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CRITERIA FOR LUNAR SITE SELECTION



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Report No. P-30

CRITERIA FOR LUNAR SITE SELECTION

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SUMMARY

The Lunar Exploration Program will require an increasingly sophisticated exploration capability. Intimately related to this is the enhanced importance of the selection of lunar landing sites. This study task has taken an overview of the lunar site selection problems and has developed a logic and methodology not only for the timely and effective selection of sites but also for the specification of key related mission design parameters.

The basic framework for lunar exploration which has been assumed is that Apollo missions will visit sites that are representative of the major provinces of the Moon and will have as a principal function, the collection of samples from the regions visited. A brief critique of the selected Apollo sites is included and within the context stated above, seven of the ten sites conform extremely well. The criticism of the other three, site 5 (recycle), Rima Bode II and Descartes is that they are too complex to allow unambiguous interpretation of the collected samples.

For further lunar exploration, the principle task is taken to be understanding the individual processes that have operated on the Moon over its lifetime. By defining the possible processes comprehensively a long list of some 34 "type sites", containing features that are unambiguously representative of individual processes, has been defined. These are not identified as specific locations on the Moon but simply as type sites.

A matrix, as shown in Figure S1, has been developed which defines the requirements for adequate exploration of each type site. Such requirements include the staytime, number of men and lunar science specialists required, the extent of mobility (horizontal and vertical) etc. The matrix is generated to show

SPECIFIC PROCESS	TYPE SITE	MAPPING	PETROGRAPHY	SELENOPHYSICS	STAY TIME (DAYS)	NO. OF MEN	SPECIALISTS	HORIZ. MOB. (KM)	POWER/MOLAB	VERTICAL MOB. (M)	SAMPLE RETURN(KG)	DRILL DEPTH(M)	NO. OF DRILL HOLES	TRENCHING (M ²)
LAVA FLOW EMPLACEMENT	LAVA FLOW	V	V	V	40	8*	V	500*	M	0	100	50	10 ²	10 ²
ASH DEPOSITION	ASH DEPOSIT	V	V	V	8	6*	V	50*	R	0	30	50	3	10 ³
DIKE & SILL EMPLACEMENT	FAULT SCARP	V	V	V	15	4	-	200	M	10 ⁴	50	0	0	10 ²
"	CRATER WALL	V	V	V	20	4	-	100	R	10 ⁴	30	0	0	10 ²
DOVE FORMATION	CONE	V	V	V	25	8*	V ₁ P	50	R	3x10 ³	100	100	1	3x10 ²
"	BULROUS DOVE	V	V	V	25	8*	V ₁ P	50	R	3x10 ³	100	100	1	3x10 ²
"	LOW DOVE	V	V	V	25	8*	V ₁ P	50	R	10 ³	100	100	1	10 ²
RECENT VOLCANISM	LTP SITE	-	V	V	10	3	V ₁	30	R	3x10 ²	10	0	0	0
VOLCANIC ASSIMILATION	MARE-UPLAND CONTACT	V	V	V	30	6*	P ₁ S	100	R	10 ³	100	100	10*	10 ²
GAS CORING	DIATREME	V	V	V	15	5	V	30	R	3x10 ²	50	100	1	10 ³
COLLAPSE	RIMLESS CRATER	V	V	V	10	4	V	10	R	0	30	30	4	10 ²
	SOFT MARE CRATER	V	V	V	10	4	V	10	R	0	30	30	4	10 ²
GRID FAULTING	GRID LINEAMENT	V	-	V	40	5	S	300	M	3x10 ³	0	0	0	10 ²
RADIAL LINEAMENT	OUTSIDE YOUNG BASIN	V	-	V	40	5	S	300	M	3x10 ³	0	0	0	10 ²
CONCENTRIC FAULTING	CONCENTRIC SCARP	V	-	V	60*	5	S	500*	R,M	10 ⁴	0	0	0	10 ²
GRABEN FORMATION	LINEAR RILLE	V	-	V	40	5	S	200	M	10 ⁴	0	0	0	10 ²
ISOSTATIC ADJUSTMENT	CRATER FLOOR	-	-	V	25	4	Sp	100	M	0	0	300*	1	0
THERMAL EXFOLIATION	OUTCROPS	-	V	-	3	2	-	-	-	0	10	0	0	10
MASS WASTING	LARGE CRATER WALL	V	-	-	20	4	-	30	R	3x10 ³	10	50	3	3x10 ²
"	PATTERNED GROUND	V	-	-	5	3	-	-	-	0	0	0	0	10 ²
"	SHALLOW SLOPE	V	-	-	5	3	-	-	-	0	0	0	0	10 ²
DRAINAGE	DIMPLE CRATER	V	-	-	5	3	-	-	-	0	0	50	3	10 ²
DEPOSITION	EJECTA BLANKET	V	V	V	50*	5	S	500*	R,M	10 ²	100	100	10*	3x10 ⁴
MAGMATIC DIFFERENTIATION	VARIETY OF DOMES & FLOWS	-	V	-	10	4	P	10	R	3x10 ²	100	100	1	10 ²
	CONTACT BETWEEN FLOW UNITS	V	V	V	7	4	P	50	M	0	100	30	10*	10 ²
DIFFERENTIATION	LOWEST SCARP EXPOSURE	-	V	-	40	4	P	100	M	10 ²	100	30	1	10 ²
"	DIATREME	-	V	-	3	3	P	30	R	0	100	0	0	10 ²
"	YOUNG BASIN EJECTA	-	V	-	30	4	P	500*	M	10 ³	100	0	0	10 ²
"	ANYWHERE	-	V	-	1	2	-	-	-	0	0	10	1	3x10 ¹
CONVECTION	RIFT AREA	V	V	V	30	4	Sp	300	M	0	30	10	100*	0
"	WRINKLE RIDGE	V	V	V	30	4	Sp	300	M	0	30	10	100*	0
SINUOUS RILLE FORMATION	SINUOUS RILLE	V	V	V	25	8*	V ₁ S ₁ S	150	M	10 ⁴	30	50	10*	10 ²
WRINKLE RIDGE FORMATION	WRINKLE RIDGE	V	V	V	45	6*	S ₁ Sp	150	RM	0	30	100	10*	10 ²
MASCON ORIGIN	MARE	-	V	V	100*	6*	S ₁ P	1000*	M	0	100	1000*	1	0
CENTRAL PEAK FORMATION	CENTRAL PEAK	V	V	V	45	5	S _T	200	M	10 ⁴	50	200	10*	0
EXPOSED RING FORMATION	EXPOSED RING	V	V	V	30	4	-	100	RM	3x10 ²	30	100	5	10 ³
MANTLED RING FORMATION	MANTLED RING	V	V	V	30	4	-	100	RM	3x10 ²	30	100	5	10 ³
GHOST RING FORMATION	GHOST RING	V	V	V	30	4	-	100	RM	3x10 ²	30	100	5	10 ³
GAS EMISSION	LTP SITES	-	-	V	1	2	-	-	-	0	10	0	0	0
ATMOSPHERIC ESCAPE	ANYWHERE/ORBIT	-	-	-	1	2	-	-	-	0	0	0	0	0
ATMOSPHERIC TRANSPORT	DAY & NIGHT SIDES	-	-	-	1	2	-	-	-	0	0	0	0	0
PRIMARY CRATERING	SMALL YOUNG CRATER	V	V	V	30	4	S	100	R	10 ³	30	300	3	10 ³
"	LARGE YOUNG CRATER	V	V	V	80*	8*	S	700*	RM	10 ⁴	100	1000*	3	3x10 ⁴ *
SECONDARY CRATERING	STREWN ROCK CRATER	V	V	-	10	4	S	-	-	10 ²	20	50	3	3x10 ²
MICROMETEORITE EROSION	ANYWHERE	-	-	-	1	2	-	-	-	0	0	0	0	0
GARDENING	REGOLITH	-	V	V	15	3	-	-	-	0	50	30	1	3x10 ²
BLEACHING/DARKENING	ANYWHERE	-	-	-	1	2	-	-	-	0	10	0	0	3x10 ²
MISSION DESIGN POINTS	(SEE FIGS. 1-10)	-	-	-	45	5	-	450	-	10 ⁴	100	200	5	2x10 ³
PERCENTAGE USE OF REQUIREMENT (%)		68	68	66	100	100	64	75	45	51	75	64	64	79

