 14 days: 3.6 to 7.2 m^3/man

  Usable volume varies between 50 and 60 percent of total cabin volume

2.5.2 Equipment Spectrum

The equipment defined in the Data Book is intended to cover the required range of capabilities with a minimum number of items. For this reason, systems that did not provide significant variations in capability or requirements were not considered. For each category of equipment, a spectrum of mission requirements was established that spans potential uses of the equipment. A series of point designs — embracing existing concepts wherever possible — was chosen so as to result in reasonable increments of mission capability. In each category, the existing designs were analyzed to extract their design, performance, and resource requirements in suitable form for this study. Where no previous analysis was available to cover a design point, new designs were generated based on previous designs where possible. The resultant range of systems is given in Tables 2-3 through 2-12.

2.5.3 Resource Planning

To ensure a good basis for comparing alternate lunar exploration programs, all MIMOSA cost and schedule data were normalized by use of a consistent approach. This approach resulted in resource estimates neither overly conservative nor unduly optimistic. Thus, the resource requirements do not reflect either "buy in" or "gold plated" costs and the estimates represent costs that NASA would expect to incur for a properly managed, normal program. The resulting cost estimates can be used with confidence to evaluate future lunar exploration programs. Although the absolute cost values generated by this approach may differ on an individual basis from other estimates, the conclusions drawn from the comparative analysis will still be valid.

The assumptions used in the resource planning are as follows:

- All costs are based on 1966 dollars.
- NASA management and support costs are not included. Data analysis costs include data reduction only.
- Resource requirements were determined only for Phase D activities (hardware design, manufacturing, and testing).

Table 2-3

LAUNCH VEHICLES

Class	Lunar Injection Capability (kg)
Atlas/Agena	380
Atlas/Centaur	1,000
Saturn IB/Centaur	6,100
Saturn V (100%)	45,500
Uprated Saturn Candidates:	
125% of basic Saturn V	54,900
150% of basic Saturn V	66,700
175% of basic Saturn V	79,400
200% of basic Saturn V	106,100

Table 2-4

FLIGHT SYSTEMS

Class	Characteristics
Command Module	Lunar Orbit Rendezvous (LOR) 3, 4, and 6 men; Direct 3 and 6 men;
Service Module Personnel	LOR; 3, 4, and 6 men; storable and cryogenic
Descent Stage Personnel	LOR; 2, 3, and 6 men; storage and cryogenic
Ascent Stage Logistics	LOR; 2, 3, and 6 men; all storable
Descent Stage	LOR; storable and cryogenic
Braking Stage	Direct; personnel and logistics; storable and cryogenic
Landing Stage	Direct; personnel and logistics; storable and cryogenic
Braking and Landing Stage	Direct; personnel and logistic; all cryogenic
Earth-Return Stage	Direct; 3 and 6 men; storable and cryogenic

Table 2-5

TRANSPORTATION SYSTEMS

Class	Characteristics
Personnel Transport	LOR; 2, 3, 4 and 6 men Direct; 3 and 6 men
Logistics Transport	LOR; up to 8,500-kg payload Direct; up to 32,400-kg payload
Orbiter Transport	Manned and unmanned
Probe Transport	Up to 1,060 kg

Table 2-6

LUNAR ROVING VEHICLES

Class	Range (km)	Staytime (days)	Payload[(a)] (kg)	Mass[(b)] (kg)
Unmanned	5	14	6.4	39
	10	–	50	67
	1,000	22	320	2,630
	1,540	33	320	3,810
	1,600	33	320	3,690
	1,600	184	370	595
	3,000	62	1,500	6,145
Manned (No Cabin)	30 per traverse	6 hrs per traverse	320	440
Two Man	400 to 800	14	320	2,630 to 3,800
Three Man	400	14	700	4,982
	800	30	1,500	5,868
	900	21	320	3,810
	1,600	42	1,500	6,145
Trailers	–	–	460 to 6,500	665 to 2,183

(a) Scientific support, and ancillary equipment; not including crew.
(b) Not including crew or scientific payload.

Table 2-7

LUNAR FLYING VEHICLES

Class	Crew Size	Range (km)	Payload (kg)	Mass[a] (kg)
Surface Exploration	1	15	40	96.5
	1	20	–	76
	2	20 to 200	–	277 to 773
	3	50 to 800	–	501 to 4,392
Return to Orbit	2	–	–	1,066
	3	–	–	1,438
Delivery from Orbit (Unmanned Descent)	3	170 after delivery	–	5,113

(a) Not including crew or payload.

Table 2-8

PERSONNEL SHELTERS

Crew Size	Staytime	Mass (kg)
2	8 to 30 days	581 to 3,307
3	30 to 180 days	3,558 to 11,540
6	180 days to 3 years[a]	9,709 to 19,800
12	180 days	13,496 to 18,143

(a) With resupply every 6 mo.

Table 2-9

SURFACE SUPPORT EQUIPMENT

Function	Characteristics
Fuel Regeneration	20- and 100-kw input, 72- and 350-hr storage
Reactor Power Supply	20- and 100-kw output, low and high temperature
Radiosotope Power Supply	5-, 10-, and 22-kw output, low and high temperature; dynamic and static conversion

Table 2-10

LUNAR PROBES

Class	Landing Mode	Performance	Mass[(a)] (kg)
Earth Launch	Soft	52-kg payload	1,060
Lunar Orbit Launch	Hard Soft	129-kg payload 175-kg payload	404 1,240
Lunar Surface Launch	Soft	100 to 300 kg payload 10 to 50 km range	120 to 318

(a) Not including payload.

Table 2-11

LUNAR ORBITER

Class	Performance	Mass(a) (kg)
Unmanned	60-kg payload/30 days 193-kg payload 2,000-kg payload/360 days	320 867 3,845
Manned	2 man/7 days 2 man/28 days 3 man/30 days 3 man/45 days	3,450 4,650 4,520(b) 6,500

(a) Not including crew and payload.
(b) Additional expendables supplied in the SM.

Table 2-12

MAJOR SCIENTIFIC EQUIPMENT

Item	Characteristics	Mass (kg)
Emplaced Scientific Stations	Early – Advanced	68 to 215
Biomedical Laboratories	Early	498
Geochemical Laboratories	Early – Advanced	156 to 1,129
Core Drill	300 m	9,243 to 13,719
Radio Telescopes	Mills Cross and Parabolic	491 to 22,250
X-Ray Telescopes	Grazing Incidence and Wide Angle	207 to 1,620
Optical Telescopes	1 to 2.5 m	1,257 to 35,410

- No costs incurred under the basic Apollo manned Lunar landing program are included – Saturn Apollo Applications Program (S/AA) missions utilizing Apollo purchased hardware reflect the prior purchase of that hardware.
- Equipment costs are based on lunar program requirements only. No sharing of development costs with other programs is assumed.

Development spans were derived by a combination of detailed schedule planning and comparison with historical data.

All equipment costs were built up from the subsystem level. The basis of the approach used in this study is a set of cost estimating relationships (CER's) developed from historical cost data and current estimates of proposed equipment. Each CER relates the behavior of cost as a function of some parameter, normally a design parameter such as mass, size, performance, etc. In developing a set of CER's, past and present items of equipment are analyzed to extract the cost and parametric data which in turn are correlated to establish cost functions at the finest level of historical cost data breakdown available (e.g., subsystem engineering, subsystem testing, systems integration, and ground support equipment). All costs are broken down into the following categories.

Recurring Procurement. This is the first unit cost and was obtained by aggregating subsystem costs derived from subsystem CER's and adding costs for sustaining engineering and systems integration. This latter item covers the prorated unit cost of systems engineering, program planning, management, quality control, and reliability functions

Recurring Operations. This is the cost of (1) launch site support, which includes launch site assembly and checkout, propellant, pad operation and maintenance, transportation, and contractor support at the launch site; (2) recurring spares derived as a percentage (5 to 12 percent) of procurement cost; and (3) recovery operations (charged as applicable to personnel earth return modules).

Nonrecurring Cost. This is the summation of all contractor costs associated with the development of a new or modified item of equipment. It excludes the cost of any facilities; these costs are shown separately. Nonrecurring cost is made up of the following elements:

- Design and development engineering
- Development testing
- Test hardware – mockups, test articles, and prototypes
- Spares – 5 to 12 percent of test hardware
- Tooling and special test equipment
- Systems inspection
- Preflight and launch support for flight testing
- Ground support equipment for test facilities
- Training and simulation
- Program management – 8 percent of the subtotal of other nonrecurring costs

Cost of Facilities. This is the cost for new government funded development and acceptance test facilities or for modifications to existing facilities required to support the development of a given item of equipment. Specific facility requirements are listed under the heading of "Major Developmental Facilities" on the Development Plan for that item of equipment appearing in the MIMOSA Data Book; MIMOSA Planning Methodology, Vol. II.

Chapter 3

CANDIDATE EXPLORATION PROGRAMS

The generation and analysis of a broad spectrum of lunar exploration programs represented a first step in the planning approach adopted for the MIMOSA study. It provided valuable information and experience that formed the basis for the next step — the formulation of a recommended exploration plan. Thus, the candidate lunar exploration programs were formulated with two principal objectives in mind:

- Evaluate a broad spectrum of post-Apollo lunar exploration programs.
- Answer specific questions posed by a planner, regarding alternate approaches to lunar exploration.

3.1 SPECIFIC PLANNING QUESTIONS

The specific planning questions used as a starting point for the selection of the candidate exploration programs are given in Table 3-1. These questions are of fundamental importance to the lunar program planner and substantiated answers will have considerable impact on shaping an exploration program.

3.2 EQUIPMENT EVOLUTIONS

A candidate lunar exploration program results from the performance of a particular scientific program with a given set of exploration equipment. Example scientific programs and the available exploration equipment have already been discussed (See subsection 2.4 and 2.5, respectively). The selected set of equipment is chosen such that a logical evolution in equipment development and capability is achieved. This equipment evolution must be structured so as to insure that effective use of the developed equipment is possible, that sensible steps in capability increase are called

Table 3-1

SPECIFIC MIMOSA PLANNING QUESTIONS

Program	● What basic equipment capability increases are required and when? ● What major decisions have to be made and when? ● How much can be done with Saturn Apollo Applications (S/AA) equipment and at what cost?
Science	● What is the influence of scientific program size on equipment selection and program cost?
Cost	● What is cost range of effective lunar exploration programs?
Operations	● Lunar Orbit Rendezvous (LOR) or direct crew delivery? ● Three or six man crew delivery?
Equipment	● Saturn V uprating – how much and when? ● LM/Truck or Direct Lunar Logistics Vehicle (LLV)? ● Required mission equipment?

for, and that equipment items of interest are included. Each equipment evolution must have a particular end-point capability in mind and, at any point in the evolution, all component systems must be operationally compatible.

With the specific planning questions in mind and the overall requirement to provide a representative spectrum of possible exploration programs, the equipment evolutions given in Table 3-2 were derived. The major equipment elements comprising each evolution are identified.

Table 3-2

CANDIDATE EQUIPMENT EVOLUTIONS

Evolutionary Step After Apollo	Equipment Capability Group													
	Small	Medium							Large					
	Ia	IIa	IIb	IIIa	IIIb	IIIc	IVa	IVb	Va	VIa	VIb	VIc	VId	VIe
Step 1	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA	S/AA
Step 2														
Saturn V Rating (%)		100	100	100	100	125	100	125	100	125	125	125	125	150
Logistics Delivery		LM/Tr.	Dir. LM	LM/Tr.	LM/Tr.	LM/Tr.	LLV	LLV	LLV	LLV	LLV	LLV	LLV	LLV
Crew Delivery(a)		LOR(2)	LOR(3)	LOR(3)	LOR(3)	LOR(3)	LOR(3)	LOR(3)	LOR(3)	LOR(3)	LOR(3)	LOR(3)	LOR(3)	Dir. (3)
Shelter Crew		2	3	–	–	–	3	3	–	–	–	–	–	–
Roving Vehicle(b)		M(2)	M(3)	M(3)	M(3)	M(3)	L(3)	L(3)	L(3)	L(3)	L(3)	L(3)	L(3)	L(3)
Step 3														
Saturn V Rating (%)				100	125	125			175	125	150	175	200	150
Logistics Delivery				Dir. LM	LLV	LLV			LLV	LLV	LLV	LLV	LLV	LLV
Crew Delivery(a)				LOR(3)	LOR(3)	LOR(3)			Dir. (6)	LOR(6)	Dir. (3)	Dir. (6)	Dir. (6)	Dir. (3)
Shelter Crew				3	3	3			6	6	6	6	6	6
Roving Vehicle(b)				M(3)	M(3)	M(3)			L(3)	L(3)	L(3)	L(3)	L(3)	L(3)

(a) Number in parentheses indicates number of men on surface.
(b) M = medium (MOLAB-type) and L = large (MOBEX-type). Number in parentheses indicates crew size.

S/AA	–	Saturn/Apollo Applications equipment
LM/TR	–	LM/Truck, unmanned logistics carrier based on growth of the LM descent stage
LLV	–	Lunar Logistics Vehicle, unmanned logistics vehicle for direct delivery of large payloads to lunar surface
Dir LM	–	Direct LM, modified LM descent stage that uses inverted service module (SM) for braking and provides direct unmanned logistics delivery capability
LOR	–	Lunar Orbit Rendezvous techniques employed for delivery
Dir	–	Direct delivery

The equipment evolutions of Table 3-2 are categorized by system capability and by the number of evolutionary steps required to achieve a certain capability. The small system capability evolution is essentially the proposed S/AA hardware – 100 percent Saturn V, two man LM/Taxi, LM/Shelter, LSSM Rover, and a modified LM (logistics LM) for delivery of logistics loads via LOR. Increased potential is obtained at the medium-capability level by use of the LM/Truck, direct LM, or LLV with either the 100 percent Saturn V or 125 percent Saturn V. Large capability evolutions are characterized by the eventual use of Saturn upratings with capabilities greater than 125 percent of the basic Saturn V (with the exception of group VIa) and include all of the six-man delivery systems considered in the study. The large capability evolutions utilize the LLV logistics delivery system and large three-man rovers. The major capability groups are further divided into subgroups according to the degree of commitment to new hardware.

Taking evolution group VIb as an example, the first evolutionary step after Apollo involves the standard S/AA hardware. The next improvement in capability is obtained through the use of a logistics LLV with a 125 percent Saturn V and maintaining the LOR delivery of a three-man crew but utilizing the uprated Saturn. The personnel taxi for transportation of crew to and from the lunar surface is designed to be compatible with the 125 percent Saturn. Mission equipment consists of a large three-man rover, which can also be used as a shelter, a general purpose flying vehicle, and any major scientific equipment demanded by the scientific program. The third evolutionary step calls for a 150 percent Saturn V, a logistics LLV, and a direct delivery personnel system (three-man) and its associated Earth-return stage. At this level, the mission equipment is supplemented by the provision of a six-man shelter for extended base operations.

The equipment evolutions presented here are those derived from MIMOSA study analyses and were extracted from a much larger list of evolutions that was prepared early in the study. A planner may, at any time, devise new evolutionary groups and their associated systems, depending on the particular planning question or exploration concept that he wishes to investigate.

As a preliminary to the generation of exploration programs, specific scientific program/equipment evolution combinations must be selected in such a way that applicable data for answering the planning questions will be provided. Table 3-3 gives the cases selected for analysis.

In general, the lower capability equipment evolutions were utilized for the lower level of effort scientific programs, although the most promising evolutions from the large and medium capability groups were also exercised at each scientific level. Again, the specific planning questions of Table 3-1 were used as the basic criteria for selection of the cases but, as the actual analyses proceeded, it was also possible to select additional cases based on the experience gained. Scientific Program A' was not used with any of the equipment evolutions. This was because it became apparent from analyses of Scientific Program B' that higher capability systems (particularly the long-range roving capability) could not be utilized efficiently with the high-level locale approach, whereas the lower capability systems would not be able to complete the scientific program.

3.3 MISSION ANALYSIS AND MODE FORMULATION

Given the scientific program to be accomplished and the equipment evolution to be used, the mission planner selects an appropriate combination of experiments within the given scientific program. This combination of experiments constitutes a mission. He then formulates a mode utilizing equipment in the given equipment evolution. Modes in the Data Book will be found useful for initial iterations, but modes can be readily tailored to suit the specific mission plan of interest. In this manner, missions are formulated responsive to the directives of the scientific program until all experiments have been satisfied.