KEY

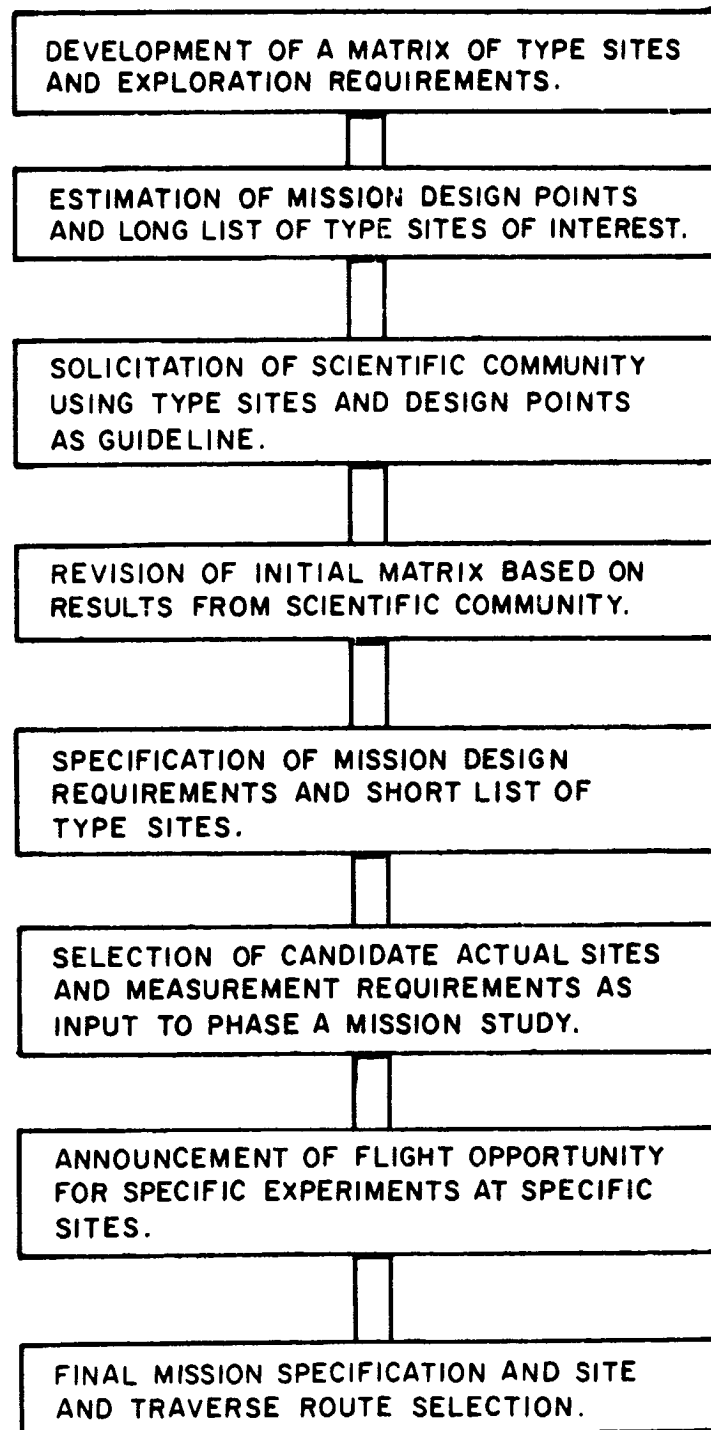
* = EXCEEDS UPPER LIMIT P = PETROLOGIST
 Sp = SELENOPHYSICIST S_T = STRATIGRAPHER
 S = SELENOLOGIST (STRUCTURAL)
 V = VOLCANOLOGIST

TABLE SI. POST APOLLO MISSION DESIGN MATRIX

the relationship between the mission design requirements and the type sites. It is used in an iterative methodology to define post Apollo mission design specifications and to provide for effective site selection.

Figure S2 shows the proposed logic for site selection using the matrix.

- (i) Site Selection Board, acting as a working group, develops a matrix of type sites and requirements,
- (ii) Use matrix to estimate mission design points (i.e. staytime, mobility, etc.), and to identify a long list of interesting type sites,
- (iii) The Site Selection Board solicits the scientific community for experiments, and the related specific site requirements using, as a guide, the type sites and mission design points from the matrix,
- (iv) The response from the scientific community is used to revise the data in the original matrix,
- (v) Analysis of the next matrix will provide for
 - a) hardened mission design points
 - b) the exclusion of type sites clearly beyond the mission design specifications
 - c) the identification of Advanced Technology and Development requirements for candidate experiments
 - d) a long list of potential sites and type sites for post Apollo missions
 - e) enough design data to perform a phase A study of mission concepts to meet the scientific requirements.
- (vi) The remaining tasks are to refine the list of sites, the mission design and the experiment requirements. These steps are iterative and should await the results of the phase A study.



PROPOSED OPERATING PROCEDURE FOR SITE SELECTION BOARD.

FIGURE S2

The preceding methodology provides a number of essential ingredients into the mission design and site selection process. First, it takes full cognizance of the very close coupling between the mission capability and the site selection. It provides that they be defined and refined iteratively and cohesively. It insists that the basic mission concepts and requirements be derived from the viewpoint of the scientific exploration of the Moon. However all other objectives are introduced in the final stages as "objectives of opportunity" and as such will play an important role in maximizing the value of the missions. Perhaps most important of all, is that it requires genuine advanced planning of the lunar exploration program using the best information available at the time. It enforces a careful definition of what has to be achieved in the program and systematically and logically obtains and analyses the necessary inputs from the scientific community and from the phase A mission analysts.

As a result of the analysis performed in this study a list of criteria have been developed which is essentially a check-off list which can be used during the site selection process. It consists of six major categories of criteria and is shown in Table S2. These criteria provide the basis for trade-offs and decisions in the selection methodology described above.

The question of traverse route selection has been considered here but no criteria have been developed. The traverse requirements in Level 3 exploration are site related and will normally be within the feature of interest. As such they will be largely an operational requirement, partially preplanned and partially real time planned. The more complex Level 4 exploration will rely heavily on long distance traverses over and between provinces. The criteria for selection of these traverse routes are as complex as for the site selection treated here. They are recommended for future study.

TABLE S2 - CRITERIA FOR SITE SELECTION

- o ESTABLISHMENT OF SCIENTIFIC PRIORITY OF TYPE SITES:
 - 1) level of exploration
 - 2) expected results
 - 3) contribution to understanding of Moon
 - 4) significance of unexpected results.
- o DEFINITION OF EXPLORATION REQUIREMENTS AT TYPE SITES:
 - 5) staytime
 - 6) number of men (including specialists)
 - 7) mobility requirements
 - 8) sample analysis or return
 - 9) drilling and trenching requirements
 - 10) lunar time of day
 - 11) experimental payload.
- o SPECIFICATION OF REQUIRED CAPABILITY
 - 12) range for each measurement requirement
 - 13) nominal design point for each parameter
 - 14) subsystem support requirements (power, data handling, communications, etc.)
- o IDENTIFICATION OF SPECIFIC EXAMPLES OF TYPE SITES
 - 15) longitude
 - 16) latitude
 - 17) area of interest at site
 - 18) complexity of site
 - 19) ambiguity of data interpretation
 - 20) closeness to other type sites.
- o ENGINEERING FEASIBILITY
 - 21) trajectory compatibility (landing, launch, rendezvous)
 - 22) weight class of payload
 - 23) compatibility with anticipated logistic systems
 - 24) safety
 - 25) mission schedule and availability
 - 26) cost
 - 27) photo reconnaissance of site
- o AVAILABILITY OF SCIENTIFIC SUPPORT
 - 28) principle investigators
 - 29) flight ready experiments
 - 30) astronaut (specialist) availability.

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The methodology as developed here is exemplary. It can and should be modified to fit the specific conditions which will exist at the time it has to be implemented. Nevertheless it is felt that the essential steps will remain and that there is enough supporting analysis in his report to permit its modification.