3.3.1 Mission Analysis

For each mission a detailed plan for performance of the selected scientific experiments is prepared. An example mission is illustrated in Fig. 3-1. Logistics equipment and

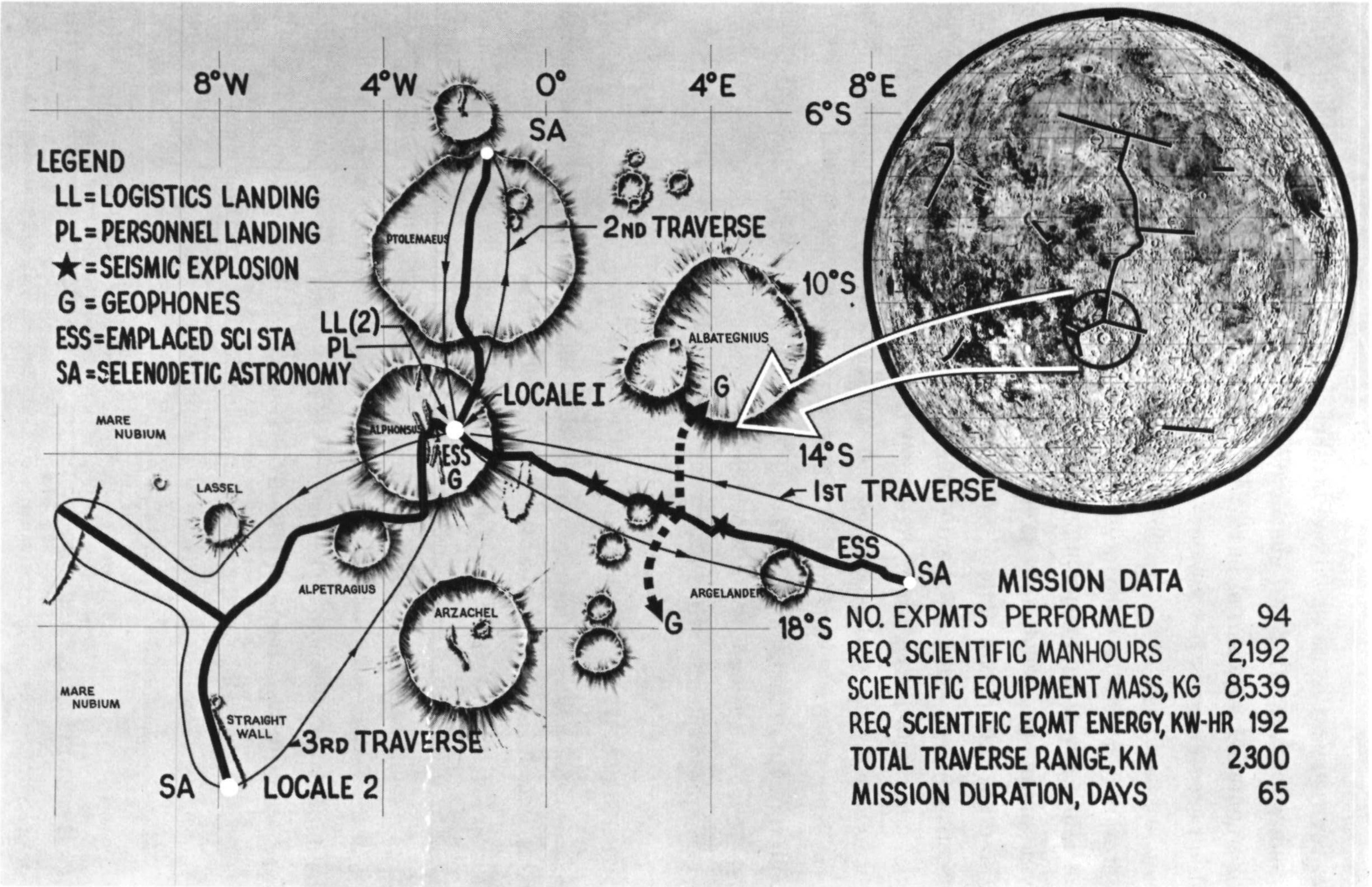


Fig. 3-1 Example Mission

Table 3-3

SCIENTIFIC PROGRAM/EQUIPMENT EVOLUTION COMBINATIONS SELECTED FOR MIMOSA STUDY

Equipment Evolution	Scientific Program				
	A	B	B'	C	C'
Small					
I-a				o	●
Medium					
II-a		o		●	
II-b			●		
III-a			●		
III-b		o			
III-c	●	●	●	●	
IV-a		●		●	
IV-b	●	●	●	●	
Large					
V-a	●	●			
VI-a	●	●			
VI-b	●	●			
VI-c	●	●			
VI-d	●				
VI-e	●	●		●	

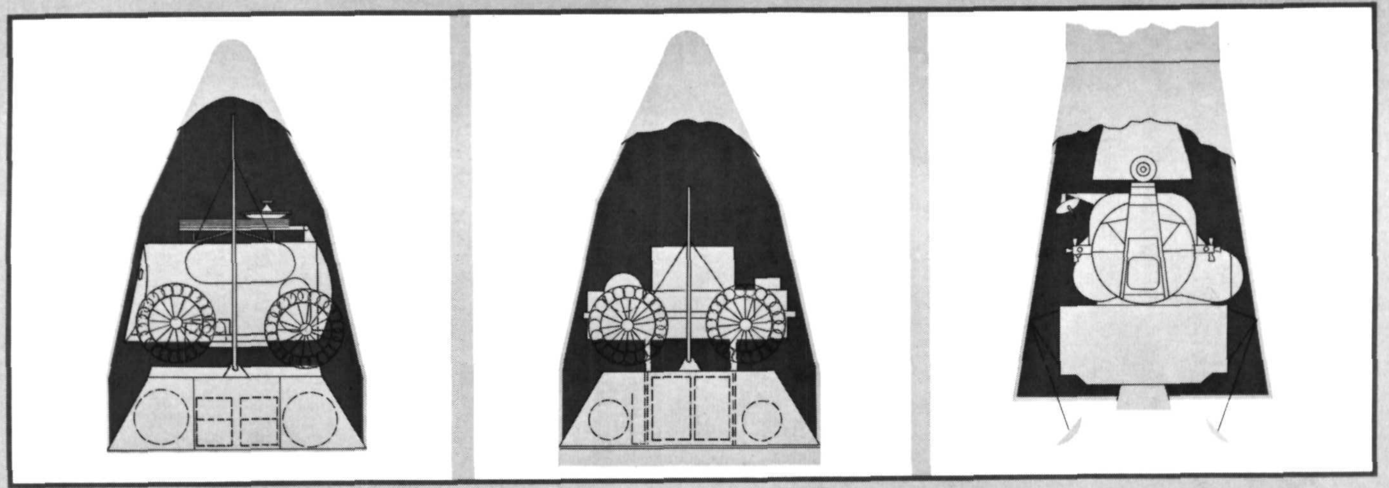
● Scientific Program Completed.
o Scientific Program Incomplete.

personnel are landed at the crater Alphonsus and two locales and three traverses are included in the mission. The first locale is Alphonsus itself; the investigations include a study of outgassing of the crater. The first traverse is made in a southeast direction into the Central Highlands. A geophone array is emplaced along the first kilometer of the path and seismic charges of approximately 2,500 kg of TNt are deposited near the center of the path. Geophones are also deposited by probes on either side of the path and automatic scientific stations are emplaced at both extremities of the path. The second traverse is to the north, with investigation of Ptolemaeus as a main objective. The third traverse includes an excursion into Mare Nubium and a visit to the Straight Wall where locale type exploration, with emphasis on geology, is performed. Selenodetical astronomical observations are performed at extremities of each path. Total distance covered by the roving vehicle for traverses 1, 2, and 3 are 750 km, 400 km, and 1,150 km, respectively. The mission data shown in the figure are taken from the computer program printout. The mission planner in formulating the mission need not achieve this degree of accuracy in his planning.

3.3.2 Mode Formulation

The mode formulated to achieve the mission described above is depicted in Fig. 3-2. It consists of a set of transportation systems and mission equipment, compatible with the equipment evolution, that provides enough capability to meet the mission requirements. In this case, the LLV, in combination with the 125-percent Saturn V, is used for logistics delivery, and two such launches are needed to meet the mass requirements. The personnel transportation system also utilizes the 125-percent Saturn V vehicle, and three men are delivered to the lunar surface via the LOR mode. The payload equipment is packaged as shown and allowance is made in the mode capability for packaging and off-loading mass requirements. As shown, the computer analysis indicated some excess capability over mission requirements. If desired, a further iteration adding additional experiments could be made to obtain a closer match to the mode's capabilities.

PARAMETER	MISSION RQMT	MODE CAPAB
STAY TIME, DAYS	65	90
MASS DELIVERED, KG	26,822	32,600
TRAVERSE RANGE, KM	2,300	7,000



LAUNCH No. 1 (LLV)

LOGISTICS:
- LARGE LRV
- EXPLOSIVES
- SCIENTIFIC EQUIPMENT

LAUNCH No. 2 (LLV)

LOGISTICS:
- LARGE TRAILER
- SURFACE-TO-SURFACE PROBES
- SCIENTIFIC EQUIPMENT

LAUNCH No. 3

PERSONNEL:
- THREE MEN DELIVERED AND RETURNED (LOR)

Fig. 3-2 Example Mode

3.4 DESCRIPTION OF CANDIDATE EXPLORATION PROGRAMS

Utilizing the planning methodology previously described, 29 basic exploration programs were generated. Of these programs, 26 could successfully complete the assigned scientific programs within the time frame under consideration (prior to 1987). Four additional programs were generated that represent variations of a basic program where the dates of introduction of new equipment were changed.

Major ground rules adopted for the generation of these exploration programs are as follows:

- Planning period: post-Apollo through 1980's
- Smooth funding rate of 1 to 2 billion dollars per annum
- S/AA equipment to be used in the period 1970 to 1973
- Suggested launch rates:
  1970 to 1975: three to four per year
  1976 to 1977: four per year
  1978 – onwards: six to eight per year
- Apollo missions: three in 1968, three in 1969
- Maximum crew staytime: 180 days

Cost and schedule data for those programs that completed the assigned science are summarized in Tables 3-4 through 3-8. The Apollo run-out costs are not included in the total program cost but are accounted for in the average funding level. The total number of Saturn V launches includes six Apollo launchings for each program together with any test launchings required in the development program. In all cases the use of S/AA hardware commenced in 1970.

More detailed descriptions of the candidate lunar exploration programs are contained in Candidate Lunar Exploration Programs, MIMOSA Technical Report – Vol. II.

Table 3-4

EXPLORATION PROGRAM CANDIDATES – COST AND SCHEDULE SUMMARY FOR SCIENTIFIC PROGRAM A

Equipment Evolution	Major Items of Equipment Evolution After S/AA and (Year of Introduction)	Average Funding Level ($B/yr)	Total[a] Saturn V Launches	Last Mission Start (year)	Post-Apollo Program Cost ($B)		
					Non-Recurring	Recurring	Total
IIIc	→ 125%[b] LM/Truck → 125% LLV (1976) (1979)	1.66	89	1986	4.19	21.30	25.49
IVb	→ 125% LLV (1976)	1.58	88	1986	3.65	20.21	23.86
Va	→ 100% LLV → 175% LLV (1976) (1980)	1.78	76	1985	6.43	19.34	25.77
VIa	→ 125% LLV (3 LOR → 6 LOR) (1976) (1984)	1.71	84	1985	5.19	19.42	24.61
VIb	→ 125% LLV → 150% LLV (1976) (1980)	1.70	89	1986	5.94	20.18	26.12
VIc	→ 125% LLV → 175% LLV (1976) (1981)	1.67	77	1986	6.85	18.74	25.59
VId	→ 125% LLV → 200% LLV (1976) (1984)	1.77	83	1985	6.84	18.79	25.63
VIe	→ 150% LLV (→ 6-Man Shelter) (1976) (1984)	1.55	84	1986	4.35	18.85	23.20

(a) Includes six Apollo launches.
(b) Percentage refers to Saturn V rating.

Table 3-5

EXPLORATION PROGRAM CANDIDATES – COST AND SCHEDULE SUMMARY FOR SCIENTIFIC PROGRAM B

Equipment Evolution	Major Items of Equipment Evolution After S/AA and (Year of Introduction)	Average Funding Level ($B/yr)	Total(a) Saturn V Launches	Last Mission Start (year)	Post-Apollo Program Cost ($B)		
					Non-Recurring	Recurring	Total
IIIc	→ 125%(b) LM/Truck → 125% LLV (1977) (1985)	1.70	84	1986	3.37	22.60	25.97
	→ 125% LM/ Truck → 125% LLV (1975) (1984)	1.71	80	1985	3.37	21.30	24.67
IVa	→ 100% LLV (1974)	1.33	61	1985	2.81	15.03	17.84
IVb	→ 125% LLV (1975)	1.51	57	1982	3.50	12.93	16.43
Va	→ 100% LLV → 175% LLV (1974) (1977)	1.54	44	1982	6.70	10.25	16.95
VIa	→ 125% LLV (3 LOR → 6 LOR) (1975) (1982)	1.59	55	1982	5.09	12.62	17.71
VIb	→ 125% LLV → 150% LLV (1974) (1978)	1.46	52	1983	5.85	11.27	17.12
VIc	→ 125% LLV → 175% LLV (1974) (1978)	1.56	46	1982	7.12	10.15	17.27
VIe	→ 150% LLV (→ 6-Man Shelter) (1974) (1981)	1.41	50	1982	4.25	10.72	14.97

(a) Includes six Apollo launches.
(b) Percentage refers to Saturn V rating.

Table 3-6

EXPLORATION PROGRAM CANDIDATES – COST AND SCHEDULE SUMMARY FOR SCIENTIFIC PROGRAM B'

Equipment Evolution	Major Items of Equipment Evolution After S/AA and (Year of Introduction)	Average Funding Level ($B/yr)	Total(a) Saturn V Launches	Last Mission Start (year)	Post-Apollo Program Cost ($B)		
					Non-Recurring	Recurring	Total
IIb	→ 100%(b) Dir. LM (1974)	1.79	84	1985	3.00	23.07	26.07
IIIa	→ 100% LM/Truck (1974) → 100% Dir. LM (1977)	1.87	86	1985	3.11	24.36	27.47
IIIc	→ 125% LM/Truck (1973) → 125% LLV (1980)	1.53	74	1986	3.89	18.95	22.84
IVb	→ 125% LLV (1973)	1.50	73	1985	3.64	17.17	20.81
	→ 125% LLV (1976)	1.48	77	1986	3.64	18.34	21.98
	→ 125% LLV (1978)	1.49	81	1987	3.64	19.92	23.56

(a) Includes six Apollo launches.
(b) Percentage refers to Saturn V rating.

Table 3-7

EXPLORATION PROGRAM CANDIDATES – COST AND SCHEDULE SUMMARY FOR SCIENTIFIC PROGRAM C

Equipment Evolution	Major Items of Equipment Evolution After S/AA and (Year of Introduction)	Average Funding Level ($B/yr)	Total[a] Saturn V Launches	Last Mission Start (year)	Post-Apollo Program Cost ($B)		
					Non-Recurring	Recurring	Total
IIa	→100%[b] LM/Truck (1975)	1.74	76	1984	1.11	22.30	23.41
	→100% LM/Truck (1978)	1.79	84	1985	1.11	24.91	26.02
IIIc	→125% LM/Truck →125% LLV	1.61	47	1980	2.65	12.06	14.71
IVa	→100% LLV (1974)	1.38	42	1980	2.00	9.80	11.80
IVb	→125% LLV (1974)	1.32	40	1980	2.69	8.28	10.97
VIe	→150% LLV (1974)	1.36	39	1980	3.26	8.24	11.50

Table 3-8

EXPLORATION PROGRAM CANDIDATES – COST AND SCHEDULE SUMMARY FOR SCIENTIFIC PROGRAM C'

Equipment Evolution	Major Items of Equipment Evolution After S/AA and (Year of Introduction)	Average Funding Level ($B/yr)	Total[a] Saturn V Launches	Last Mission Start (year)	Post-Apollo Program Cost ($B)		
					Non-Recurring	Recurring	Total
Ia	→S/AA (100% LM) (1970)	1.77	81	1985[c]	0.44	24.99	25.43

(a) Includes six Apollo launches.
(b) Percentage refers to Saturn V rating.
(c) Scientific program completed except for two 100-km paths.

3.5 EVALUATION OF CANDIDATE EXPLORATION PROGRAMS

The main elements of a lunar exploration plan are shown in Fig. 3-3. This "road map" of lunar exploration was used as background for the evaluation of the basic planning questions. Distinct increases in equipment capabilities are visualized for the performance of various phases of the exploration program. Three decision points are identified that relate to alternate options available for changing the capability of the exploration equipment. In the MIMOSA study it was assumed that decision 1 had been made and that the immediate post-Apollo era would utilize proposed S/AA equipment only.

3.5.1 Factors Affecting Decision Points 2 and 3

Each decision point of course precedes the operational introduction of the equipment providing the capability change. The basic questions posed in Table 3-1 can be specifically related to each decision point in the following manner:

- Decision Point 2

  Can the continued use of S/AA equipment effectively satisfy the scientific objectives?
  What crew level is required for exploration?
  Do requirements for Saturn V uprating exist at this point in the program?
  Is the LM/Truck or the LLV a better choice of logistic modes?
  What is the influence of scientific program size on the choice of equipment for the post-S/AA time period?
  When should and when could a commitment be made to an improved capability?
- Decision Point 3

  Does a requirement exist for six-man crew delivery systems?
  Can the LOR personnel delivery mode still be used effectively or is a direct delivery mode desirable?
  What Saturn V upratings, if any, are required to accomplish the later phases of exploration?
  What is the influence of scientific program size on the choice of equipment?
  When should a commitment be made to an increased capability?