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CRITERIA FOR POST APOLLO SITE SELECTION

1. INTRODUCTION

It is an understatement to say that the value of the lunar exploration program is critically dependent on the specific sites that are chosen for lunar landings. This has been shown to be true for the Apollo program. With the greatly increased sophistication of the post Apollo program, site selection will relate even more critically to the mission worth. However the problems of site selection are not isolated but are intimately entwined with the planned extent of lunar exploration, with the specific measurements that will have to be made, and with the particular exploration capabilities that can be made available at the sites. This report presents an overview of the site and traverse selection problems for the post Apollo period. It develops a comprehensive list of type sites which will require study and it defines the essential mission requirements that will be needed at each "type site". Further it utilizes these requirements to specify a logic or methodology by which NASA can perform site selections in conjunction with an evaluation of mission requirements. It was not the intent of this study to select specific post Apollo sites, using only pre-Apollo information, but rather to develop the criteria and methodology for the site selection.

Section 2 of this report discusses an overall framework for Apollo lunar exploration and identifies grossly the type sites that should be included at each level. Section 3 discusses and critiques the Apollo sites already selected by the NASA Site Selection Board. Section 4 discusses a comprehensive list of type sites and features representative of lunar processes. Section 5 develops a philosophy for site selection for post Apollo exploration. Section 6 develops a matrix of measurement and mission requirements as a basis for the site selection logic which is presented in Section 7.

2. OVERALL FRAMEWORK FOR LUNAR EXPLORATION

In a previous report (Sullivan et al 1970), four distinct levels of lunar exploration are developed based principally on the scientific requirements of lunar exploration but leading to the requirements for exploitation of the Moon. Briefly the four levels are:

- (i) Reconnaissance - the purpose of this level is to survey the moon via photography and remote sensing in order to provide base maps and maps of the distribution of lithologic, mineralogic and structural units over the lunar surface,
 - (ii) Sampling of homogeneous systems - this level will provide ground truth for level 1 and generally characterize both large provinces of the moon, and the whole moon, in terms of their physical and chemical properties,
 - (iii) Determination of feature related processes - at the completion of this level, all process which are or have been active on the Moon will have been studied and characterized in single cycle areas. This will enable the process to be recognized readily in areas of complex selenology,
 - (iv) Comprehensive region exploration and exploitation - this level utilizes the information gathered in the three earlier levels for the purpose of total lunar exploration, colonization and exploitation.
- Of these 4 levels, only the levels 2 and 3, are of interest in the present study. These are discussed in greater detail below.

2.1 Level 2 - Sampling of Homogeneous Systems

This level requires point landings at sites selected as being representative of the entire Moon or of lunar provinces and important features. The science objectives are entirely met by means of limited exploration of, and sample retrieval from the immediate areas of the landing, in-situ selenophysical measurements, and particle and field measurements. Specifically, this activity will permit the identification and classification of representative surface materials according to composition, age, biological content, and physical properties. The primary accomplishments of this level, resulting from missions to numerous carefully selected sites, will be the provision of representative ground-truth data to calibrate orbital and astronomical data, a good probabilistic determination of the past or present existence of biological or prebiological forms, a further determination of the homogeneity or extent of heterogeneity of lunar systems, a first-order determination of the presence of water and exploitable minerals, an evaluation of restrictions on future mobility and shelter emplacement, and a considerable body of new lunar theories and hypothesis.

The information will prove or disprove current theories regarding the origin and evolution of the Moon and its similarities to, and differences from the Earth's characteristics. This level will provide the most useful data regarding the possibilities of life-forms in that it will relate any biologic evidence with compositional and structural features and thereby greatly increase the probability of selecting the most promising biological sites for later levels.

According to the rationale of level 2, the individual mission sites must be chosen to represent homogeneous provinces and/or scientifically significant features. The homogeneous sites must have characteristics, in so far as can be determined from the orbital reconnaissance of level 1 which are typical of the province in which they lie, so that the information obtained from each site is

of significance regarding a large portion of the Moon, or hopefully the entire Moon. By this definition it is to be understood, once such a homogeneous province has been defined, that the actual location of the landing site within the province is not critical and that from a scientific standpoint extensive traverse capability is not required. Large fractions of the various lunar maria, the majority of exposed ejecta from Imbrium or Oriental, and portions of the cratered upland plains between Maurolycus and Janssen are examples of areas where level 2 landing sites would yield the desired scientific information.

In contrast to the homogeneous site, a second class of level 2 sites is representative of significant features. These individual features will definitely lack internal homogeneity, but each feature must represent a homogeneous class of features. In this case, the actual touch down point is of importance in that it must be very close to the specific feature of interest. The purpose of this second type of mission is to characterize the general properties of a particular type of feature. Examples of such sites include one or more of the Marius hills, a fresh impact center, a central peak, and a sinuous rille. This exemplifies the difference between level 2 and the later level 3 exploration. Even at the same site, level 2 relies heavily on sample analysis to characterize the site whereas level 3 would require a detailed exploration to investigate the processes of formation and its time history.

In either case, the common characteristic of level 2 sites is that they are representative of major portions of the Moon, and therefore provide general knowledge of its physical characteristics.

Level 2 activity requires the capability to land on the Moon and return to earth, at least two men, a minimum of 1 km mobility for one man, life support for 1-to-3 day staytimes, and selenophysical experiments. The experimental payload should include provision for sample collection and return, seismometry, life detection, and measurement of heat flow, atmospheric properties and environmental particles and fields. Clearly, the

present Apollo system satisfies the mission need for level 2 exploration. Table 1 summarizes the above definition of level 2.

2.2 Level 3 Determination of Feature Related Processes

This level of activity provides for understanding of the individual processes that have shaped the lunar surface. Its primary distinctions from level 2 are that it applies to features that will unambiguously reveal the processes which formed them and that it requires an extended stay time and manned traverse capability. It will provide ground-truth data to calibrate the interpretations of the processes indicated in the orbital survey of level 1 and the characterization of level 2 and it will provide for an extensive pruning of the theories of lunar evolutionary events.

In contrast to Apollo sites, level 3 sites will most probably all lack any physically homogeneous characteristics, since this phase is devoted to the examination, identification, and classification of significant lunar processes. In this case the sites and features are to be selected on the basis of their formation by a single lunar process. In concept then it should not be difficult to determine unambiguously the characteristic signatures of the processes, signatures that will be required for a determination of the developmental history of complex areas where many such processes have acted. Examples of "process sites" are areas where maria fill material has originated and been deposited (i.e. fresh lava flows), recent impact craters, areas of recent mass wasting, and dimple craters.

The accomplishment of level 3 will require what amounts to an order of magnitude extension of level 2 capabilities. Greater payloads will have to be landed on the surface. Staytime will have to be extended to 2-6 weeks. Mobility will have to be increased to some 100-km radii, and three dimensional (including depth) investigations must be included. Greater capability will be required for mobile experiments and in situ analysis. Among the more important capabilities are those required for multiple

TABLE 1

LEVEL 2 - SAMPLING OF HOMOGENEOUS SYSTEMS

<u>Rationale:</u>	Provide ground truth for Level 1 data Characterize homogeneous systems	
<u>Results:</u>	Selection from major origin theories Gross characterization of Moon Confirm or deny hypotheses from Level 1 Generation of hypotheses on lunar processes Bound range of variables	
<u>Requirements:</u>	Point landing Sites typical of lunar provinces Sample collection from homogeneous area Limited mobility Emplaced selenophysical experiments	
<u>Candidate Concepts:</u>	Apollo LM, Manned ROVER	
<u>Type Areas:</u>	<u>PROVINCES</u>	<u>FEATURES</u>
	*Oldest mare	Diatreme
	Youngest mare	*Young crater
	Upland fill	*Volcanics
	*Basin ejecta blanket	"Ring dike"
	Farside mare	*Central peak
	Farside uplands	*Sinuous rilles
	Median age mare	
	Upland old crater interior	
	Upland Inter crater Chaos	

*Included in Current 9 Apollo Sites

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measurements over 100's of km, active seismic experiments, shallow drilling, gravimetry, magnetometry, heat flow and electromagnetic probing. We are equating this level 3 with post Apollo missions for the purpose of providing a science basis for this study.

Table 2 gives a brief summary of the above definition of level 3.