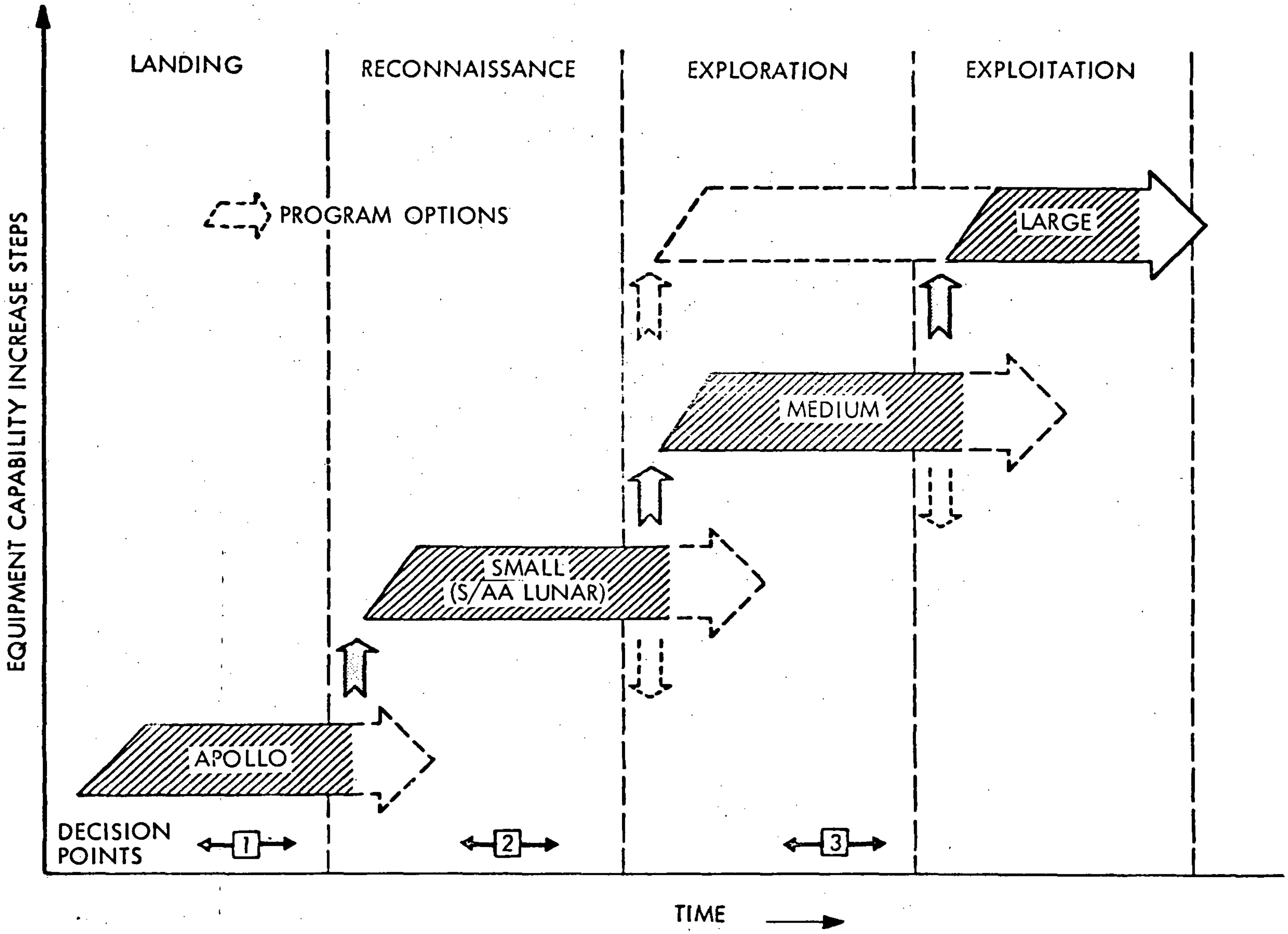


Fig. 3-3 Basic Elements of a Lunar Exploration Plan

Decision point 2 was given major consideration in the study because of its proximity in time. Decision point 3, which was studied primarily to identify its influence on decisions to be made at decision point 2, is less important at this time and will be influenced strongly by a planning, fiscal, political, and technical environment that cannot be forecast accurately at present.

3.5.2 Summary of Results

Although a variety of comparative evaluation parameters are available from the wealth of exploration program data generated (cost, scientific manhours, scientific mass, staytime, number of Saturn V launches, etc.), none of these alone represents an absolute comparison criterion, so all factors must be considered. In the analysis of the MIMOSA results, emphasis was placed on minimum program cost, potential scientific achievement (as indicated by scientific manhours assigned to experiments and scientific mass delivered), equipment evolutionary possibilities, and program flexibility to changing emphasis and constraints.

The total program cost displayed by the various exploration programs generated (Tables 3-4 to 3-8) during the study is graphically shown on Fig. 3-4 as a function of the total scientific manhours produced by the particular program. This figure is a summary of the total program costs for all the cases examined and utilizes scientific manhours performed during the program as an indication of scientific activity. Generally, this quantity is the same for a given scientific program.

It can be seen that program costs associated with use of the lower capability systems are relatively high. The S/AA evolution is limited to the performance of Scientific Program C' since mobility limitations restrict its use to locale exploration only. The LM/Truck logistics system is not as effective as the LLV and the LLV exhibits greater flexibility to changing program demands. The Saturn V uprating requirement is not critical when the LLV logistics delivery system is employed. In fact, the 100-percent Saturn V and LLV combination performs quite satisfactorily against Scientific Programs A and B. Further, it can be seen that the higher capability systems are equally effective when used against the large or small scientific programs.

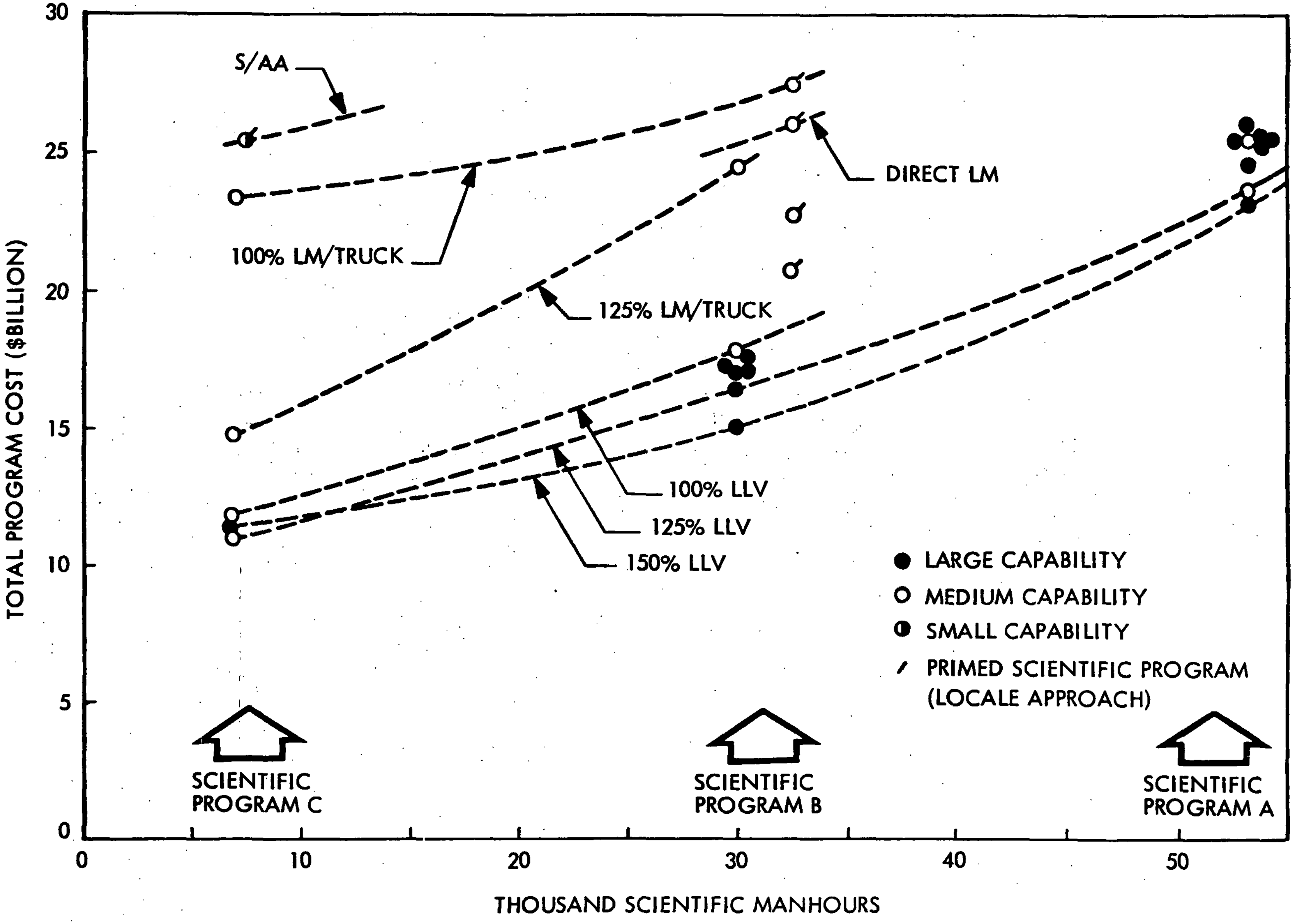


Fig. 3-4 Cost Effectiveness of Candidate Transportation Systems

Of particular interest is the fact that two of the equipment evolutions, viz., S/AA → 150-percent LLV (evolution VIe) and S/AA → 125-percent LLV (evolution IVb), yield the lowest costs for each level of scientific effort.

These results imply that the equipment evolutions that are most cost effective for a given size of scientific program are also the most cost effective when the scope of scientific activity is changed. A more graphic illustration of this point is given in Fig. 3-5 where total program cost is presented as a function of equipment capability for the three levels of science performed. For this display, the capability of the evolution is represented by the ultimate landed payload potential of the logistics transportation system.

The inset sketch on Fig. 3-5 illustrates the pre-MIMOSA contention that a close and direct relationship existed between the scope of scientific activity desired and the capability level of the equipment performing that scientific effort, i.e., that rather austere science demands would most efficiently be satisfied by equipment of limited capability and that only very ambitious science programs could effectively utilize high capability exploration modes. In fact, the MIMOSA analysis showed this contention to be erroneous. This is demonstrated by the fact that the minima of all cost curves in the main figure occur over the same range of equipment capability. Thus, a particular equipment evolution can be selected that yields minimum program costs for a wide range of scientific program size. Commitment to the selected hardware may be made with confidence that future changes in scientific scope will not involve large cost penalties. Of course, this conclusion is not true for very low levels of scientific activity. However, over the range of scientific effort examined in MIMOSA (3,000 to 60,000 scientific manhrs), the preferred choice of equipment evolution is insensitive to the size of the scientific program.

When cumulative cost per scientific manhr was used as an indication of exploration efficiency, it was found that this parameter was reduced by a factor of 10 throughout a typical program as a result of proceeding from S/AA to LLV and associated systems.

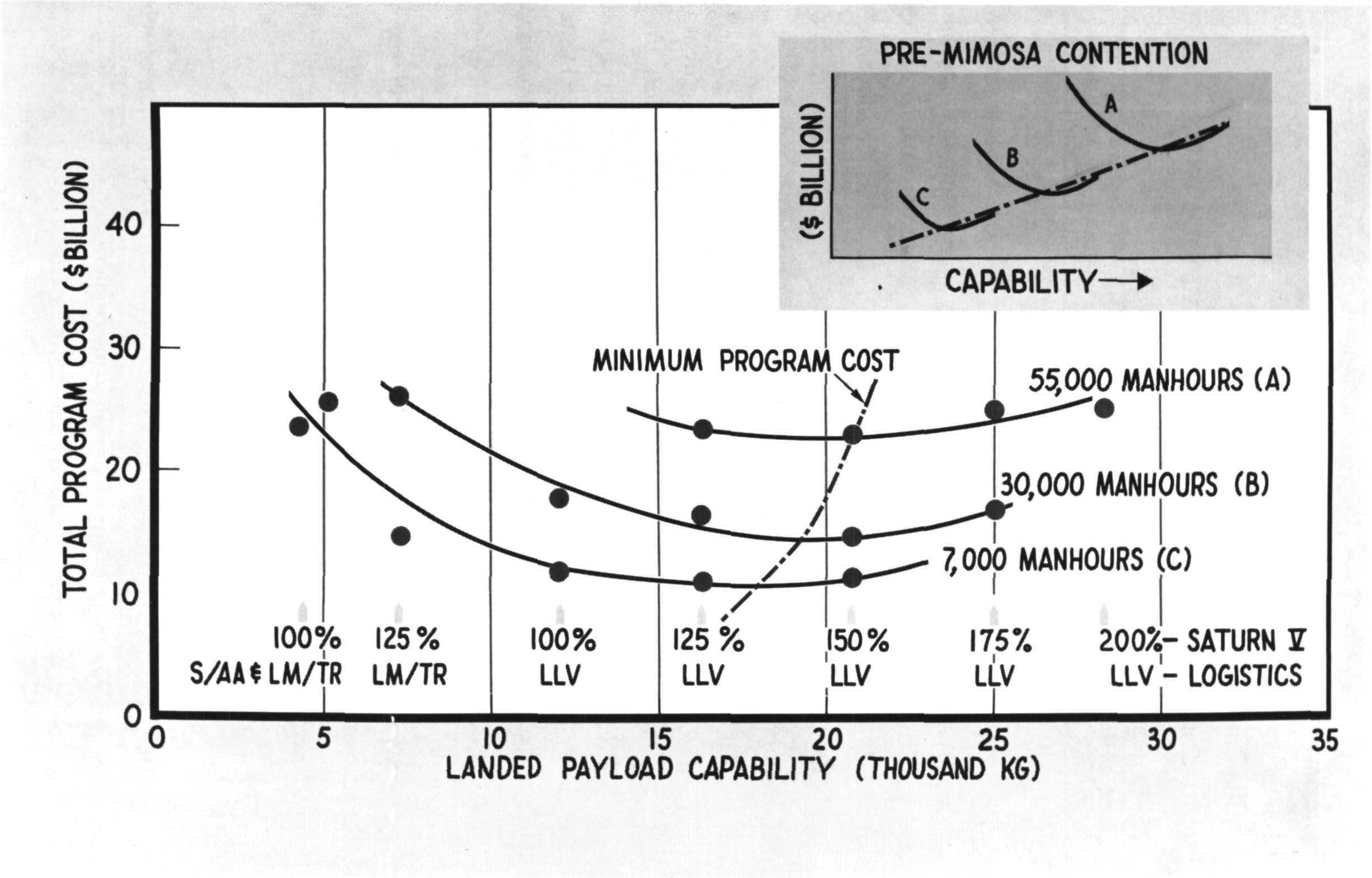


Fig. 3-5 Influence of Scientific Program on Equipment Selection

Specific operational efficiencies, based on the slopes of curves representing scientific manhours performed and scientific mass delivered as a function of total program cost, for three of the major candidate transportation systems, are as follows:

System	Operational Efficiency	
	$M/Scientific Manhr	$M/Scientific Mass (kg)
S/AA	4.0	0.7
LM/Truck	1.6	0.07
125% LLV	0.9	0.04

These values are based on path-type exploration; improved efficiencies are obtained when the systems are used for the operation of a large base.

3.5.3 Conclusions From Program Analysis

The exploration programs generated during the MIMOSA study were derived from the use of particular sets of exploration equipments utilized in an evolutionary manner to perform specific scientific programs under a given set of ground rules. Bearing these assumptions in mind, the conclusions to be drawn from the analysis of the spectrum of exploration candidates are summarized in Table 3-9. The conclusions are stated in the form of answers to the basic planning questions posed at the start of the program generation. The analyses leading to these conclusions are presented in Candidate Lunar Exploration Programs, MIMOSA Technical Report - Vol. II.

Table 3-9

CONCLUSIONS FROM CANDIDATE EXPLORATION PROGRAM ANALYSIS⁺

Question	Answer
PROGRAM	
● What major decisions on programs and associated equipment capability should be made and when?	● Three major decision points identified regarding capability change: Continue Apollo or S/AA – Immediate Continue S/AA or Medium – 1969 to 1972 Continue Medium or Large – 1975 to 1980 ● Decision point 2 most critical for ensuring low-cost program with high scientific return
● How much can be done with Saturn Apollo Applications (S/AA) ?	● Can only perform C-level science program (7,000 manhr) at a cost of $25 billion over a period of 15 yr
SCIENCE	
● What is influence of scientific program size on equipment selection and cost?	● Selection of exploration equipment is insensitive to size of scientific program. ● Total program cost is affected significantly* (See next page.) ● Largest scientific program does not fully tax the higher capability evolutions

⁺Answers are only valid within scope of programs investigated.

Table 3-9 (Cont.)

Question	Answer
COST	
• What is cost range of effective exploration programs?	• *A level (55,000 scientific manhr) approximately $24 billion • *B level (30,000 scientific manhr) approximately $17 billion • *C level (7,000 scientific manhr) approximately $11 billion
OPERATIONS	
• LOR or direct crew delivery?	• LOR mode is as cost-effective as direct delivery but involves operational problems for long staytime
• Three or six-man delivery?	• Three man delivery systems slightly more economical than six-man systems (approx. 10%)
EQUIPMENT	
• LM/Truck or direct Lunar Logistics Vehicle (LLV)?	• LLV is most cost effective – offers savings of 20 to 30% in total program cost
• Saturn V uprating?	• Assuming LLV, Saturn V uprating does not strongly influence cost; minimum uprating dictated by three man delivery requirement (100 to 125%)
• Mission equipment?	• Three-man Lunar Roving Vehicle (range approx. 800 km) is essential • Large lunar shelter required only late in program (approx. 1980)

Chapter 4
RECOMMENDED LUNAR EXPLORATION PLAN

The final step in applying the MIMOSA planning tool to a typical planning exercise consisted of formulating a recommended plan for lunar exploration. This plan utilizes the approach, summarized in Fig. 3-3, that was derived during the analysis of the broad spectrum of candidate programs, and reflects the answers obtained to the specific planning questions. A more detailed analysis was made of the three key decision points using a limited set of selected exploration equipment. The consequences of assuming the available program options resulted in three alternate exploration programs that constitute typical examples of implementing the exploration plan.

4.1 GUIDELINES AND APPROACH TO PLAN FORMULATION

4.1.1 Guidelines

The guidelines given below were approved by NASA for the final phase of the MIMOSA planning analysis and take note of the information gained from the previous planning phase and inject the constraints of a realistic planning environment. These guidelines were as follows:

- Maintain program options through an awareness of the possible use of alternate equipment capabilities; in particular, ensure adaptability to any major Saturn V uprating that might be available from a future planetary program.
- Demonstrate potential to accommodate an increasing demand for scientific capability.
- Assume no major R&D commitment before FY 1970.
- Plan on a funding level of less than $1.5 billion per year for lunar operations.

- Strive for commonality of equipment with other potential space programs.
- Ensure maximum use of developed equipment.
- Assure modest launch rates – three to four per yr through 1970's and six per yr through 1980's

The prevailing theme expressed by these guidelines is the recognition of a need for (1) flexibility to future changing demands through the selection of adaptable equipment and sensible design points, and (2) cost effectiveness and low risk achieved through maximum use of well established techniques coupled with the efficient utilization of developed hardware.