3. EVALUATION OF APOLLO LANDING SITES

Since the Apollo system provides capabilities which are very close to those required by our level 2, we have evaluated the 10 proposed Apollo sites based on the level 2 definitions given above. A complete description of the 10 sites can be found in several NASA documents (Bellcomm 1969) and thus only a brief description and our evaluation of the sites are given here.

- 3.1 Landing Site 2 - Tranquillity Base, the site of man's first step on the Moon is situated on the Western side of Mare Tranquillitatis. This site proved to be an excellent example of a level 2 site in that it is representative of the old mare fill which covers most of Tranquillitatis.
- 3.2 Landing Site 7 - Surveyor III and Apollo 12 landing sites are included in this area South of Copernicus which is located in old mare material. An excellent level 2 site similar to Landing Site 2.
- 3.2B Landing Site 5 (recycle) - A young mare site south of the Kepler. This site is a contingency site for Site 7 above and the choice is constrained by the Site 7 mission requirements. It seems to contain both young mare fill and material from Kepler. Thus the site lacks the homogeneity required for a level 2 site and it probably will be difficult, if not impossible to be sure of the

TABLE 2

LEVEL 3 - DETERMINATION OF FEATURE-RELATED PROCESSES

<u>Rationale:</u>	Analyze structural, stratigraphic, petrographic and other physical relationships of individual features to indicate process of formation
<u>Results:</u>	Identification and characterization of individual processes Confirm or deny theories and hypotheses
<u>Requirements:</u>	Mobile science payload (100 km) Man is essential Staytime 2-6 weeks Extensive leave behind science to monitor activity Shallow and medium drill Sites exemplifying individual processes
<u>Mission Concepts:</u>	3 men - 14 day crew capsule (using orbital base) 3 men - 90 day shelter (using orbital base) Manned ROVER, LFU (vertical mobility)
<u>Type Processes:</u>	Volcanism Tectonics Gradation Lithologic Differentiation Interior Processes Unique Features Atmospheric Processes Impact Cratering Solar Wind and Radiation

origin of samples from this mixed environment.

- 3.3 Fra Mauro Formation - The Fra Mauro is a stratigraphic unit which consists of the material ejected from the Imbrium basin. This site is excellent in terms of the level 2 criteria.
- 3.4 Rima Bode II or Littrow Area - Rima Bode II is a linear rille associated with the young, fresh craters of a crater chain. The Rima Bode II site is a good level 2 site in that a distinctive young volcanic unit is present at the site and that there is reason to believe that deep seated material may also be present at the surface. However, there is some concern that the site lacks homogeneity in that there are at least three possible sources of volcanic material and therefore there may be uncertainty as to the origin of any material collected. This site probably would make a better "process" site.
- The Littrow Area which occurs in Mare Serenitatis, is a complex, mare-upland transitional area, complicated by fresh ejecta and therefore lacks the necessary qualifications for a level 2 site. Though interesting, this site really requires a level 3 exploration capability.
- 3.5 Censorinus (Northwest) - An excellent example of a level 2 feature, in this case a small, (3.8km) fresh impact crater well suited for level 2 exploration. It may also serve a dual role as an excellent level 3, "process" site for a later mission.
- 3.6 Tycho (rim) - Another excellent example of a level 2 feature, in this case a large, young crater. It might also provide several process sites for level 3 and should be studied in great detail eventually.

- 3.7 Copernicus (peak) - Similar to Tycho rim site. Main feature of the central peak site, in terms of the level 2 missions, lies in the promise of obtaining deep seated material. This site is also a good level 3 site in that the exploration of crater floor formations is a major part of the stated objective.
- 3.8 Descartes - A complex upland area near Mare Nectaris, the area may be volcanic in nature. If orbital reconnaissance could more clearly define the nature of the region and its significance, it might prove to be a fair level 2 site. However, the present definition of the site requires it to be classified as a level 3 site.
- 3.9 Marius Hills - These volcanic hills located in Oceanus Procellarum provide many excellent level 2 sites. In addition they provide an excellent area for investigation during the 3rd level of exploration.
- 3.10 Hadley/Apennine - The Hadley rille occurs at the foot of the Apennine Mountains at the eastern edge of Mare Imbrium in Palus Putredinis. This site really consists only of Rima Hadley, which is an excellent level 2 feature. It is also noted that the mission plan for this site calls for some 30 km of traverse capability, which, if actually required would remove this site from our list of level 2 sites. It is felt however, that an excellent level 2 mission could be done here.

Thus, according to our evaluation: Site 5, Rima Bode II or Littrow Area, and Descartes are not good sites for Apollo missions in that the present system does not provide enough capability to fully capitalize on the information available at the site. Thus we would rather see these three missions, and any Apollo rebuy, be

flown to areas where sample collection and emplaced experiments would fully exploit the site and add to our general knowledge of the Moon. Such sites could be selected from the type areas listed in Table 1. We suggest that substitute areas for the three unsatisfactory sites might be the upland fill near Maurolycus, the Flamsteed ring, Mare Serenitatis (young mare) and the dark halo craters in Alphonsus.

4. POST APOLLO (LEVEL 3) TYPE SITES

Level 3 exploration, as defined above, will provide an understanding of the individual processes that have occurred on the Moon over the course of its evolution. Furthermore, it requires that wherever possible single cycle areas (where only one type process has acted) be chosen to characterize each process unambiguously.

A total of nine major groups of processes that appear to have been active on the Moon have been identified as:

- i) Volcanism
- ii) Tectonics
- iii) Gradation
- iv) Lithologic differentiation
- v) Interior processes
- vi) Formation of unique features
- vii) Atmospheric processes
- viii) Impact cratering and
- ix) Solar wind and radiation effects.

The above list is not in order of either importance or extent on the Moon. In most instances the process groups are self descriptive but the one group needing some explanation relates to unique features. This is a catch all for those features on the Moon which apparently are not analogous to those on Earth and therefore for which no formation process has been clearly identified. In the last analysis it may well be that these

features were formed by processes within the other groups but for the present at least they must stand on their own.

The specific processes that constitute each of the process groups are then identified which leads directly to the specification of type sites. A complete derivation of these type sites is shown in Table 3. It is important to note that by ensuring the completeness of the list of process groups and by further ensuring the completeness of the specific processes comprising each group, a fully comprehensive list of type sites has been generated. It remains then to interpolate such a list into a site selection methodology.

5. LUNAR SITE SELECTION

Given a total list of type sites that should be included in the Level 3 exploration program, it is necessary to develop a logical and progressive system for selecting the most appropriate landing site (which may contain more than one type site) for each specific mission. It is essential to include in the selection process a cognizance of both the measurement requirements of the site and the exploration capability that can be delivered to the site. The methodology proposed here, by requiring a careful development of the exploration needs at each type site, provides a basis for specifying the design parameters for Lunar missions and allows a responsive selection of landing sites.

In the definition of the requirements it is essential to note that it is the scientific objectives of Lunar exploration that are used. It is strongly felt that although utilization and other objectives will necessarily form a part of all lunar missions, they should not be used as the basis for mission design or site selection. They should be considered as "objectives of opportunity" in that given a specific mission, scheduled to a specific landing site and meeting specific lunar objectives, then a concerted effort should be made to maximize the

TABLE 3

DEVELOPMENT OF LEVEL 3 TYPE SITES

GENERAL PROCESS	SPECIFIC PROCESS	TYPE SITE	OBSERVATIONS TO MAKE OR HYPOTHESES TO TEST
VOLCANISM	Lava flow emplacement	Lava flow	Was it fluid basalt? Was it highly frothed? Look for source Differences from earth? Subsurface cavities? Subsurface flow units?
	Ash deposition	Ash flow	Vertical fall or hori- zontally moving fluidized system?
	Diatreme activity	Dark halo crater	Nature of particles in halo - is it ash? Collapse or entirely gas coring?
	Dome for- mation	Cone	Exact analog of ter- restrial cinder cone?
		Gentle dome	Basaltic? Exact analog of terres- trial shield volcano?
		Rough "bulbous" dome	More andesitic than rough dome? Resurgent?
	Recent volcanism	Confirmed LTP sites	Nature of activity: Flows? Gas eruptions?
	Active volcanism	Active site (if found)	Nature of eruption Temperature of effluents Gas content

TABLE 3 (Cont.)