4.1.2 Approach to Plan Formulation

The approach adopted for the formulation of a plan of lunar exploration, is summarized in Fig. 4-1, and represents a synthesis of the conclusions drawn from the candidate program analyses which has been assimilated into a general exploration plan under the NASA-provided guidelines. The logical step increases in capability and the associated decision points developed during the broad spectrum analyses are maintained in this plan to allow for alternate options within the overall plan.

The Saturn Apollo Applications (S/AA) equipment is representative of a number of possible candidates that can be introduced at decision point 1, and no attempt was made to optimize performance in this area. The Augmented LM(ALM) is used for delivery of two men to the surface and the logistics LM (i.e., a stripped LM ascent stage) is used for logistics delivery. The Saturn V rating is the minimum required,for delivery of the ALM within the MIMOSA operational ground rules. Mission staytimes are limited to 14 days.

At decision point 2, two options are available – either exploration is continued with the S/AA equipment (continued S/AA) or a capability increase to the medium level is possible. At the medium capability level, three-man surface operations with a large rover for mobility are assumed, and a single stage LLV is introduced for logistics. The LOR

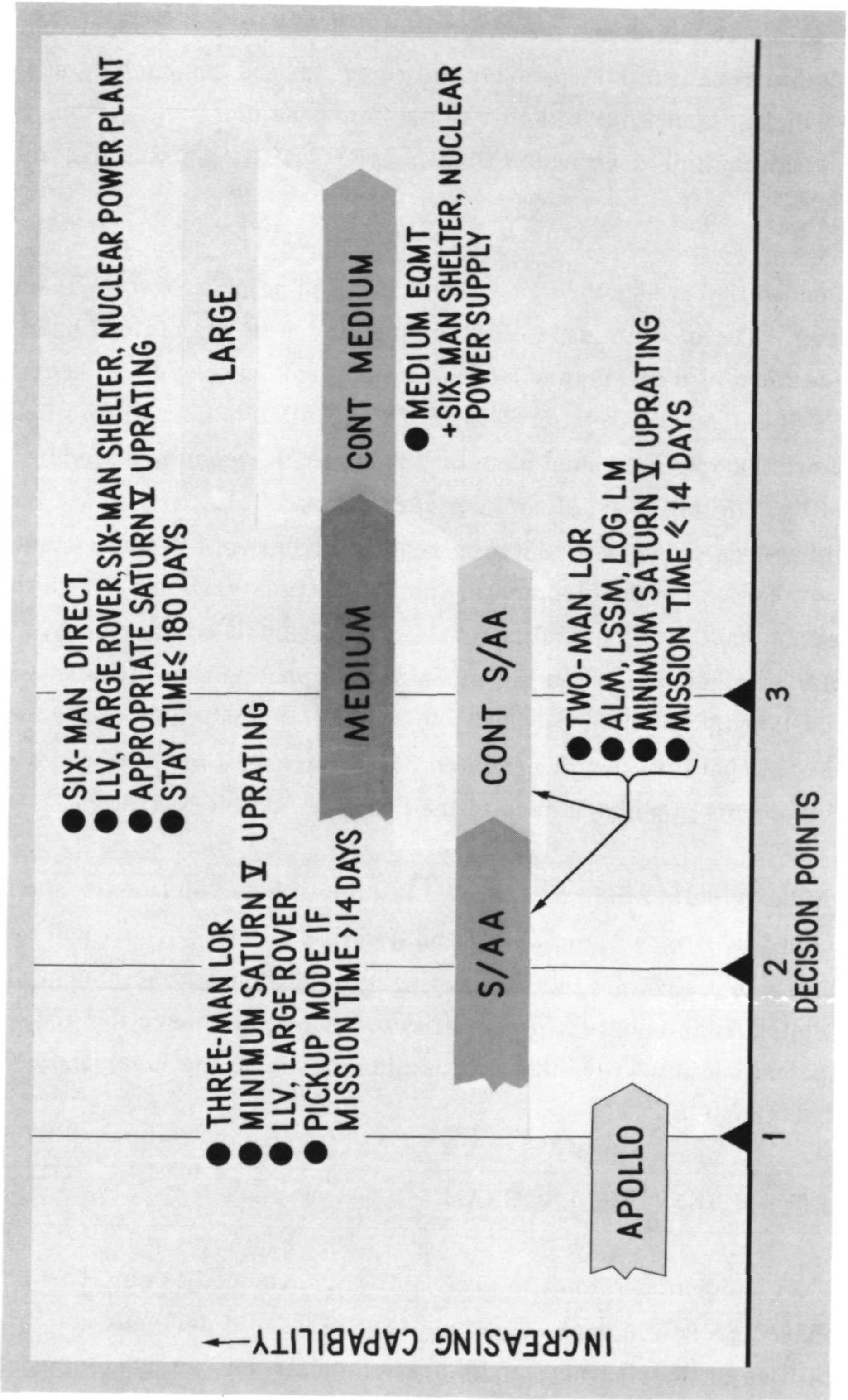


Fig. 4-1 Approach to Plan Formulation

delivery of crew is maintained and the Saturn V uprating is the minimum required by this flight mode. A conservative approach to crew return is assumed by use of an additional crew pickup launch for mission times in excess of 14 days. This obviates the need for a long staytime deactivated CSM in orbit with its possible reliability problems.

If the medium capability is assumed, a further decision point is eventually encountered (decision point 3). The medium capability equipment can be maintained but additional equipment in the form of a six-man shelter and a nuclear power supply is required for the introduction of extended base operations. The possible use of a large Saturn V launch vehicle provided by a manned planetary program is accommodated by a stepup to large capability. In this case, direct delivery of a six-man crew to the lunar surface is possible and should be utilized when required from operational considerations. To minimize new equipment developments, the LLV stages associated with the Saturn V used at the medium and large capability levels should exhibit commonality. Therefore, a two-stage LLV is suggested at the higher Saturn V uprating that utilizes two of the single stages used at the medium capability level. The actual value of the Saturn V uprating at the large capability then depends on the requirement for six-man direct delivery with the compromised performance of the two stage delivery system.

In keeping with the guideline to be responsive to increasing evolutionary scientific demands, a scientific program must be postulated that allows for part and eventually all of the scientific objectives to be achieved with the increasing equipment capability options. This integrated scientific program is described in subsection 4.2. The selection of the actual equipment designs for use in developing the lunar exploration plan is given in subsection 4.3

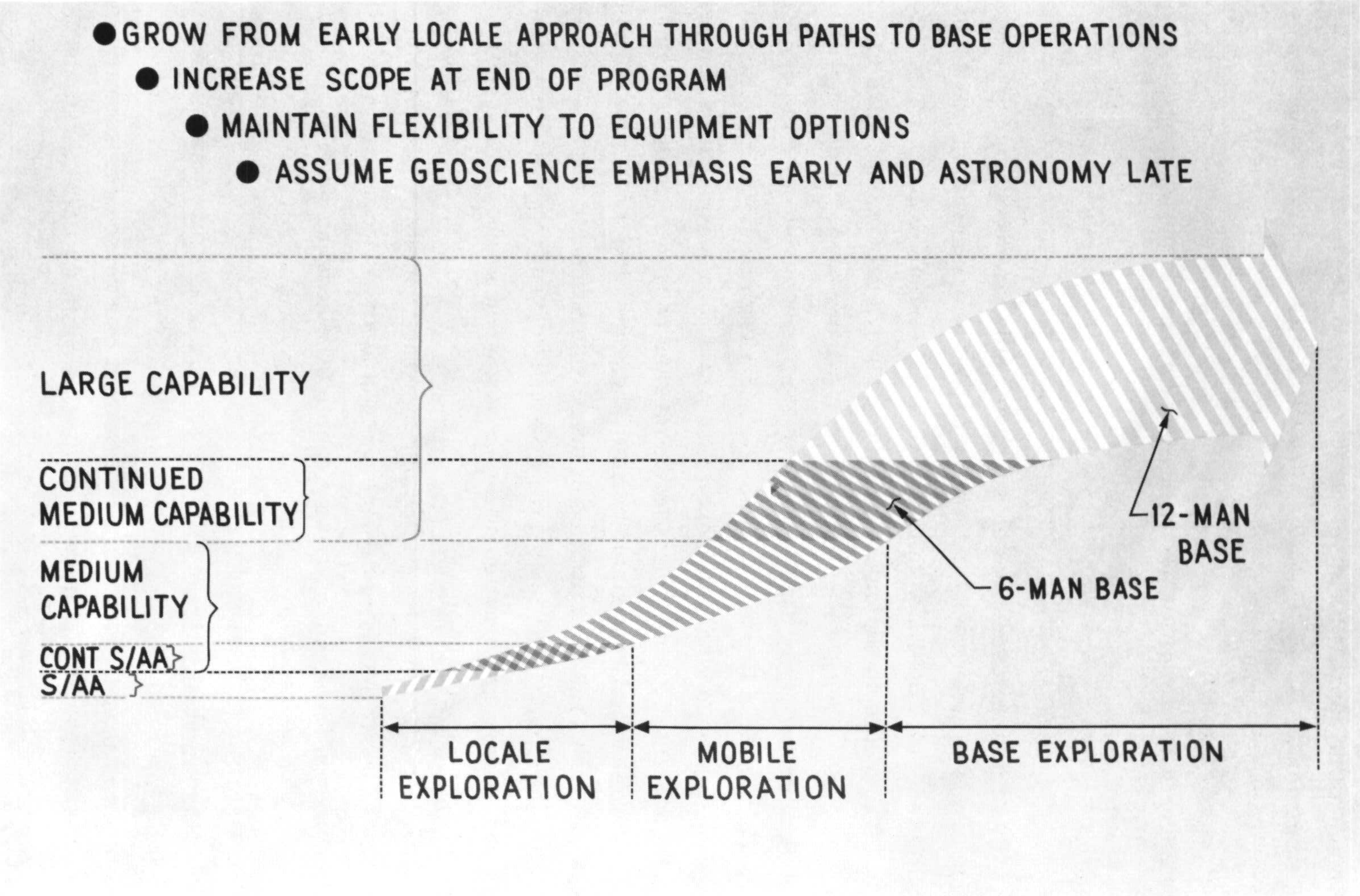
4.2 INTEGRATED SCIENTIFIC PROGRAM

The concept of an integrated scientific program was developed to satisfy a postulated desire for a phased growth in sophistication of the scientific demands and to accommodate the capabilities of the alternate equipment options. The integrated program embodies much of the approach and scientific content of the previously developed Scientific Programs A, B, and C. However, the total scope of the integrated program is considerably greater than that of Scientific Program A. This enlargement of scope is achieved mainly through an extension of the extralunar investigations characteristic of semipermanent base activities during the later phases of the exploration program.

4.2.1 General Principle

Figure 4-2 illustrates the concept of an integrated scientific program. The scope of the program grows in accordance with the increased equipment capability from the somewhat limited locale approach initially, through a mobile exploration phase, to base exploration. The available equipment options, as previously defined, are accommodated by phasing the scientific requirements in a manner such that they are compatible with the available capability. Thus the science to be performed with the S/AA and continued S/AA equipment is limited to locale-type investigations. Introduction of the medium capability systems permits completion of the locale exploration and performance of long traverses. Augmentation to the medium capability equipment list or the switch to the large capability systems permits the completion of the final phase of the mobile exploration era and the initiation of base exploration and the conduct of serious extralunar investigations. The integrated science program postulates the need for an eventual 12-man semipermanent scientific and engineering laboratory/observatory on the lunar surface. As will be shown later, the large capability systems can meet this demand readily. The medium capability equipment can feasibly meet this demand but not within the program restraints (launch rate and yearly expenditure); a decision then to retain the medium level capability may restrict the manning level at the base to six men.

The science accomplished with any equipment option represents a balanced program in itself so that accomplishment of part of the integrated program (e.g., if an extended lunar base is not achieved) represents achievement of a reasonable scientific program of reduced scope. At the same time, each portion can form an integral part of an



- GROW FROM EARLY LOCALE APPROACH THROUGH PATHS TO BASE OPERATIONS
  - INCREASE SCOPE AT END OF PROGRAM
    - MAINTAIN FLEXIBILITY TO EQUIPMENT OPTIONS
      - ASSUME GEOSCIENCE EMPHASIS EARLY AND ASTRONOMY LATE

Fig. 4-2 Integrated Scientific Program

evolving total scientific program that is achieved by sequential utilization of the increasing capability. Overlapping of the exploration phases resulting from the sequential use of the options is indicated by the crosshatched areas of Fig. 4-2.

4.2.2 Integrated Scientific Program Description

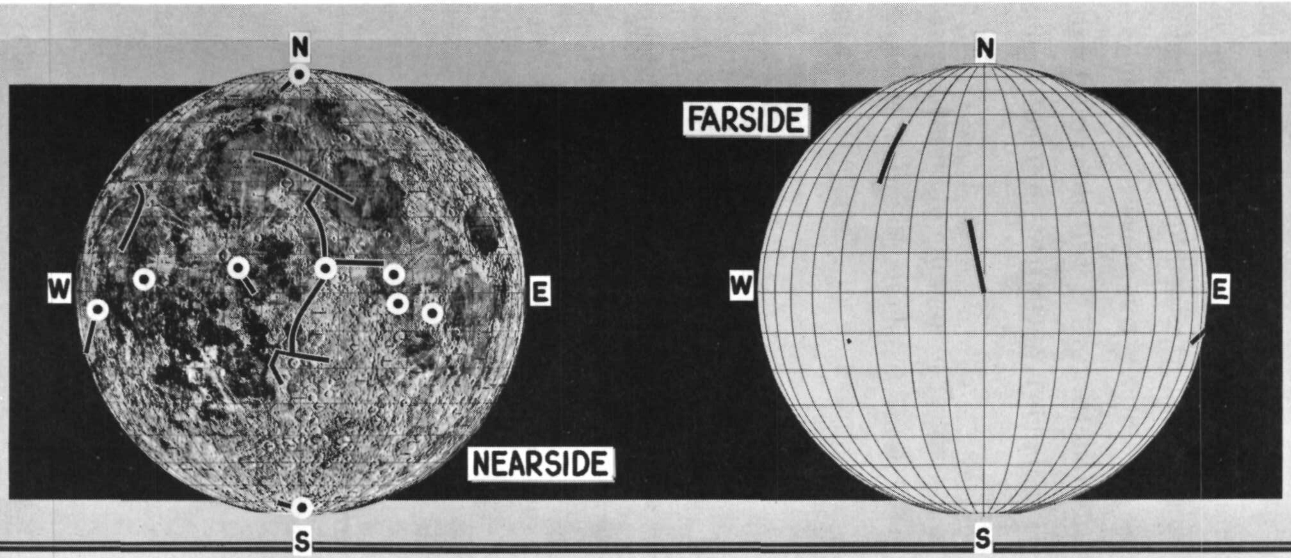
A complete description of the integrated scientific program and its constituent missions as implemented for the various equipment options is contained in Recommended Lunar Exploration Plan, MIMOSA Technical Report, Vol. III. The total integrated program is summarized in Fig. 4-3, which illustrates the surface pattern for exploration and some of the main program parameters.

The number of locales and the total path length involved in the integrated program correspond closely to those of Scientific Program A. However, the integrated program demands about 50 percent more scientific equipment mass delivered to the lunar surface and requires about twice the scientific manhours for completion of all activities as compared with Program A. The integrated scientific program shows a markedly reduced explosives requirement (about one-third of that for Program A) for active seismology. The excessive demands of the earlier experiment mechanization prompted the consideration of a more efficient deployment of explosives and geophones to accomplish the same scientific goals.

The integrated scientific program, if completed, would demand a total of 100,000 scientific manhr and about 235,000 kg of scientific equipment. The distribution of demands for scientific mass and manhours among 5 major scientific disciplines is shown in Fig. 4-4. Requirements by lunar geoscience and astronomy account for 86 percent of the total manhr and 97 percent of the scientific mass demand.