GENERAL PROCESS	SPECIFIC PROCESS	TYPE SITE	OBSERVATIONS TO MAKE OR HYPOTHESES TO TEST
VOLCANISM	Volcanic assimilation	Mare- upland contacts (at damaged structures)	Melting at contacts? Metamorphism? Cause of destruction
	Dike & sill emplacement	Fault scarp or fresh crater wall	Search for examples of dikes & sills
TECTONICS	Collapse	Rimless crater	Can crater be identified as collapse feature? What is nature of sub- surface cavity?
	Radial lineament formation	Lineament field out- side young basin	Sources of lineaments Look for exposed fault scarps Map jointing Separate tectonic linea- ments from exogenic striations (e.g. gouges from flying fragments)
	Concentric- Faulting	Concentric scarps around basins	Confirm normal faults Look for exposed outcrops Look for dikes, sills Look for flows Is bedding upturned? Extent of talus slopes at bases Due to sagging as basin filled with extruded lava?
	Graben & Horst for- mation	Linear rille	Evidence for doming? Direction of stresses Nature of floor struc- ture (uplifts) Look for dikes, sills in walls Look for flows in walls Are wall beds upturned?

TABLE 3 (Cont.)

GENERAL PROCESS	SPECIFIC PROCESS	TYPE SITE	OBSERVATIONS TO MAKE OR HYPOTHESES TO TEST
TECTONICS	Isostasy	Medium old crater floor	Has there been isostatic adjustment? Determine effective viscosity Relation of isotasy to central peak
GRADATION	Thermal exfoliation	Any outcrop	Has diurnal thermal cycle caused exfoliation? Any evidence for action of water/ice or other volatiles?
	Mass wasting	Large crater walls	Interplay of slumping & faulting Extent of downslope motions Effect in smoothing craters
		Patterned ground	Extent of downslope motions Relation of motion to patterning Identification of talus at base?
	Isostasy	Fault scarp	Extent of downslope motion Extent of covering or baring of bedrock Identification of talus at base?
	Drainage	"Dimple crater"	Evidence for cavity underneath
	Deposition processes in ejecta	Ejecta blanket (basin & large crater)	Evidence for base surge Evidence for turbulent motion Estimate of density and mass transport rate in ejecta "cloud".

TABLE 3 (Cont.)

GENERAL PROCESS	SPECIFIC PROCESS	TYPE SITE	OBSERVATIONS TO MAKE OR HYPOTHESES TO TEST
LITHOLOGIC DIFFEREN- TIATION	Differen- tiation in magma	Variety of dome morpho- logies	Are different dome forms of dome different rock types? Are more craggy domes more acidic?
		Vicinity of contact between "blue" & "red" maria "Wood's spot" or similar color anomaly	What are differences in lava composition to account for change in color? Is colorimetric anomaly related to differentiation?
INTERIOR PROCESSES	Differen- tiation	Lowest exposure in large scarp	Any evidence for vertical gradients in composition?
		Diatreme	Evidence for ultrabasics from depth?
		Ejecta from young basin	Evidence for ultrabasics from depth? Correlation of radial range from basin with depth variations
		Any site for sele- nophysical measures	Detect structure deep within moon & indicating presence or absence of differentiation
	Convection	Possible rift or spreading areas	Possible connection between wrinkle ridges and midocean ridges

TABLE 3 (Cont.)

GENERAL PROCESS	SPECIFIC PROCESS	TYPE SITE	OBSERVATIONS TO MAKE OR HYPOTHESES TO TEST
FORMATION OF UNIQUE LUNAR STRUCTURES	Sinuuous rille formation	Sinuuous rille	Confirmation of erosion and transport by flow Nature of flowing material Possible relation to water or volatiles? Possible relation to Lava? Nature of crater at "head" of rille
	Wrinkle ridge	Wrinkle ridge	Confirmation of lava flow sources at ridges Identification of com- pression or rifting Search for folding
	Mascon formation	Mascon related mare	Are mascons due to layers of dense lava on surface? Or buried bolides? Or other anomalies? Is nickel-iron involved?
	Formation of "exposed" pre- mare rings (e.g. Flamsteed ring)	"Exposed" pre-mare ring	Are they the tops of pre- mare craters exposed above lava? Are they ring-dikes? Evidence for assimilation
	Formation of "mantled ring" (e.g. Ptolemaeus B)	"Mantled ring"	Cause of relief Are they buried impact craters? Has original structure been completely assimi- lated or just buried? Is regolith different than in surroundings?
	Formation of "ghost rings" (e.g. in Orbiter mare photos)	"Ghost ring"	Cause and extent of relief Are they buried craters? Are they melted or isostatically destroyed craters that formed in molten flows?

TABLE 3 (Cont.)

GENERAL PROCESS	SPECIFIC PROCESS	TYPE SITE	OBSERVATIONS TO MAKE OR HYPOTHESES TO TEST
UNIQUE STRUCTURES	Formation of central peaks	Central peak (young crater)	Are they igneous extrusive features? Are they rebound structures? Relation to wall slumping? Relation to crater for- mation?
ATMOSPHERE PROCESSES	Gas Emission	Confirmed LTP site (or active site if found)	Composition of gases Association with heat anomalies Association with volcanism Search for sublimates and surface deposits
	Escape of atmosphere	Anywhere on surface and in orbit	Test time rate of change of composition as correlated with known inputs from rocket exhausts and other man- made sources Test rate of loss against atomic mass Test mobility and transport from light to dark side
IMPACT CRATERING	Primary cratering	Large (D>50 km) young crater	Confirm primary impact origin Nature of bolide (Ni-Fe? Chondrite? Cometary?) Modification processes
		Inter- mediate (D~10 km) young crater	Confirm primary impact origin Nature of bolide (Ni-Fe? Chondrite? Cometary?) Modification processes
		Small (D~1 km) young crater	Confirm primary impact origin Nature of bolide (Ni-Fe? Chondrite? Cometary?) Modification processes Origin of inner ring-bench in some craters due to thin regolith? Diagnostic features

TABLE 3 (Cont.)

GENERAL PROCESS	SPECIFIC PROCESS	TYPE SITE	OBSERVATIONS TO MAKE OR HYPOTHESIS TO TEST
IMPACT CRATERING	Gardening	Any Surface on regolith (pick sites of dif- ferent aged regolith)	Rate of turnover Mixture of cosmic material Rate of deepening Net mass loss or mass gain?
	Micro- meteorite erosion	Any surface site	Rate of microerosion and turnover Mass loss or mass gain? Admixture of cosmic material
SOLAR WIND AND RADIATION EFFECTS	Bleaching darkening, sputtering	Any surface site	Effects of surface exposure

usefulness of the mission by including additional experiments for exploitation of either the Moon or space science in general. As an essential corollary to this scientific basis for site selection it is important that the scientific community at large be included in and involved in the process which leads to the final mission design and site selection.

A preliminary specification of the requirements needed at each type site are tabulated in the form of a matrix in the next section. A system for developing mission design parameters from the matrix is discussed. Finally a logic for a full post Apollo site selection scheme is proposed.

At this point, however, it is important to place the lunar traverse, and its route selection process, into perspective. By utilizing the lunar exploration definitions of levels 2 and 3 above, extensive traverse capabilities are not required as part of the Apollo program although a case has been made for a well instrumented geophysical traverse to examine boundaries between lunar provinces. For level 3 missions a manned traverse capability is essential as a means of site exploration but not as a means of lunar exploration. Thus the traverse route selection is largely an operational (partially pre-planned and partially real time planned) requirement and is secondary to the base site selection. For level 4 missions, the traverse route becomes critical since it is then a major contributor to lunar exploration and exploitation. The criteria for traverse route selection will be as important to level 4 as site selection is to level 3. It is, however, beyond the scope of the present study. In the development of the requirements in the next section, only the total traverse distances (horizontal and vertical) are specified for each type site together with an indication of whether a manned roving vehicle (Rover) or a mobile shelter (Molab) is required.