4.3 EQUIPMENT SELECTION

Following the approach outlined in Fig. 4-1, specific design requirements were identified for the various equipment options associated with each decision point. During the



● NUMBER OF LOCALES	9	● SCIENTIFIC EQUIPMENT MASS, KG	
● TOTAL PATH LENGTH, KM	7,500	● MINOR EQUIPMENT	30,000
● NUMBER OF EXPERIMENTS	222	● MAJOR EQUIPMENT	205,000
● NUMBER OF 300-M HOLES	10	● TOTAL MASS OF EXPLOSIVES, KG	50,000
● SCIENTIFIC MANHOURS	99,500	● TOTAL EARTH RETURN MASS, KG	22,000

Fig. 4-3 Integrated Scientific Program Description

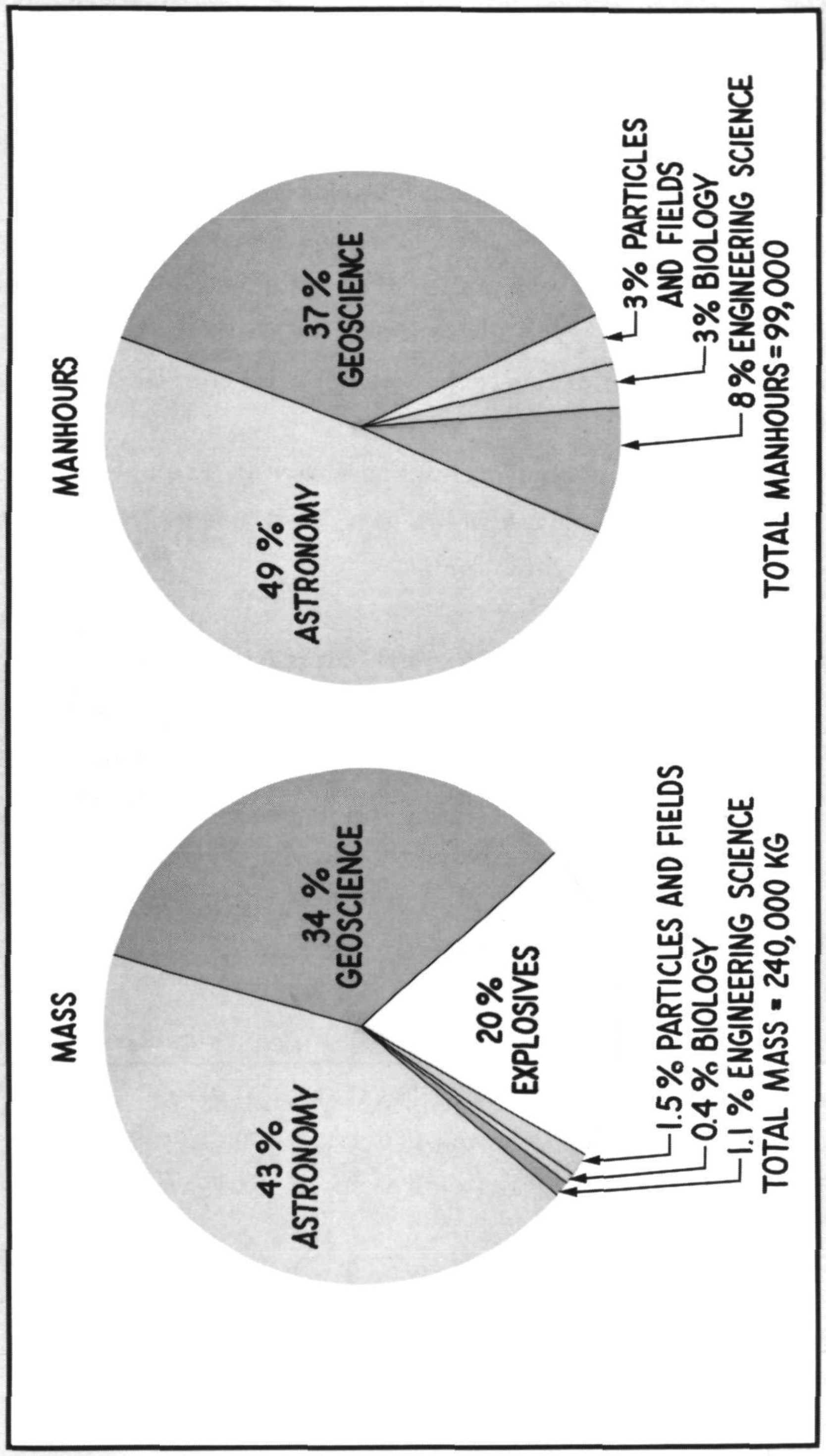


Fig. 4-4 Integrated Scientific Program, Distribution of Manhours and Mass

earlier phases of the study, a large number of equipment items had been defined and used for a comparative analysis of the candidate lunar exploration programs. This list of candidates was analyzed with the objective of selecting a minimum number of equipment items that could accomplish the various demands of the recommended lunar exploration plan. To further limit the number of equipment items, it was deemed desirable that they should be derivable in an evolutionary manner from previously developed equipment, wherever possible. The selected equipment for each era of the plan are listed in Table 4-1. The rationale for selection is presented in Recommended Lunar Exploration Plan, MIMOSA Technical Report, Vol. III.

Although an appreciable number of items are shown in Table 4-1, there are a few items that characterize each phase which have been boxed. New developments required in each phase are indicated by an asterisk.

The S/AA phase is characterized by a short-duration, two-man system provided by the Augmented Lunar Module (ALM) Shelter, and limited mobility provided by the Local Scientific Survey Module (LSSM). No major scientific equipment is included. The transportation systems are based on an uprated Saturn V (111 percent of the basic Saturn V capability) which permits lunar module descent augmentation, provides 14-day equatorial capability for two men during the S/AA phase, and allows three-man delivery to the lunar surface during later program phases.

The initial phase of the medium-level program is characterized by a highly capable three-man roving vehicle augmented with a trailer to provide an extended mobility capability. The transportation systems provide a direct delivery capability for logistics through the use of a Lunar Logistics Vehicle (LLV). The major scientific equipment consists of a 300-m drill.

The extension of the medium level program is characterized by an extended base operation using a six-man shelter and a nuclear power supply. The transportation systems are the same as used in the initial phase of the medium-level program. The major scientific equipment includes the 300-m drill, as well as an array of optical, x-ray, and radio telescopes.

Table 4-1

RECOMMENDED EQUIPMENT LIST AND UTILIZATION

Phase/Operation	Transportation System/ Flight System	Mission Equipment	Major Scientific Equipment
Apollo Two men, 48-hr Maximum Staytime at equatorial sites	*Personnel 1111-03[a] (Launch Vehicle)1221-03 Basic Saturn V		
	*Personnel 1111-05 *Launch Vehicle 1231-04 (111% Saturn V) *Command Module 1311-03 (3-man) *Service Module 1324-02 *Descent Stage 1331-02	*LRV 2421-01 (LSSM) *Manned Orbiter 2222-03 (3 man) NASA Rack 2222-02 *Unmanned Orbiter 2211-03	
Saturn/Apollo Applications Two men, 13-day Staytime Logistics Capability – 5,650 kg -LOR Equatorial Sites	*Logistic 1133-03 Launch Vehicle 1231-04 (111% Saturn) Command Module 1311-03 Service Module 1324-02 Descent Stage 1331-02	*Probe, Soft Landing, Lunar Orbit Launch 2122-01 *Probe Hard Landing, Lunar Orbit Launch 2121-01	
Two Men on Surface One Man remains in orbit	*Manned Orbiter 1152-04 Launch Vehicle 1231-04 (111% Saturn) Service Module 1324-02 *Unmanned Orbiter 1161-01 *Launch Vehicle 1212-01 (Atlas/ Centaur)	*Shelter 2321-05 (2-man ALM, 13 day)	

*Indicates New Development

☐ Indicates Principal Items Characterizing the Phase

(a) Data Book identification number

Table 4-1 (Continued)

Phase/Operation	*Transporation/System* Flight System	Mission Equipment	*Major Scientific* Equipment
Continued Saturn/Apollo Applications Two Men, Up to 30-day Staytime Logistics Capability – 5,650 kg -LOR All Sites Accessible Crew is Retrieved by Pickup Transport	Personnel 1111-05[(a)] Logistics 1133-03 *Personnel 1111-07 (pickup) Launch Vehicle 1231-04 Command Module 1311-03 Service Module 1324-02 Unmanned Orbiter 1161-01 *Explosives Transport 1151-02 *Launch Vehicle 1213-01 (Saturn IB/Centaur)	LRV 2421-01 (LSSM) Unmanned Orbiter 2211-03	
Medium Level Three Men up to 60-day Staytime Logistics Capability 14,100 kg (Direct) Extended Mobility Crew is delivered and Retrieved by Pickup Transport	*Personnel 1113-02 Launch Vehicle 1231-04 *Command Module 1313-02 (4-man) Service Module 1324-02 *Ascent Stage 1342-02 Descent Stage 1331-02 *Logistics 1143-01 Launch Vehicle 1231-04 *Braking and Landing Stage 1442-08 Explosives Transport 1151-02	Unmanned Orbiter 2211-03 *LRV 2423-03 (3-man, 14 day, 400 km, 700 kg) *LRV 2423-04 (3-man, 30 day, 800 km, 1,500 kg) *LRV 2423-05 (Use with Trailer) *LRV 2434-01 (Cargo Trailer)	*Drill 3213-02 (300-m)

*Indicates New Development

▭ Indicates Principal Items Characterizing the Phase

(a) Data Book identification number

Table 4-1 (Continued)

Phase/Operation	Transportation/System Flight System	Mission Equipment	Major Scientific Equipment
Medium Level (Cont.)	*Development Test Transport 1171-01 Launch Vehicle 1214-01 (Saturn IB) (Used for development test of 1442-08)	*LRV and Trailer Combination 2434-02 (3-man 60-day 1,600 Km, 2,500 Kg) *LFV 2511-02 (1-man 3.4 km Radius, 40 kg, 1 stop)	
Continued Medium Level Same as Medium Level with the Addition of a 6-man Shelter and a Nuclear Supply Providing Staytimes up to 3 yr with 6 mo Resupply and Crew Rotation	Personnel 1113-02[(a)] Logistics 1143-01 Unmanned Orbiter 1161-01 Explosives Transport 1151-02	LRV 2423-04 LRV 2423-05 LRV 2434-01 LRV and Trailer 2434-02 *Shelter 2325-08 6 man - 3 yrs) *Nuclear Supply 2722-04 (22 kw Isotope/ Brayton)	Drill 3213-02 (300 m) *Radio Telescope 3222-01 (Mills Cross) *Radio Telescope 3223-01 (Parabolic) *Radio Telescope 3224-01 (Mills Cross) *X-Ray Telescope 3231-01 (Grazing Incidence) *X-Ray Telescope 3231-02 (Wide Angle) *Optical Telescope 3242-02 (1m) *Optical Telescope 3242-05 (Solar) *Optical Telescope 3243-01 (2.5-m)

*Indicates New Development

☐ Indicates Principal Items Characterizing the Phase

(a) Data Book identification number

Table 4-1 (Continued)

Phase/Operation	Transportation/System Flight System	Mission Equipment	Major Scientific Equipment
Large			
Same as Continued Medium Level with the Addition of Another 6-man Shelter, Providing a 12-man Capability. Personnel Delivery is 6 Man Direct. Logistics Capability is 27,100 kg Direct.	*Personnel 1124-08 (6-Man Direct) *Launch Vehicle 1251-04 (188% Saturn V) *Braking Stage 1421-04 *Landing Stage 1431-05 *Earth Return Stage 1454-03 *Command Module 1412-03 *Logistics 1147-05 (27,100 kg) Launch Vehicle 1251-04 Braking Stage 1421-04 Landing Stage 1442-08 Unmanned Orbiter 1161-01 Explosives Transport 1151-02 Development Test Transport 1171-01 (Development Test of 1454-03)	LRV 2423-04(a) LRV 2423-05 LRV 2434-01 LRV and Trailer 2434-02 LRV 2511-02 Shelter 2325-08 (2 each) Nuclear Supply 2722-04 Unmanned Orbiter 2211-03	Drill 3213-02 Radio Telescope 3222-01 Radio Telescope 3223-01 Radio Telescope 3224-01 X-Ray Telescope 3231-01 X-Ray Telescope 3231-02 Optical Telescope 3242-02 Optical Telescope 3242-05 Optical Telescope 3243-01

*Indicates New Development

☐ Indicates Principal Items Characterizing the Phase

(a) Data Book identification number

The large program is characterized by a 12-man base operation using two of the six-man shelters. The transportation systems are based on an uprated Saturn V with a capability of 188 percent of the basic Saturn V. This uprating is based on the requirement to deliver six men to the lunar surface by a direct flight mode where the transportation system utilizes two of the LLV stages previously developed for use (singularly) with the 111 percent Saturn V. The major scientific equipment is the same as in the continuation of the medium-level program.

4.4 PLANNING CONSIDERATIONS

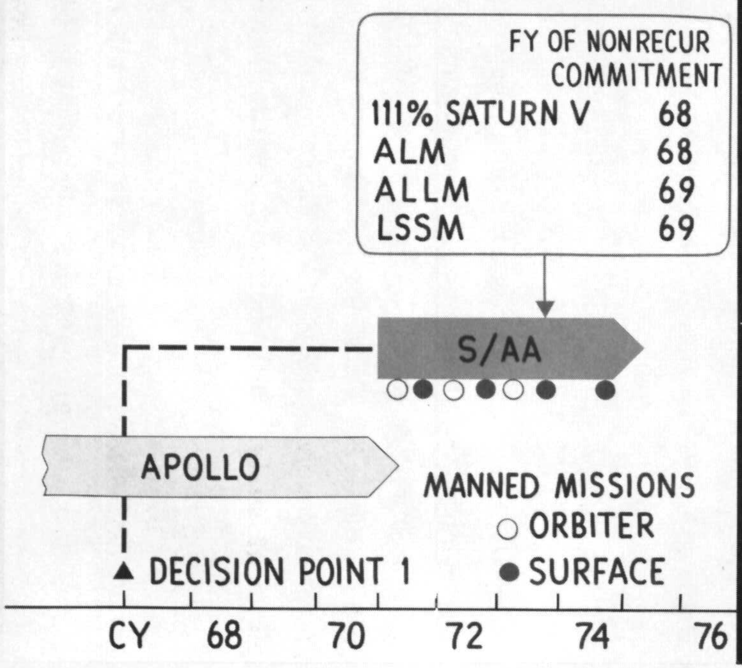
With the general approach formulated, a scientific program defined, and a specific set of equipment selected, it was possible to proceed with an analysis of the major program-shaping factors that must be considered in the formulation of a lunar exploration plan. These factors were evaluated through an examination of the three decisions points that had previously been tentatively identified (Fig. 4-1). This section summarizes the planning implications associated with the equipment options available at each decision point and the resulting exploration programs. The detailed analysis is given in Recommended Lunar Exploration Plan, Vol. III, MIMOSA Technical Report.

4.4.1 Decision Point 1

Decision Point 1 involves two options for continued lunar exploration: either continue with Apollo or introduce the S/AA Systems. It was assumed that a decision to proceed with the S/AA hardware will be made in the near future utilizing the NASA-recommended equipment given in Table 4-1. Thus, for the long-range plan being developed here, the main consideration involves the performance and development schedule requirements of the S/AA equipment, and the influence of this initial phase of exploration on the overall plan.

The S/AA phase of exploration is summarized in Fig. 4-5. Three manned orbital and four manned surface missions are postulated to perform the initial part of the integrated science program. Twelve Saturn V launches are involved in this phase which

SCHEDULE AND EQUIPMENT



COST AND PERFORMANCE

S/AA ONLY

COST ($ BILLION)			PERFORMANCE			
TOTAL	NON-RECUR	HDWR PROC	TOTAL SAT. V LAUNCH.	SURF. SCI MASS (KG)	SURF. SCI M-HR	AVG COST PER SURF. SCI M-HR ($M)
6.8	0.9	4.8	12	4,000	400	17.0

Fig. 4-5 First Decision Point Summary

results in 400 surface scientific manhr and 2,000 orbital scientific manhr at a total cost of $6.8 billion spread over a 7-yr period.

Development schedules and costs (Phase D hardware development) for the major items of equipment in the S/AA inventory are presented in Fig. 4-6. Initial commitment of funds occurs in FY 1968 for development of the 111-percent Saturn V and modification of the associated Service Module. Annual and cumulative funding requirements are shown through FY 1971 when the S/AA systems become operational. If the development cost of additional minor equipment items is included, a total nonrecurring investment of $0.9 billion is obtained.

To ensure a smooth transition from Apollo to S/AA, decision point 1 occurs in CY 1967. However, as indicated in Fig. 4-6, the actual commitment of R&D funds is spread over about 4 yr with a maximum commitment (nonrecurring and recurring) of about $1 billion in FY 1970. Maximum expenditure of nonrecurring funds is $290 million and occurs in FY 1970.

4.4.2 Decision Point 2

This decision point is the most important of the three identified since it presents the first opportunity to step up to a capability potential for extensive lunar surface exploration. Two major options are available: (1) continue at the S/AA level of locale type exploration, or (2) commit funds for new equipment to provide a capability at the medium level for extensive traverses.

Program Options and Funding. Figure 4-7 presents a summary of program data relevant to the six yr following the introduction of the new hardware. Six manned, six-man missions are associated with each option at a total cost of approximately $5 billion and funding level of about $1 billion/yr in each case. However, a marked improvement in the operational performance is evident when the medium capability is utilized rather than continuing at the S/AA level. Associated with the greater scientific manhr (factor of 8) and scientific mass (factor of 9) achievements, is an increase in the depth of

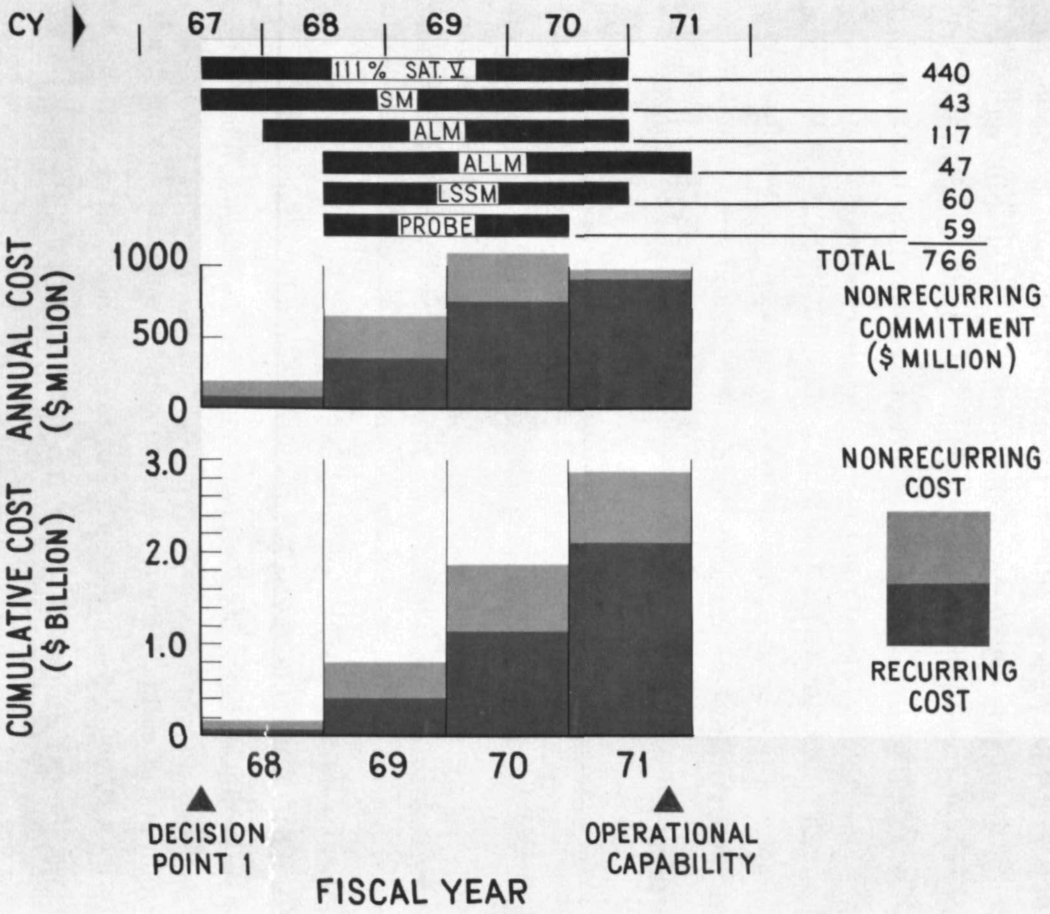
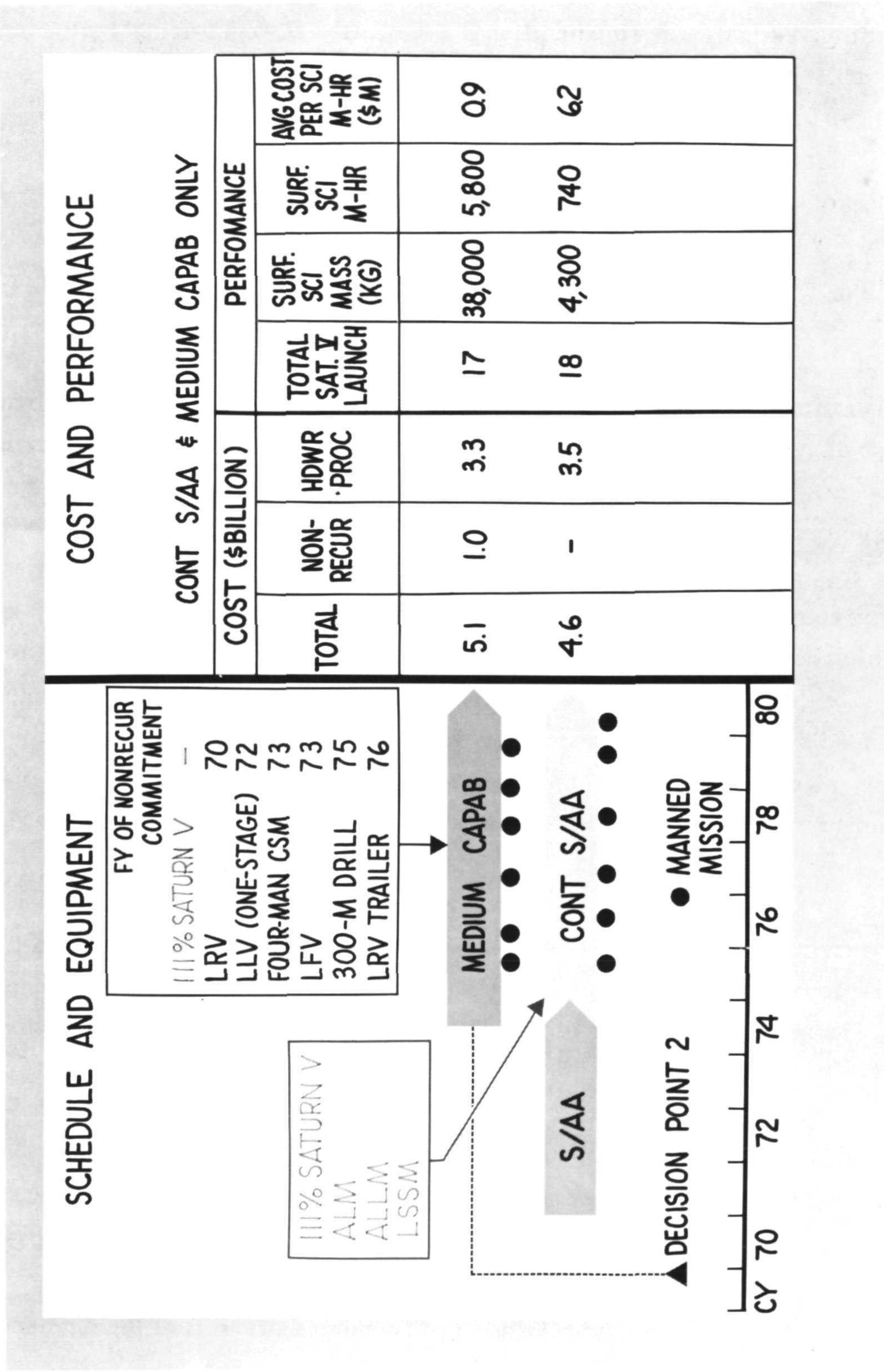


Fig. 4-6 Anatomy of Decision Point 1



CONT S/AA & MEDIUM CAPAB ONLY

COST ($BILLION)			PERFOMANCE			
TOTAL	NON-RECUR	HDWR PROC	TOTAL SAT. V LAUNCH	SURF. SCI MASS (KG)	SURF. SCI M-HR	AVG COST PER SCI M-HR ($M)
5.1	1.0	3.3	17	38,000	5,800	0.9
4.6	-	3.5	18	4,300	740	6.2

Fig. 4-7 Second Decision Point Summary

scientific investigation. This additional penetration is represented by the use of the 300-m drill, more extensive seismic experimentation, increased replications of experiments, and greater surface coverage.*

An anatomy of decision point 2 is given in Fig. 4-8 in terms of development schedules and cost for the major items of new equipment associated with the medium-level program. As observed, the commitment of funds is spread over a period of 7 yr. In accordance with the guidelines, no commitment to new developments is made until FY 1970. This means that decision point 2, at the earliest, falls in CY 1969. An initial commitment of $50 million is required in FY 1970 towards the development of the large roving vehicle, which is the longest lead time item. Peak funding for new equipment occurs in FY 1974 and amounts to about $375 million. A total nonrecurring investment of $1 billion is involved.

The important conclusion to be drawn from the analysis of decision point 2 is that considerably greater potential for scientific return can be expected in return for a commitment to the medium capability equipment for approximately the same total cost and annual funding level that a continuation of the program at the S/AA level would entail. Further, since the funding commitment to new equipment occurs over a period of 7 yr, this improved performance can be achieved at a relatively low investment risk.

Effect of Delay. The data given in the preceding section were predicated on a decision point occuring in CY 1969. The utilization of the more capable equipment displayed a potential for the accomplishment of 5,800 surface scientific manhr between 1974 and 1980. The program influence of delaying decision point 2 was investigated. The results are given in Table 4-2.

These results are based on the assumption that lunar exploration continues at the S/AA level during the period of delay. Table 4-2 shows that on the average a penalty of $880 million is incurred for each year of delay. This amount is approximately equal to the

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*Details of each mission are contained in Appendices A and B of Recommended Lunar Plan, MIMOSA Technical Report, Vol. III.

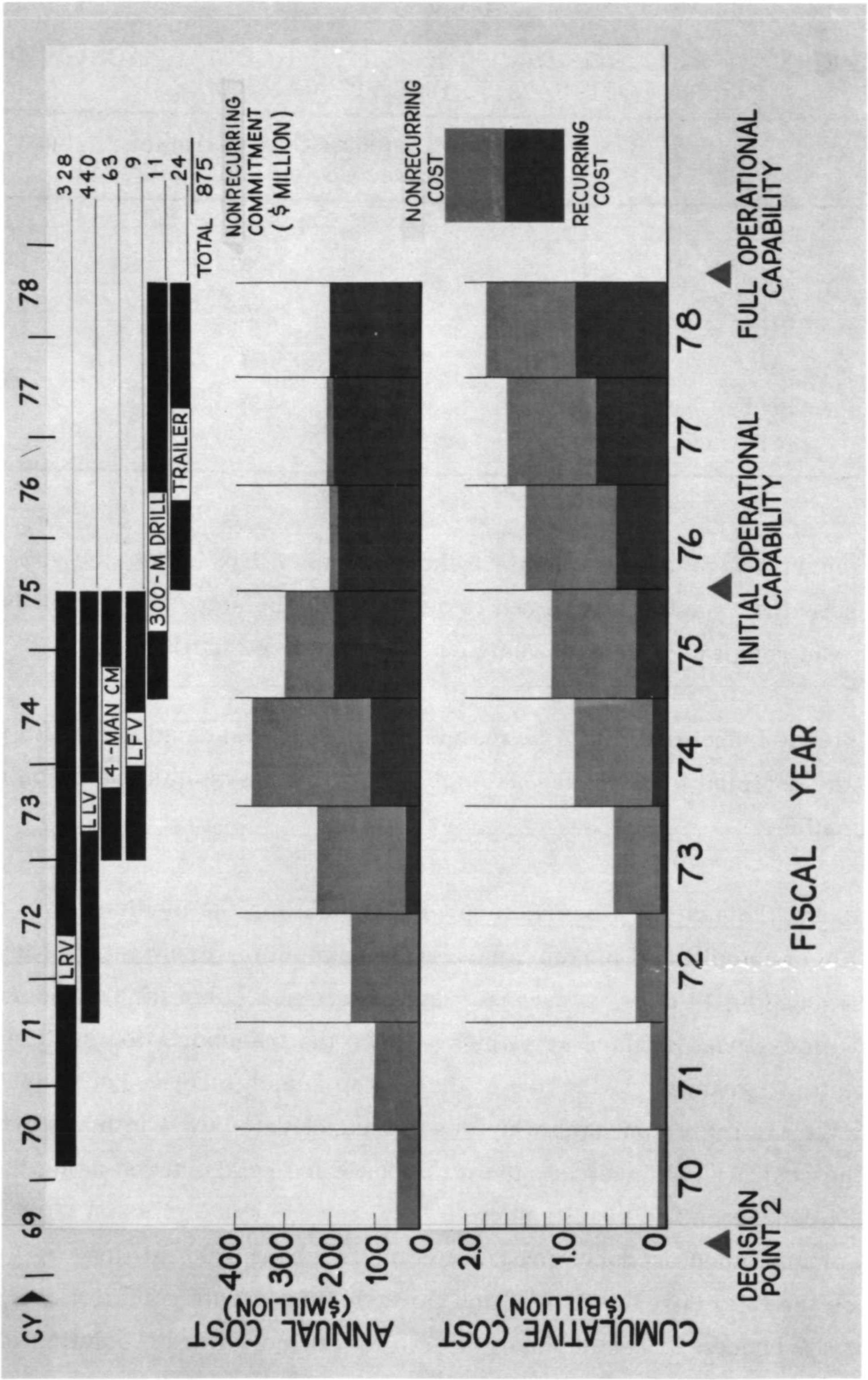


Fig. 4-8 Anatomy of Decision Point 2

Table 4-2

EFFECT OF DELAY OF DECISION POINT 2 – COST TO ACHIEVE 5,800 POST-S/AA SCIENTIFIC MANHOURS

FY of Decision	Incremental Cost to Achieve 5,800 Surface Scientific Manhr ($B)
1970	0.0
1971	0.3
1972	1.25
1973	2.2
1974	3.4
1975	4.4

total nonrecurring investment to achieve the new capability. Also, the year in which the 5,800 scientific manhr is achieved is delayed. If the step-up decision is delayed until 1975, the requisite scientific manhr are not realized until 1983.

Thus if a steady launch rate is to be maintained and the assumed scientific program achieved, the decision to introduce the higher capability systems should be made as soon as possible.

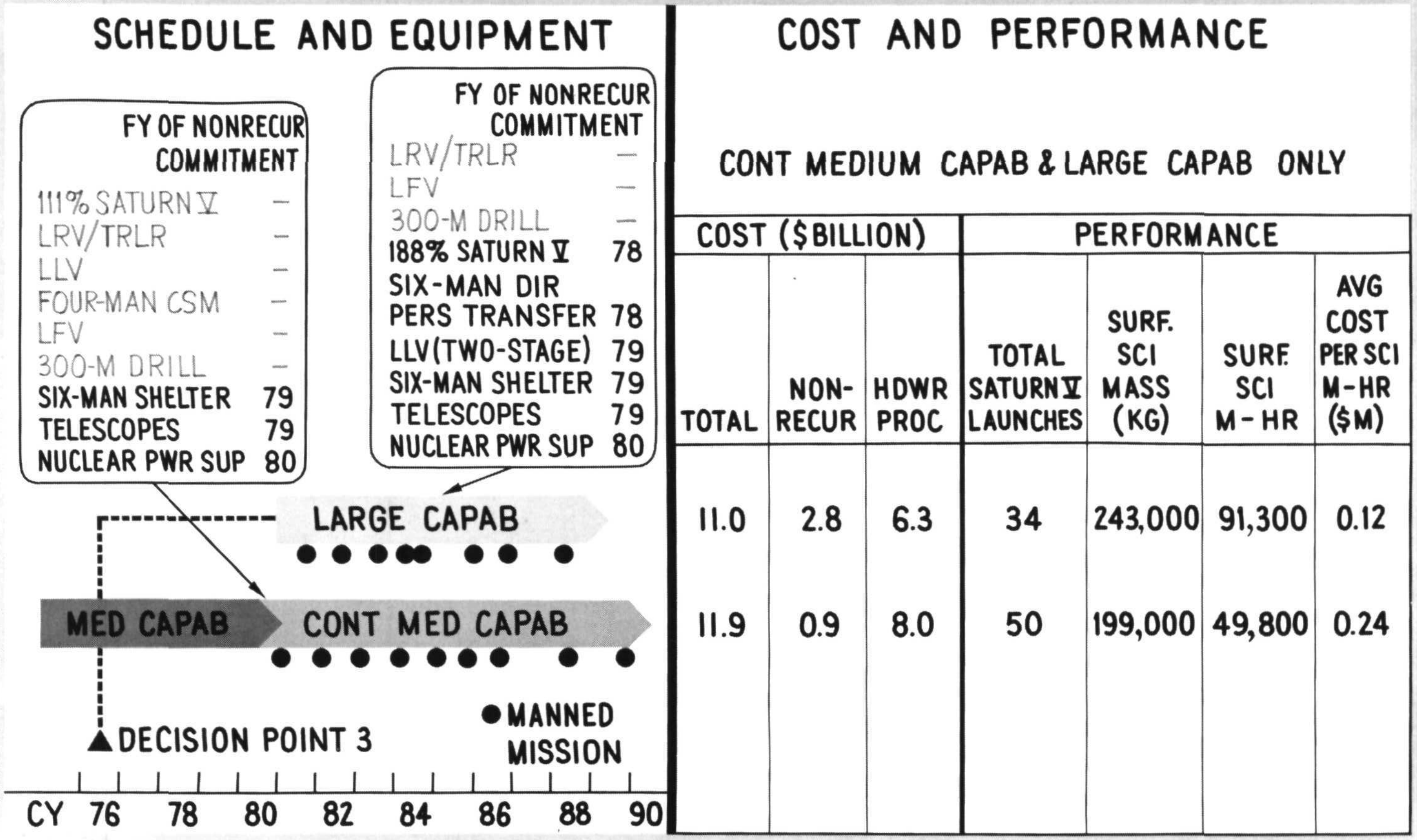
Effect of Pickup Launch for Crew Return. In formulating the medium-level exploration program, an additional pickup launch was assumed for crew return for mission staytimes exceeding 14 days as a conservative approach permitting three-man lunar missions with extended surface staytimes. Since the transportation system is a major contributor to program cost, the use of the pickup launch incurs significant additional costs over the alternate approach which uses a deactivated CSM in lunar orbit. To estimate the cost penalty involved, the missions were restructured using the deactivated CSM concept. The results showed that, for the same mission frequency, eliminating the pickup launch reduces program costs by about $300 million per yr after 1975 and reduces the total cost by $1.4 billion through 1980. This potential cost saving is significant. A concerted development effort is justified toward a solution of the operational problems associated with a long-time deactivation of the CSM while in lunar orbit.

4.4.3 Decision Point 3

The options available at decision point 3 are (1) continue exploration at the medium level by the introduction of a few additional items of new equipment as shown in Table 4-1, or (2) increase the scope of exploration through the introduction of large capability systems. The alternate programs are summarized in Fig. 4-9 for the time period 1980—1990. The large capability is achieved through an investment of $2.8 billion in nonrecurring funds, $0.9 billion of which would be required to continue at the medium level. This increased investment results in a considerably greater potential for lunar exploration as evidenced by the greater scientific mass transported to the surface in support of the extended 12-man base (approximately 2 yr) and three six-man bases (approximately 6 mo) and almost double the scientific manhr when compared with the medium-level program. The latter supports one six-man base over a period of 2 yr.

Funding rates are about $1.5 billion per year over the period of interest. Total costs amount to $11.9 billion and $11.0 billion for the continued medium and large capabilities, respectively. The medium program cost, however, includes $2.1 billion that is attributable to use of the pickup launch concept. A considerable part of this cost would be saved if a long staytime orbital CSM were developed.

Funding commitments to either option again occur over a period of some years. The timing of decision point 3 is not critical and will be governed by the demands of an extended base and the plan for manned planetary exploration. The latter would provide an added impetus for the development of six-man delivery systems and the introduction of the large (188%) Saturn V. At the large capability level, the uprated Saturn V was introduced in 1982. This ensures about 5-yr usage of the medium-level equipment, is compatible with present predictions for the planetary program, and can be accommodated within the guideline funding constraints. To meet these restraints, decision point 3 must occur in 1976.