6. THE MISSION DESIGN MATRIX

Table 4 is a matrix of the mission and measurement requirements for each of the type sites identified in the previous section. The requirements are those estimated by a group of Astro Sciences Center scientists based on the scientific objectives described in

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SPECIFIC PROCESS	TYPE SITE	MAPPING	PETROGRAPHY	SELENOPHYSICS	STAY TIME (DAYS)	NO. OF MEN	SPECIALISTS	HORIZ. MOB. (KM)	ROVER/MOLAB	VERTICAL MOB. (M)	SAMPLE RETURNING	DRILL DEPTH (M)	NO. OF DRILL HOLES	TRENCHING (M ²)
LAVA FLOW EMPLACEMENT	LAVA FLOW	V	V	V	40	8 ^h	V	500 ^h		0	100	50	10 ²	10 ²
ASH DEPOSITION	ASH DEPOSIT	V	V	V	8	8 ^h	V	50 ^h		0	30	50	10 ³	10 ³
DIKE & SILL EMPLACEMENT	FAULT SCARP	V	V	V	15	4	-	200		10 ⁴	30	0	0	10 ²
"	CRATER WALL	V	V	V	20	4	-	100		10 ⁴	30	0	0	10 ²
DOME FORMATION	CONE	V	V	V	25	8 ^h	V _P	50	R	3x10 ³	100	100	1	3x10 ²
"	BULBOUS DOME	V	V	V	25	8 ^h	V _P	50	R	3x10 ³	100	100	1	3x10 ²
"	LOW DOME	V	V	V	25	8 ^h	V _P	50	R	10 ³	100	100	1	10 ²
RECENT VOLCANISM	LTP SITE	-	V	V	10	3	V _I	30	R	3x10 ²	10	0	0	0
VOLCANIC ASSIMILATION	MARE UPLAND CONTACT	V	V	V	30	6 ^h	P _S	100	R	10 ³	100	100	10 ^h	10 ²
GAS CORING	DIATREME	V	V	V	15	5	V	30	R	3x10 ²	50	100	1	10 ³
COLLAPSE	RIMLESS CRATER	V	V	V	10	4	V	10	R	0	30	30	4	10 ²
	SOFT MARE CRATER	V	V	V	10	4	V	10	R	0	30	30	4	10 ²
GRID FAULTING	GRID LINEAMENT	V	-	V	40	5	S	300	M	3x10 ³	0	0	0	10 ²
RADIAL LINEAMENT	OUTSIDE YOUNG BASIN	V	-	V	40	5	S	300	M	3x10 ³	0	0	0	10 ²
CONCENTRIC FAULTING	CONCENTRIC SCARP	V	-	V	60 ^h	5	S	500 ^h	R _M	10 ⁴	0	0	0	10 ²
GRABEN FORMATION	LINEAR RILLE	V	-	V	40	5	S	200	M	10 ⁴	0	0	0	10 ²
ISOSTATIC ADJUSTMENT	CRATER FLOOR	-	-	V	25	4	Sp	100	M	0	0	300 ^h	1	0
THERMAL EXFOLIATION	OUTCROPS	-	V	-	3	2	-	-	R	0	10	0	0	10
MASS WASTING	LARGE CRATER WALL	V	-	-	20	4	-	30	-	3x10 ³	10	50	3	3x10 ²
"	PATTERNED GROUND	V	-	-	5	3	-	-	-	0	0	0	0	10 ²
"	SHALLOW SLOPE	V	-	-	5	3	-	-	-	0	0	0	0	10 ²
DRAINAGE	DIMPLE CRATER	V	-	-	5	3	-	-	-	0	0	50	3	10 ²
DEPOSITION	EJECTA BLANKET	V	V	V	50 ^h	5	S	500 ^h	R _M	10 ²	100	100	10 ^h	3x10 ⁴
MAGMATIC DIFFERENTIATION	VARIETY OF DOMES & FLOWS	-	V	-	10	4	P	10	R	3x10 ²	100	100	1	10 ²
	CONTACT BETWEEN FLOW UNITS	V	V	V	7	4	P	50	M	0	100	30	10 ^h	10 ²
DIFFERENTIATION	LOWEST SCARP EXPOSURE	-	V	-	40	4	P	100	M	10 ²	100	300	1	10 ²
"	DIATREME	-	V	-	3	3	P	30	R	0	100	0	0	10 ²
"	YOUNG BASIN EJECTA	-	V	-	30	4	P	500 ^h	M	10 ³	100	0	0	10 ²
"	ANYWHERE	-	-	V	1	2	-	-	-	0	0	10	1	3x10 ¹
CONVECTION	RIFT AREA	V	V	V	30	4	Sp	300	M	0	30	10	100 ^h	0
"	WRINKLE RIDGE	V	V	V	30	4	Sp	300	M	0	30	10	100 ^h	0
SINUOUS RILLE FORMATION	SINUOUS RILLE	V	V	V	25	8 ^h	V _S S	150	M	10 ⁴	30	50	10 ^h	10 ²
WRINKLE RIDGE FORMATION	WRINKLE RIDGE	V	V	V	45	6 ^h	S _S Sp	150	RM	0	30	100	10 ^h	10 ²
MASCON ORIGIN	MARE	-	V	V	100 ^h	6 ^h	S _P	1000 ^h	M	0	100	1000 ^h	1	0
CENTRAL PEAK FORMATION	CENTRAL PEAK	V	V	V	45	5	S _T	200	M	10 ⁴	50	200	10 ^h	0
EXPOSED RING FORMATION	EXPOSED RING	V	V	V	30	4	-	100	RM	3x10 ²	30	100	5	10 ³
MANTLED RING FORMATION	MANTLED RING	V	V	V	30	4	-	100	RM	3x10 ²	30	100	5	10 ³
GHOST RING FORMATION	GHOST RING	V	V	V	30	4	-	100	RM	3x10 ²	30	100	5	10 ³
GAS EMISSION	LTP SITES	-	-	V	1	2	-	-	-	0	10	0	0	0
ATMOSPHERIC ESCAPE	ANYWHERE/ORBIT	-	-	-	1	2	-	-	-	0	0	0	0	0
ATMOSPHERIC TRANSPORT	DAY & NIGHT SIDES	-	-	-	1	2	-	-	-	0	0	0	0	0
PRIMARY CRATERING	SMALL YOUNG CRATER	V	V	V	30	4	S	100	R	10 ³	30	300	3	10 ³
"	LARGE YOUNG CRATER	V	V	V	80 ^h	8 ^h	S	700 ^h	RM	10 ⁴	100	1000 ^h	3	3x10 ⁴
SECONDARY CRATERING	STREWN ROCK CRATER	V	V	-	10	4	S	-	-	10 ²	20	50	3	3x10 ²
MICROMETEORITE EROSION	ANYWHERE	-	-	-	1	2	-	-	-	0	0	0	0	0
GARDENING	REGOLITH	-	V	V	15	3	-	-	-	0	50	30	1	3x10 ²
BLEACHING/DARKENING	ANYWHERE	-	-	-	1	2	-	-	-	0	10	0	0	3x10 ²
MISSION DESIGN POINTS	(SEE FIGS. 1-10)	-	-	-	45	5	-	450	-	10 ⁴	100	200	5	2x10 ³
PERCENTAGE USE OF REQUIREMENT (%)		68	68	66	100	100	64	75	45	51	75	64	64	79

KEY

* = EXCEEDS UPPER LIMIT P = PETROLOGIST
 Sp = SELENOPHYSICIST S_T = STRATIGRAPHER
 S = SELENOLOGIST (STRUCTURAL)
 V = VOLCANOLOGIST

TABLE 4. POST APOLLO MISSION DESIGN MATRIX

detail in a previous report (Sullivan et al 1970) and their knowledge and experience of lunar exploration techniques. It is included here as an example. Its particular virtue is that it allows the site selection process to be considered as an integral part of the mission design process as will be discussed in the next section.

In Table 4 the list of type sites is taken from Table 3 above. The requirements are discussed briefly below:

- 6.1 Mapping, Petrography, Selenophysics - These columns indicate the need for the respective class of exploration activity at the type sites. It is also implied that there will be a need for real time planning of these activities based on the results of the previous day's work and analysis.
- 6.2 Staytime - The estimate of staytime is based on the scale and extent of the site, on the amount of drilling, trenching and mapping, and on the amount of travel required to explore the site. In addition the expected complexity of the type site weighs heavily in the estimate of the duration of the mission. Fig. 1 shows the distribution of staytime requirements amongst the type sites. The first peak represents the time just to set up emplaced station science at a few type sites. The more general requirement is shown in the main peak. On the basis of this distribution an attempt is made to provide an upper limit to the staytime requirements that should be designed into post Apollo missions. This estimate of 45 days then represents a zero order design point which can be refined later in the selection process.

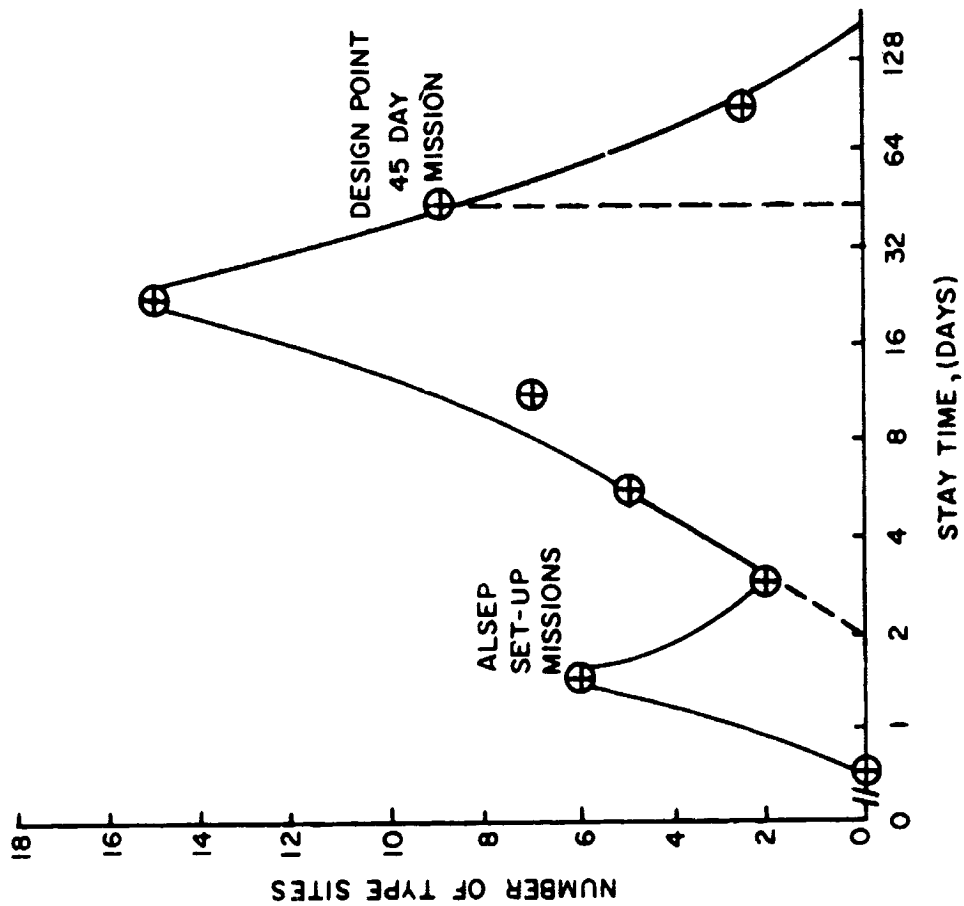


FIGURE 1. LEVEL 3 REQUIREMENT FOR STAYTIME

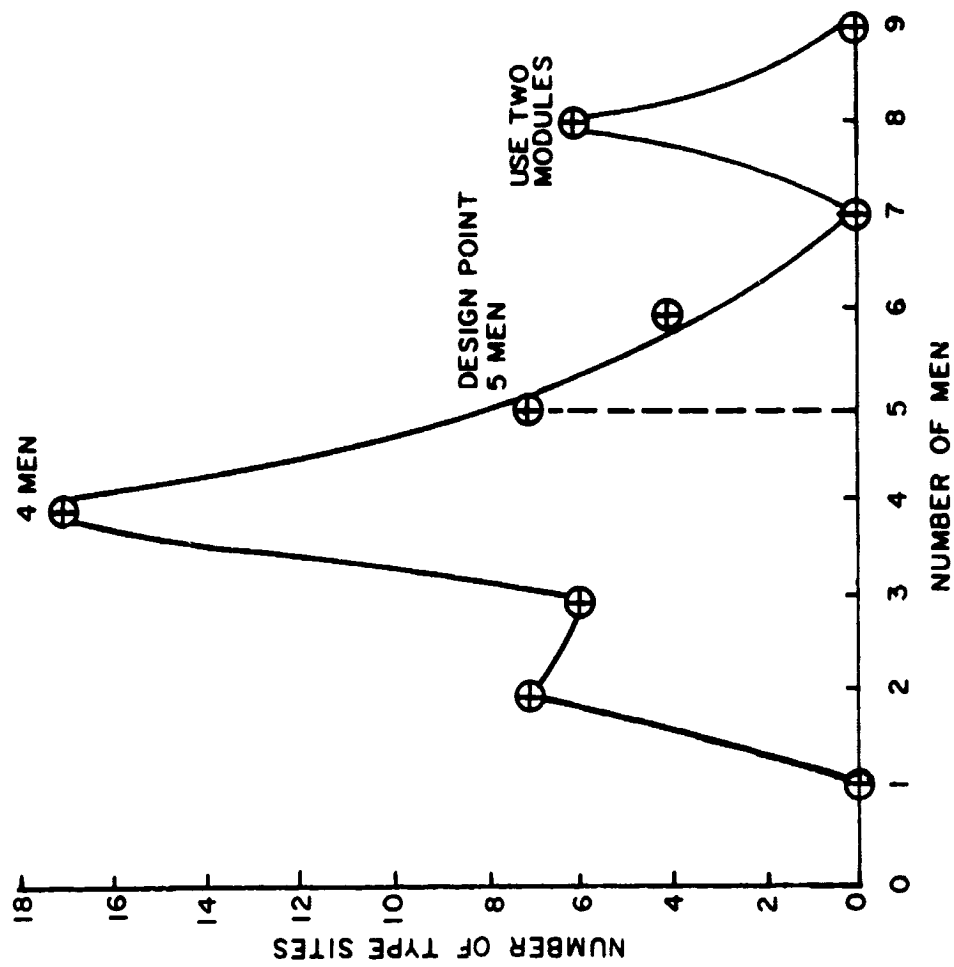


FIGURE 2. LEVEL 3 REQUIREMENT FOR NUMBER OF MEN

- 6.3 Number of Men - The estimate of the number of men is strongly dependent on the need for in-situ scientists at the type site. First, it is assumed that each mission will have at least one selenologist on board. In addition many of the type sites (63%) require additional scientific specialists.
- The crew then consist of the specialists plus at least one selenologist and an estimated one technician per scientist. In some cases (i.e. lava flow) the size of the feature and the need to travel quite extensively dictates the need for one or two additional technicians. It is assumed that a two man astronaut (non scientific) crew will also serve as technicians. Fig. 2 shows the distribution of number of men amongst the type sites. The primary requirement leads to a mission specification for 5 men. There is a secondary requirement for more men which could presumably be achieved using two 5-man modules.
- 6.4 Specialists - The types of specialists needed on the mission are directly related to the science task to be performed at the type site. The specialists identified are volcanologists (V), selenologists (S), selenophysicists (Sp), stratigraphers (St) and petrologists (P). A total of 63% of the type sites will require specialists.
- 6.5 Horizontal Mobility - The mobility requirements are of course heavily dependent on the size of the area to be explored, the complexity of the site, and the number of traverses and side trips which are required. This horizontal mobility is exclusively within the boundaries of the type sites. Fig. 3 shows the distribution of horizontal mobility requirements for the 75% of the type sites to which it is applicable. A design point of 400 km has been estimated as a major requirement. Many objectives can be satisfied with a smaller 25 km mobility.