SCHEDULE AND EQUIPMENT

FY OF NONRECUR COMMITMENT	
111% SATURN V	–
LRV/TRLR	–
LLV	–
FOUR-MAN CSM	–
LFV	–
300-M DRILL	–
SIX-MAN SHELTER	79
TELESCOPES	79
NUCLEAR PWR SUP	80

FY OF NONRECUR COMMITMENT	
LRV/TRLR	–
LFV	–
300-M DRILL	–
188% SATURN V	78
SIX-MAN DIR PERS TRANSFER	78
LLV(TWO-STAGE)	79
SIX-MAN SHELTER	79
TELESCOPES	79
NUCLEAR PWR SUP	80

COST AND PERFORMANCE

CONT MEDIUM CAPAB & LARGE CAPAB ONLY

COST ($BILLION)			PERFORMANCE			
TOTAL	NON-RECUR	HDWR PROC	TOTAL SATURN V LAUNCHES	SURF. SCI MASS (KG)	SURF. SCI M-HR	AVG COST PER SCI M-HR ($M)
11.0	2.8	6.3	34	243,000	91,300	0.12
11.9	0.9	8.0	50	199,000	49,800	0.24

Fig. 4-9 Third Decision Point Summary

Effect of Cost Sharing With Planetary Program. To examine the influence of sharing nonrecurring costs with a postulated planetary program, it was assumed that the planetary program as a by-product would provide the Saturn V uprating; the cost of modifying planetary hardware to provide a six-man CM and lunar shelter would be charged to the lunar program. The reduced funding to achieve the large capability lunar program is summarized in Table 4-3.

Table 4-3

LUNAR PROGRAM COST SAVING DUE TO COMMONALITY WITH PLANETARY PROGRAM

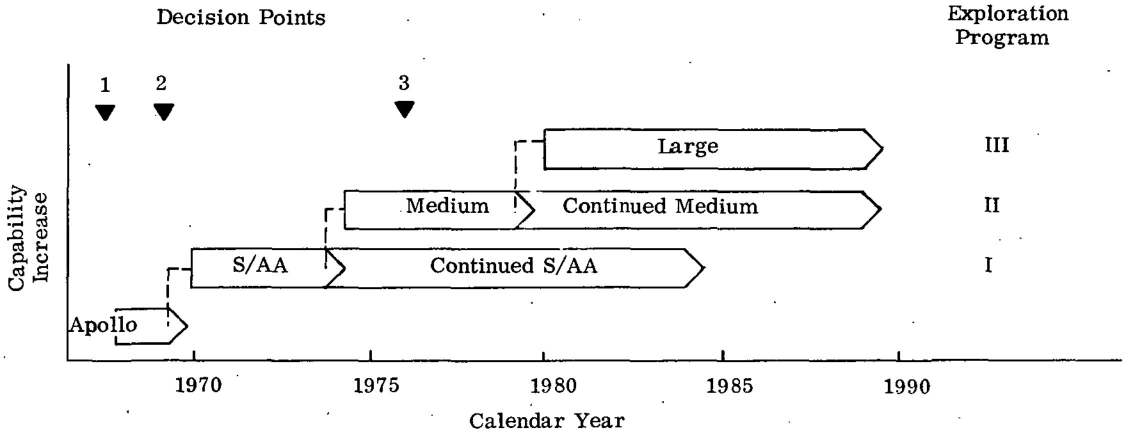
Equipment	Nonrecurring Cost Saving	
	(%)	($M)
188% Saturn V	100	984
Six-Man CM	75	382
Six-Man Shelter	75	316
Total		1,682

4.5 POTENTIAL LUNAR PROGRAMS

The recommended plan for lunar exploration, presented in this chapter, advocates not a single program with a single set of hardware but a number of program alternates stemming from management options at three key decision points to be encountered over the next 10 yr. The eventual lunar exploration program will depend upon the equipment decisions made and the timing of those decisions. Table 4-4 summarizes three examples of the types of programs that could result from the decision alternates. A complete description of these programs is given in Recommended Lunar Exploration Plan, Technical Report, Vol. III.

Table 4-4

SUMMARY OF EXAMPLE LUNAR EXPLORATION PROGRAMS



Program Parameter (Post-Apollo)	Program		
	I	II	III
General			
Program Start Date	1971	1971	1971
Program End Date	1984	1989	1988
Number of Missions	27	34	34
Number of Manned Surface Missions	14	18	18
Total Manhr on Surface	18,000	188,000	306,000
Total Mass Delivered to Surface (kg)	132,000	469,000	608,000
Maximum Surface Crew	2	6	12
Science Accomplishment			
Science Manhr – Surface	2,200	56,000	97,500
Science Manhr – Orbit	2,000	2,000	2,000
Science Manhr – Base	0	41,000	86,000
Science Mass – Surface (kg)	17,000	241,000	285,000
Science Mass – Orbit (kg)	5,500	5,500	5,500
Number of Extended Bases	0	1	4
Traverse Range (km)	3,100	9,700	14,700
Resource Allocation			
Number of New Equipment Starts	11.0	24.0	29.0
Total Saturn V Launches	45.0	79.0	63.0
Total Program Cost ($B)	14.8	23.8	22.9
Nonrecurring Cost ($B)	0.9	2.8	4.7
Recurring Cost ($B)	13.9	21.0	18.2

Chapter 5

SIGNIFICANT RESULTS

The MIMOSA planning methodology is an efficient working tool for providing well substantiated answers to lunar exploration planning questions. As such, it represents a valuable aid to NASA program planners. The tool provides a standard logic for lunar program generation and analysis. Mechanization of data handling, routine calculations, and data presentation is achieved through use of a thoroughly checked computer program. The methodology has been developed in such a way that the planner is always in the analysis loop and can make decisions from the data presented. In addition to developing this planning tool, the MIMOSA study illustrated that the methodology could be used in a meaningful manner.

Many of the results derived during the MIMOSA study are dependent on original assumptions. Such assumptions, of course, are governed by the planning environment and represent some of the very parameters that the MIMOSA tool is intended to study. For this reason, the significant results presented in the following paragraphs should be interpreted in the light of the MIMOSA groundrules related to:

- Science – Basic goals as currently conceived by the scientific community with emphasis on geology early and astronomy later
- Funding – Continuous at 1 billion to 2 billion dollars per year
- Launch Rates – modest, three to four per yr initially and six to eight per yr later
- Equipment – Maximum use of Apollo technology, evolutionary development of capability
- Operations – Emphasis on manned exploration and traverse-type investigations

A summary of major conclusions drawn from the MIMOSA study follows.

5.1 INFLUENCE OF SCIENCE

- The achievement of geoscientific goals of lunar scientific exploration calls for the performance of experiments at widely separated surface locations. These experiments are best accomplished by performing long traverses over the lunar surface.
- The performance of active seismology experiments requires delivery of substantial amounts of chemical explosives, which amounts to about 20 percent of the total mass of scientific equipment delivered to the Moon during an exploration program.
- Earth return-mass requirements (scientific samples, films, etc.) are considerable: for the integrated scientific program, the return mass requirements exceed the projected Command & Service Module (CSM) capabilities by a factor of 6. A critical review of the basis for these requirements is indicated and, if the requirements are realistic, subsidiary techniques for improving Earth return mass capability should be developed.
- Generally, the fulfillment of scientific manhour requirements is more difficult to achieve than the fulfillment of scientific mass requirements. This fact is particularly relevant to the early phases of exploration.
- For the scientific programs developed in MIMOSA, geology and astronomy experiments provide over 90 percent of the scientific mass requirements and over 80 percent of the scientific manhour requirements.
- The size of the scientific program to be attempted strongly influences total exploration-program costs. For three typical scientific programs considered in MIMOSA (Programs A, B, and C) the resulting scientific manhours are in the approximate ratio 8:4:1 and the most economical associated program costs are approximately 2.5: 1.5:1.

5.2 EXPLORATION EQUIPMENT

- A modest equipment inventory permits extensive lunar exploration.
- The use of an efficient logistics delivery system is an important factor in reducing total exploration cost. In particular, the direct lunar logistics vehicle (LLV) shows significant cost and performance advantages over the unmanned logistics version of the LM descent stage (LM/Truck).

- Only a modest uprating of the Saturn V launch vehicle will be required for lunar exploration. Generally, requirements are for a launch vehicle with a capability in the range of 111 to 125 percent of the standard Saturn V rating to be introduced in the early 1970's. More extensive upratings can only be used efficiently if long-term bases are assumed. Critical uprating requirements arise from personnel delivery considerations.
- A large roving vehicle with a range of about 800 km is required in the mid-1970's to enable long traverses to be accomplished with a "mobile base." Considerable advantages (in range capability and program cost effectiveness) can be gained by supplementing the basic rover by means of a trailer. Such a combination could be developed to satisfy traverse requirements of up to 1,500 km that result from the MIMOSA scientific programs. The roving vehicle should accommodate at least three scientist/astronauts.
- The main requirement for a lunar flying vehicle arises from a likely need to visit places that are inaccessible to surface rovers in support of scientific observations. A one-man flyer ("pogo-stick") with a range of 7 km, should suffice.
- Large (six-man) shelters and nuclear power stations are not required until 1980 or later.
- The choice of cost-effective exploration equipment for the post-Apollo era is not affected by the actual and eventual scope of scientific activity, associated with lunar exploration, over the range of programs examined in MIMOSA (this range encompases scientific programs as austere as 3,000 scientific manhours and as abundant as 100,000 scientific manhours).

5.3 OPERATIONS

- Post-Saturn Apollo Applications (S/AA) surface manning levels required for the exploration programs derived in the MIMOSA study are three men in the 1970's and six to twelve men in the 1980's.
- Three-man Lunar Orbit Rendezvous (LOR) delivery techniques can be utilized through the 1970's; six-man direct-delivery techniques can be used efficiently in support of extended bases in the 1980's.

- The program cost penalty associated with use of separate launches for crew pickup justifies a concerted effort toward developing a long-term deactivated CSM for lunar orbital storage during long staytime lunar-surface missions.

5.4 PROGRAM AND RESOURCE

- Three key decision points, regarding commitment to new capability developments will be encountered approximately during 1967, 1969, and 1976 in a nominally paced exploration program.
- Limited lunar exploration through 1984 can be conducted at the S/AA capability level for approximately 1 billion dollars yearly funding and a 15 billion dollars total program cost.
- Extensive lunar exploration through the late 1980's is possible with uprated systems for essentially the same yearly funding rate of 1 billion dollars and at a total cost of approximately 23 billion dollars.
- The nonrecurring costs associated with these programs are relatively small and amount to 1 billion dollars for the S/AA systems and from 2.8 billion to 4.7 billion dollars for the two alternatives, identified in the recommended plan, that use the uprated systems.
- The sensitivity of the program resource demands to selection of the Earth-to-Moon transportation systems can be clearly understood from the distribution of total program cost by equipment category observed in the program resource results:
  - Transportation System — 80 percent
  - Mission Equipment — 10 percent
  - Major Scientific Equipment — 4 percent
  - Other (integration, minor science, etc.) — 6 percent
- Extensive lunar exploration can be conducted at a funding rate of about one-third the present manned space flight budget and at a total cost approximately equal to that commited to Apollo.

Chapter 6
TECHNOLOGY IMPLICATIONS

The lunar exploration plan described in Chapter 4 is implemented by a set of recommended exploration equipment selected in accordance with the conclusions drawn from the analysis of a broad spectrum of candidate exploration programs designed to satisfy the guidelines adopted for the plan. This equipment exhibits an evolutionary growth of exploration capability that generally relies on present state-of-the-art technology. However, there are several areas where additional research and/or development is required, or could provide data, criteria, and design concepts that would permit system simplification, weight-reductions, and greater reliability. This chapter describes those areas.

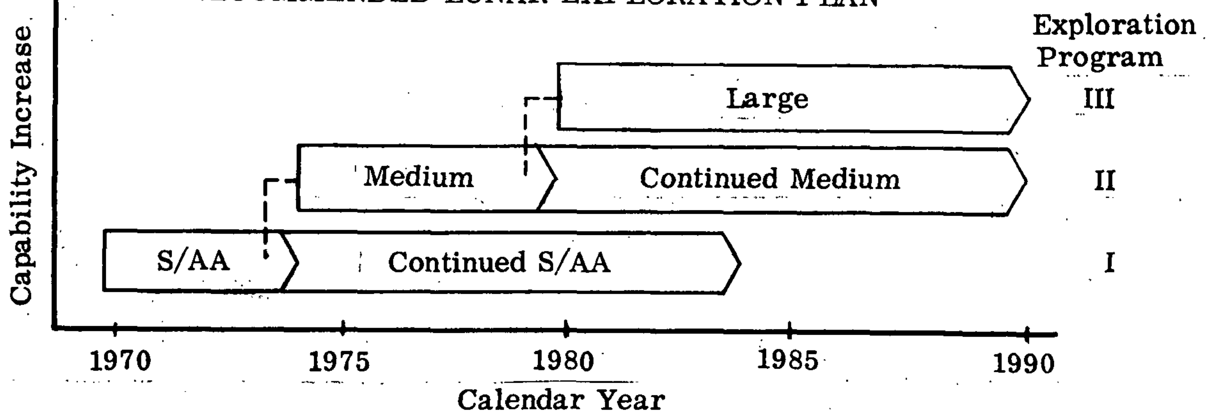
Table 6-1 summarizes the technological areas requiring considerable attention and relates these areas to the program options contained in the exploration plan. The equipment items affected by the technological implications and the associated equipment schedules are also shown.

Program I is characterized by a short duration, two-man system consisting of the Augmented Lunar Module Shelter (ALM), and limited mobility provided by the Local Scientific Survey Module (LSSM). The transportation systems are based on an uprated Saturn V with a capability of 111 percent of the basic Saturn V. No major scientific equipment is included. Since these equipments represent near term developments, the major technological problems have been resolved and only minor problems remain.

The initial phase of the medium-level program, Program II, is characterized by extended mobility provided by a large three-man roving vehicle augmented by a trailer. The transportation systems are based on an uprated Saturn V with a capability of 111 percent of the basic Saturn V. Direct delivery capability for logistics is provided through the use of a Lunar Logistics Vehicle (LLV). The major scientific equipment consists of a 300-m drill.

Table 6-1

TECHNOLOGICAL PROBLEM AREAS ASSOCIATED WITH ALTERNATE OPTIONS OF THE RECOMMENDED LUNAR EXPLORATION PLAN



Problem Area	Exploration Program Phase	Associated Equipment	Associated Equipment Schedule			
			Program II		Program III	
			Development Start	Operational Introduction	Development Start	Operational Introduction
Deep Drill Lubrication and Cooling	Medium	300-m Drill	1874	1978	-	-
Carbon Dioxide Removal Water Recovery Oxygen Recovery	Continued Medium and Large	Six-Man Shelter	1981	1986	1978	1983
Large Telescope Optics		Optical Telescopes	1978	1983	1979	1983
High-Temperature Radioisotope Fuel Capsule Radioisotope Fuel Shipping Cask Heat Transfer to Space		Nuclear Power Supply	1980	1986	1979	1985

The extension of the medium level program is characterized by an extended base operation using a six-man shelter and a nuclear supply. The transportation systems are the same as used in the initial medium level program. The major scientific equipment includes the 300-m drill as well as an array of optical, x-ray, and radio telescopes.

The large program, Program III, is characterized by 12-man base operation using two of the six-man shelters. The transportation systems are based on an uprated Saturn V with a capability of 188 percent of the basic Saturn V, and provide direct delivery of a six-man crew. The major scientific equipment is the same as in the *continuation of the medium level program.*

No major technological problems were identified for the program representing the lower level capability (Exploration Program I) that utilizes the Saturn Apollo Aplications (S/AA) equipment. If the medium capability equipment option is exercised, the problem of lubricating deep core drills must be solved. The other major technological problems identified are common to the continued medium and large capability equipment options. These are associated with the requirements for a long duration shelter, nuclear power supply, and large optical telescopes. The technological development requirements are discussed in the following subsections.

The first subsection (6.1) is devoted to those technological advances associated with the equipment in Exploration Program I. However, because the early part of Program I also forms part of Programs II and III, the requirements given also apply to Programs II and III. The second subsection (6.2) identifies the technological advances that apply to the equipment used in the later stages of Exploration Programs II and III (medium and large capability level). These advances are common to both programs. Each subsection is further divided by technological area as follows:

(1) Biotechnology and Human Engineering
(2) Electronics and Control
(3) Materials and Structures

(4) Nuclear Systems
(5) Propulsion and Power Generation

The technological development problems discussed in this chapter are relevant to the equipment contained in the recommended equipment list. Many of these problems and their solutions are also applicable to other similar equipment that might be selected for lunar exploration. Since design concepts for uprated versions of the Saturn V launch vehicle are still under consideration by NASA, no attempt is made in this report to identify the technological problem areas associated with their development.

6.1 EXPLORATION PROGRAM I

6.1.1 Biotechnology and Human Engineering

Waste Processing by Vacuum Drying. To minimize contamination of the lunar surface, it is proposed that all solid human waste be vacuum dried and stored. A number of laboratory vacuum drying waste processing systems have been built and tested. The feasibility of this concept has been demonstrated, but further work is required to provide a unit suitable for operational use. The following methods need to be investigated: (1) loading and unloading waste material to minimize operator involvement, (2) reducing drying time by increasing contact between heating source and the waste material, and (3) preventing clogging of valves, seals, and filters by waste material.

Pressure Suit Life. The longer duration missions that employ considerable extravehicular activity will place a severe strain on the life of suit joints, seals, cables, hoses, gloves, and the pressure shell. The current suit development program should be broadened to include increasing suit life and resistance to damage.

Portable Life Suport Systems. One of the most critical operations in missions currently under consideration is the extravehicular exchange of a spent Portable Life Support System (PLSS) for a fully charged one. Mission requirements dictate that this exchange be made on the lunar surface by a single astronaut. Since the present PLSS and spacesuit designs do not permit this exchange, several modifications to the PLSS are necessary. For instance, a dual connector fitting must be developed for the suit that would allow the oxygen connection from two PLSS's to be attached to the suit. Also, research is required on means to seal and disconnect the PLSS to this fitting. Requirements for the thermal protection during PLSS switching also should be investigated. Furthermore, the PLSS switching operation will require a longer PLSS-to-suit hose than presently exists on the PLSS and pressure drop and flow rate effects on blower sizing must be re-evaluated.

Lunar Surface Environment Simulation. Detailed hardware designs, operation plans, and crew safety are dependent on a realistic appraisal of astronaut capabilities on the lunar surface. A more realistic simulation of the lunar surface environmental constraints would be beneficial in determining these capabilities more precisely. Although elements of the lunar environment have been simulated, they have not been integrated into a lunar surface test bed. To provide the required realism, such a test bed should synthesize the following lunar environment elements with mockups, prototypes or simulators of the hardware systems under consideration: one-sixth gravity, lunar illumination levels, lunar surface characteristics, vacuum, and lunar thermal conditions.

Human Factors. To accurately assess the capability of a crew to accomplish the scientific experiments and nonscientific activities assigned to a mission, simulation facilities similar to those suggested above should also be used to evaluate human performance. Typical tests that should be performed in a fully representative environment include the following:

- Time-line studies of all scientific and nonscientific tasks
- Evaluation of the capabilities of an astronaut to perform equipment maintenance. The results will influence aspects of equipment design such as active versus standby redundancy and spare parts provisions.
- Analysis of astronaut metabolic rates associated with various activities to determine consumption of expendables and ensure realistic planning of astronaut activities

6.1.2 Electronics and Control

No requirements for technological advances were recognized in this area.

6.1.3 Materials and Structures

Thermal Coatings. The use of surface coatings with optimum absorptive and emissive characteristics is of utmost importance for passive thermal control of exploration equipment. A good deal of information is available concerning the absorptivity and emissivity of many materials in Earth-orbital environment. The problems and limitations associated with the use of these materials depend on the durability of the surface finish as a function of time and environment.

For lunar applications, surface finishes should be subjected to a simulated lunar environment for extended periods of time at various temperature levels and temperature cycles.

Micrometeoroid Protection. The external surfaces of exploration equipment must protect the equipment from micrometeoroid penetration. In many applications, a structural aluminum skin backed by multilayer thermal insulation is used for this purpose. Due to a lack of knowledge of the penetration phenomenon, the present designs are generally conservative and have a resultant mass penalty. A micrometeoroid penetration test program would provide data that would permit optimization of the present designs. Current experimental programs should be expanded to include investigation of a greater range of materials and possible fire hazard. Fuel tank walls are particularly vulnerable to micrometeoroid damage since direct exposure to the flux is generally involved. These items should be given particular emphasis in the tests.

Lubricants. Friction between moving parts of exploration equipment must be reduced by the use of lubricants. These lubricants must perform their function over a wide range of temperatures and in a vacuum. Two possible solutions – solid films and low volatility grease – should be investigated. Solid film material should remain stable down to 10^{-11} mm of Hg pressure and over a temperature of -100°C to 150°C. Low volatility grease should exhibit fairly constant sublimation rates under the same conditions of pressure and temperature.

Cold Welding. Cold welding refers to the adhesion of one piece of material to another as a result of contact between them over an extended period of time in a vacuum. If this occurs during the 6-mo lunar surface storage period required for all mission equipment used in the exploration plan, the operation of moving parts such as wheels and controls would be impaired. Investigations leading to the understanding and prevention of this phenomena should be undertaken.

6.1.4 Nuclear Systems

No requirements for technological advances were recognized in this area.

6.1.5 Propulsion and Power Generation Systems

Traction Drive Mechanism. The traction drive mechanism of lunar roving vehicles incorporates a hermetic seal diaphragm or bellows that transmit high tangential torques while being cycled at high frequency and amplitude in the transverse direction. The capability of these parts to survive over long lifetimes in a lunar environment is questionable and must be verified experimentally.

6.2 EXPLORATION PROGRAMS II AND III

6.2.1 Biotechnology and Human Engineering

Carbon Dioxide Removal. To provide a breathable atmosphere for the astronauts, the amount of carbon dioxide in the shelter atmosphere must be maintained at or below an acceptable level. Removal of carbon dioxide can be accomplished by (1) chemical absorption of the carbon dioxide in expendable lithium hydroxide, (2) absorption of the gas in a regenerable molecular sieve, and (3) electrochemical concentration. For long duration missions, use of the expendable lithium hydroxide imposes severe mass penalties and development of either of the remaining techniques becomes essential.

The molecular sieve removes CO_2 by a two-step method. First, the process gas stream is dried to a low dew point in a silica gel bed; then CO_2 is removed in a molecular sieve bed. Both beds can then be regenerated by desorption in vacuo. A sizeable quantity of contained water and some oxygen is dumped to vacuum during each cycle. If the CO_2 is to be subsequently processed rather than dumping, the bed is regenerated by the application of heat.

The electrochemical concentration process accomplishes CO_2 concentration without the prior removal of water. Since the electrochemical concentration does not require the prior removal of water, it is considered inherently more reliable than the molecular sieve with its associated valves and hardware, and is to be preferred for long-term lunar applications. Although the feasibility of the electrochemical concentrator technique has been demonstrated, long-term reliability and material life and compatibility problems must be solved.

If one of the regenerable systems is not made available and lithium hydroxide were to be used, the result would be a severe mass penalty. For example, in the case of a six-man, 3-yr mission, a lithium hydroxide system would result in a total mass requirement of 7,600 kg, while one of the regenerable systems would impose a requirement of only 280 kg.

Water Recovery. Water must be provided to the astronauts for drinking and washing. Water is also required in the PLSS for cooling. Of course water can be supplied from Earth; however, transportation mass requirements can be conserved by recovering a major portion of the required water from urine, humidity condensate, and wash water. Possible water recovery processes include air-evaporation distillation, vapor-compression distillation, and vacuum distillation.

The air-evaporation system can operate either adiabatically or isothermally. In the adiabatic system, the air stream provides the latent heat of vaporization for evaporating the water. In the isothermal system, heat is supplied directly to the water and the air flow rate is determined by its water-carrying capacity. After water evaporation, the air stream passes through a condenser where the water is removed.

In the vapor-compression system, contaminated water is evaporated, the vapor compressed, and finally condensed. The condensing vapor supplies the latent heat required by the evaporating water. This system is more complicated than the air-evaporation system because the evaporation-condenser is one unit, and must therefore have two separate sets of fluid flow passages.

The vacuum-distillation system utilizes the vacuum of space to evaporate water at reduced pressures and temperatures. The vapor is then condensed at the reduced pressure. A low-temperature coolant and warm heat-transport fluid are required for this system.

The adiabatic air-evaporation system has received the most development effort to date and has been tested in simulated, manned tests. This system is less complex than the others because of the separate evaporation unit and the absence of any high-temperature components, and is easier to maintain because of its simpler design. An operational flight unit has not been developed.

Lack of a water recovery system will result in a severe mass penalty. For example, the water requirement for a six-man level, 3-yr mission is 57,000 kg. With water recovery, only 8,750 kg of this total need be transported from Earth. Savings of this nature justify a concerted effort toward the development of reliable water regenerating systems.

Oxygen Recovery. For a shelter to be habitable, the amount of oxygen in the shelter atmosphere must be maintained at an acceptable level. Oxygen can be supplied from Earth; however, a major portion of the required oxygen can be obtained by recovery from carbon dioxide. The principal methods of oxygen recovery are presently considered: the Sabatier process, consisting of hydrogenation of CO_2 to methane and water, and the Bosch process, consisting of hydrogenation of CO_2 to carbon and water. These techniques require electrolysis of the product water to obtain oxygen.

The simplest and most highly developed method of recovering oxygen from CO_2 is by the Sabatier process. The reaction takes place at a low temperature (290° C) with full oxygen recovery and long catalyst life. The primary disadvantage is that half of the required hydrogen is lost in the methane vented overboard. Makeup hydrogen is obtained from the electrolysis of additional water stores.

The Bosch reaction involves the one-step reduction of CO_2 to carbon and water. The process operates at higher temperature than the Sabatier (670°C) and the low oxygen conversion efficiency requires extensive recycling and severe catalyst loss and cleaning problems. Its major advantage is that no hydrogen makeup is required.

Except for the CO_2 methanization portion of the Sabatier process, none of the equipment required has been translated into flight hardware. Although no particular technological problems are envisioned for either of the two processes, further development is required and a selected concept must be interpreted into flight hardware.

Lack of an oxygen recovery system will result in an appreciable mass penalty. For example, the oxygen available in the carbon dioxide generated during a six-man level, 3-yr mission amounts to 4,700 kg. In comparison, the mass of an oxygen recovery unit is only 1,000 kg.

Lunar Roving Vehicle Vibrations. The long term effect of low frequency vibrations on the driver and passengers of a lunar roving vehicle is unknown. The effect of these vibrations may result in nausea, the impairment of visual acuity (which in turn could affect the ability to read controls and displays and the discerning of geographical points of interest), and the impairment of operation of the control stick. The effect of such vibrations on an astronaut should be evaluated. These evaluations should take into account the amplification factors resulting from transmitting the vibrations through the structure, the driving station, and the spacesuit.

Lunar Flying Vehicle Free-Flight Simulation. Definitive data are lacking on man's ability to fly and land a flying vehicle in the lunar environment under the constraints of lunar lighting and visual conditions, unfamiliar surface features, reduced gravity, and the pressure suit. The Lunar Module (LM) is designed for a single, relatively hard landing at a level, unobstructed site. On the other hand, an exploration flying vehicle must make repeated landings at many unfamiliar sites, possibly on rough and difficult surfaces.

Due to the lack of suitable lunar flight data, a conservative approach has been taken in the design of flying vehicles. Flight instrumentation and landing stability and impact capability have been designed into the vehicle, in excess of that usually employed on Earth VTOL vehicles. If better data could be obtained of man's ability to navigate, control, and land a small lunar flying vehicle, it might be possible to make design simplifications to reduce weight, cost, and development time.

Previous work in this field has employed either fixed-base simulation devices or the free-flight Lunar Landing Research Vehicle (LLRV), landing on a familiar prepared hard surface.

To research man's ability to recognize, fly to, and land on lunar surfaces under varying lighting angles, a small, free-flight, rocket supported, simulated lunar vehicle should be developed. This vehicle can be flown over a realistic lunar scene of the correct albedo and illuminated from various angles. Using a pressure-suited operator, typical lunar sorties can be flown simulating all lunar tasks, both in-flight and at the exploration site.

6.2.2 Electronics and Control

Telescope Alignment. A critical requirement for the effective use of large aperture diffraction-limited optics is a star tracking system capable of maintaining alignment of the optical system for periods on the order of an hour with a tracking error less than 0.01 sec of arc. It is not know that present technology can provide this degree of precision. A star tracking system fulfilling the accuracy requirements must be developed if large scale optical telescopy is to be performed on the Moon.

6.2.3 Materials and Structures

Lubrication and Cooling of Deep Drills. The feasibility of core drilling at depths up to 1,000 ft in a vacuum environment remains to be demonstrated. The practice of deep core drilling on Earth generally involves the use of water-based drilling muds to lubricate and cool the drill bit and to carry away the drilling debris from the bottom of the hole. It is not clear that a similar technique can be used on the Moon. Most fluids will boil off in a vacuum environment while nonvolatile fluids can be expected to modify or contaminate lunar core drill samples in an unacceptable manner. Current designs for 100-ft drills contemplate the use of a gas in a closed system for cooling. It is not known whether this technique would be applicable to a 1,000-ft drill. Since deep drilling is one of the major objectives of the exploration programs, further investigation of the operational feasibility of these techniques should be conducted.

Large Telescope Optics. The main reason for considering the establishment of optical telescopes on the Moon is to perform astronomical studies with the full theoretical capability of diffraction-limited optical systems. For lunar based telescopes of appreciable size (an aperture of 1 m or more) it remains to be demonstrated that optical surfaces with the required degree of precision can be produced by present technology. Moreover, the stress during transporting such optical component to the Moon and the problem of attaining adequate control of the thermal environment on the Moon raise doubts about the feasibility of maintaining the figure of the optical surfaces within requisite tolerances. The optical figure should be maintained within 0.01 wavelengths; a thermal gradient of as little as 0.1°/m would be intolerable. Before making a commitment to develop a large telescope, this question should be resolved.

Low Conductivity Tank Support Structure. The thermal analysis of the lunar flying vehicle propellant feed system indicated that the major heat transfer to the propellant tank is through the tank supports. This fact is generally true for all propulsion systems whose propellants require thermal control. The common approach is to employ supports of high strength-to-weight ratio material, usually a light metal with high thermal conductivity, attached directly to the tank wall. The net result is almost always a thermal short as compared with the heat flux to the tank by other means, unless the tank support is optimized from the thermal aspect. Several nonconventional types of tank supports have been suggested in the literature, e.g., chains. However, empirical methods of analysis to estimate the heat transfer through such supports are not generally available and would be valuable in efforts to optimize tank support structure. A test program to obtain thermal design data for nonconventional tank supports is recommended.

High Temperature Insulation. High performance, high temperature insulation is important for reducing the weight of structures in proximity to high temperature heat sources (for example, a recessed rocket engine in a lunar flying vehicle). An example of a current design is a multilayer combination of columbium and copper foils interspaced with quartz.

Further investigation of systems employing different combinations of foils and/or spaced materials as well as study of opacified powder types of high-temperature insulating materials are recommended. Development of such efficient heat protection systems would result in significant total system weight savings.

Energy Dissipation Devices. Energy must be dissipated in the landing gear of a lunar flying vehicle and in the suspension system of a lunar roving vehicle. Flying vehicle landing gears must absorb energy with a device that does not require servicing between landings. The use of crushable aluminum honeycomb, as in the LM system, is not practical because of the replacement problem, and Earth-type air/oil struts are undesirable because of the temperature extremes and leakage problems. Studies have disclosed that the simplest energy absorber for lunar use would dissipate the energy by means of friction surfaces. Many extremely simple and reliable friction type absorbers have been made to operate in the Earth environment. However, for lunar use, all of these devices require a solution to the same problem – developing friction surface materials suitable for the lunar environment. These must provide a high coefficient of friction, but not cold weld under vacuum storage conditions.

A basic research and test program is recommended to develop materials having the required properties in a lunar environment for use in these friction devices. These materials should provide high coefficient of friction, resistance to cold welding, and resistance to cold flow under pressure at lunar environmental temperatures. Vacuum chamber tests should be run on outgassed samples finished to the required surface tolerances at the extremes of temperature and pressure likely to be encountered in actual designs.

The damping characteristics of the flying vehicle landing gear could be improved if the landing gear were attached to the vehicle with a material having high internal damping properties. Composite and bonded materials for fiberglass/metal laminates should be developed and tested for this application. Such experimental data and developments could be used in the design of energy absorbers for all lunar applications.

Current design of lunar roving vehicle suspension systems incorporate the use of fluid damper materials. The selection of a fluid with a freezing point below -100°C should be given further attention. The fluid, in combination with an appropriate orifice design, should provide constant damping over a wide temperature range.

6.2.4. Nuclear Systems

High Temperature Fuel Capsule. The heat source for a radioisotope nuclear power plant consists of fuel capsule containing the radiosotope. Current designs of fuel capsules provide for a lifetime of 1 yr at 700°C. Nuclear power systems of the type contained in the MIMOSA recommended equipment list (22-kwe power output) will require fuel capsules with a lifetime of 3 yr, operating at a temperature of 1,000°C. The problems associated with the development of this item should be fully investigated with particular emphasis on the development of suitable capsule materials.

Fuel Capsule Shipping Cask. The fuel capsule shipping cask is used for shipping the fuel capsules from Earth to the lunar base, and for storing the fuel capsules on the lunar surface. It provides for impact survival and complete containment of the fuel for any credible accident either on the launch pad, during launch, in transit, during landing, during lunar storage, and in mission operation. To ensure atmospheric survival, a reentry shape is required. Single capsule shipping casks are in development. For a 22-kwe system as conceived in the MIMOSA study, 48 fuel capsules are required. A shipping cask capable of transporting up to ten fuel capsules appears feasible. In view of the total mass reduction associated with the use of the larger system, the development problems connected with this concept should be resolved.

Radiators. Nuclear power plants generate approximately 8 to 9 times as much waste heat as electrical energy. Since this waste heat must be transferred to space, a large area radiator is required. The radiator is usually composed of thin walled tubes subject to puncture by micrometeoroids. For this reason, it is desirable to have each tube isolated from the others so that the puncture of one tube will not affect the others. Such a feature is provided by the heat pipe radiator composed of isolated tubes. A heat pipe fluid such as water is vaporized by receiving heat from the working fluid, flows upward and outward through finned tubes that have high emissivity external surfaces, condenses in the finned tubes by rejecting the heat of vaporization to space, and flows as a liquid down the tube to repeat the cycle. The heat pipes are grouped into panels.

There are two problems associated with this system. One problem is the packaging of the large area radiator into the transportation system. A possible solution is to fabricate the radiator from flexible material so that the radiator can be rolled up for transport and unrolled for operation. To date, only rigid radiator panels have been constructed and tested. A radiator that can be suitably packaged for transportation must be developed. The other problem is the fact that the radiator depends on the two phase flow of the heat pipe fluid. The mechanism of two phase flow in a low gravity environment is not well understood and requires further investigation.

6.2.5 Propulsion and Power Generation

Rocket Exhaust Temperature Reduction. On the one-man lunar flying vehicle, a heat shield is provided to protect the astronaut from heat radiated from the rocket and from the exhaust plume. Rocket engines employing LM propellants at the most efficient mixture ratio operate at a relatively high combustion temperature. Temperature can be reduced greatly with a moderate sacrifice in specific impulse by use of a fuel rich mixture ratio, or by employing hydrazine as a monopropellant. The lower specific impulse may be offset by a reduction in the heat shielding required.

To obtain tradeoff analysis and design data, rocket test data would be desirable. It is recommended that tests be conducted on 100-lb throttlable engines using fuel rich

LM propellants, and hydrazine monopropellant to collect data on thrust chamber and exhaust plume heating effects.

Rocket Exhaust Plume Effects. Very little reliable data are available on the shape and interactions of the exhaust plumes of single or multiple engines or possible effects of the exhaust plumes on surrounding media. Tests should be conducted in Earth orbit to investigate the temperature and degradation effects of a rocket exhaust plume on adjacent structure and thermal coatings. Similar tests should evaluate possible effects on the transmission of electromagnetic radiation through the plume.