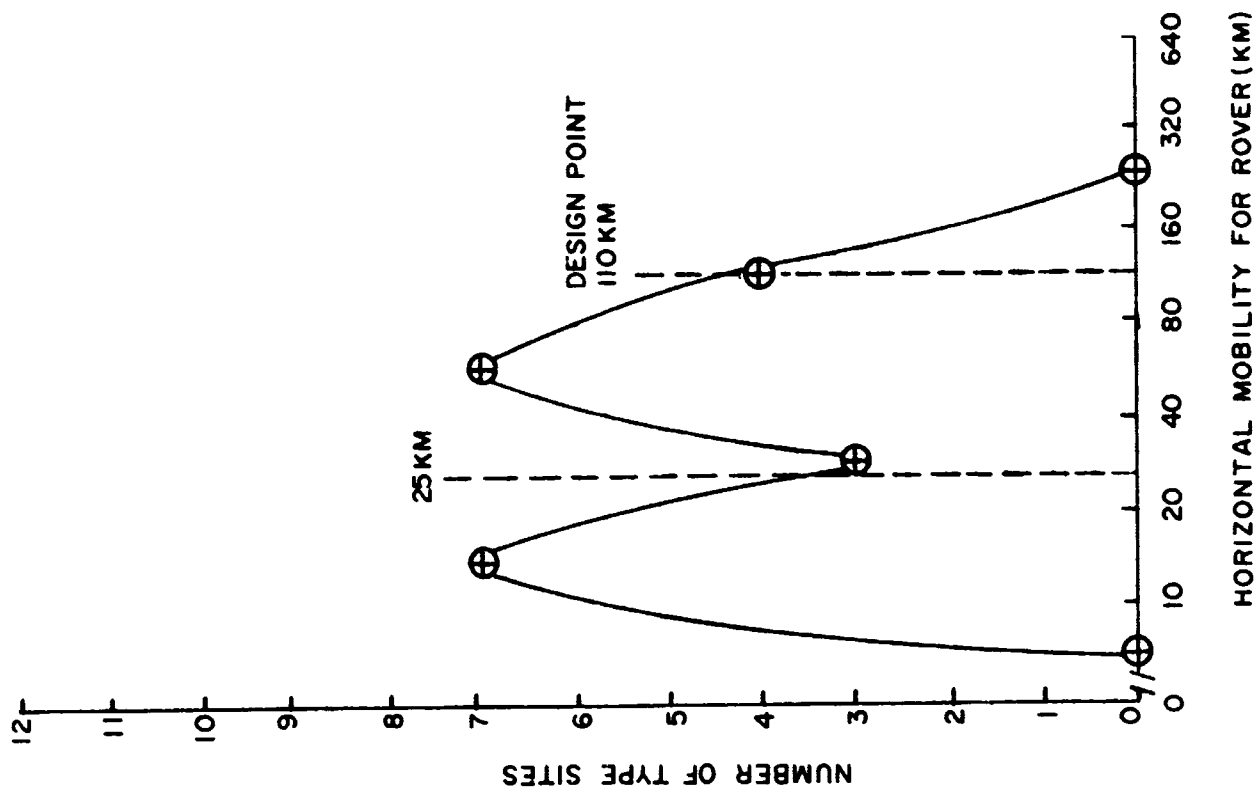


FIGURE 4. LEVEL 3 REQUIREMENT FOR ROVER MOBILITY.

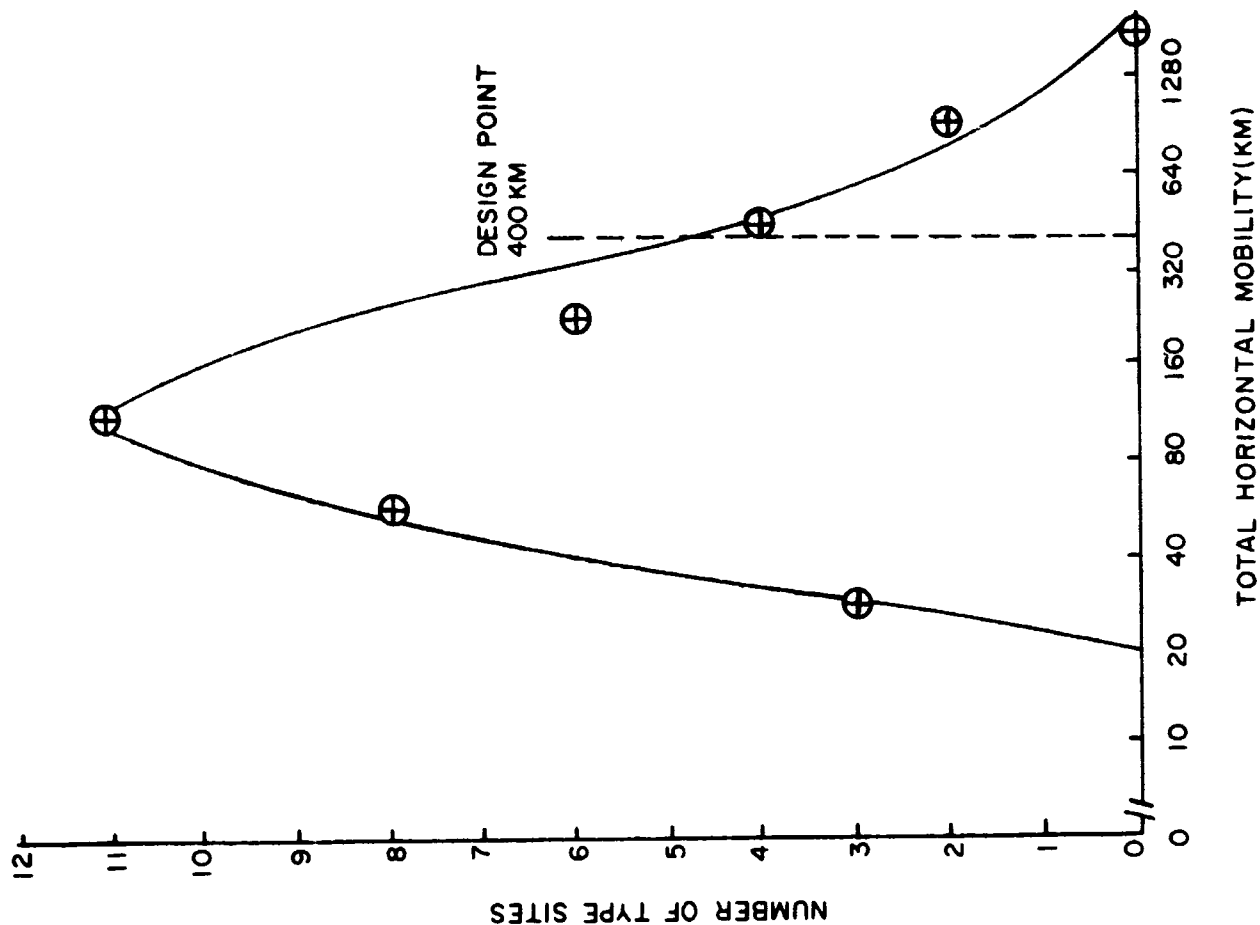


FIGURE 3. LEVEL 3 REQUIREMENT FOR HORIZONTAL MOBILITY.

- 6.6 Rover/Molab - The rover is to be used for small sites where the men can live and do laboratory work in the LM shelter and have need only for local (~10 km) transportation for themselves and their equipment. The molab is a mobile unit which provides laboratory and living space. In cases where both molab and rover are used together, about 10% of the total travel is assumed to be rover travel. Fig. 4 shows the distribution of mobility requirement for the rover for the 45% of type sites that require one. The curve is bimodal, and the higher requirement for 110 km rover mobility has to be taken as the preliminary design point. Fig. 5 shows the respective distribution for the molab. The estimated design point of some 450 km is naturally much higher than for the rover.
- 6.7 Vertical Mobility - The estimate of the total amount of vertical movement (assuming a device similar to a Lunar Flying Unit) is based on an estimate of the topography of the feature to be explored and the number of trips up and down which will be needed to explore it. Fig. 6 shows the distribution of vertical mobility requirements over the 51% of type sites to which it applies. A design point which will provide a total of 10^4 meters of vertical mobility has been estimated.
- 6.8 Sample Return - From many of the type sites, more complete analysis of the sample will be required than can be performed in the LM shelter or molab. In these cases the estimates of the mass of the return samples is based on the science requirements, and the need for accurate petrographic, chemical and dating analysis. Fig. 7 shows the distribution of sample return requirements as a function of the 75% of type sites that can usefully take advantage of it. The curve has no particular form

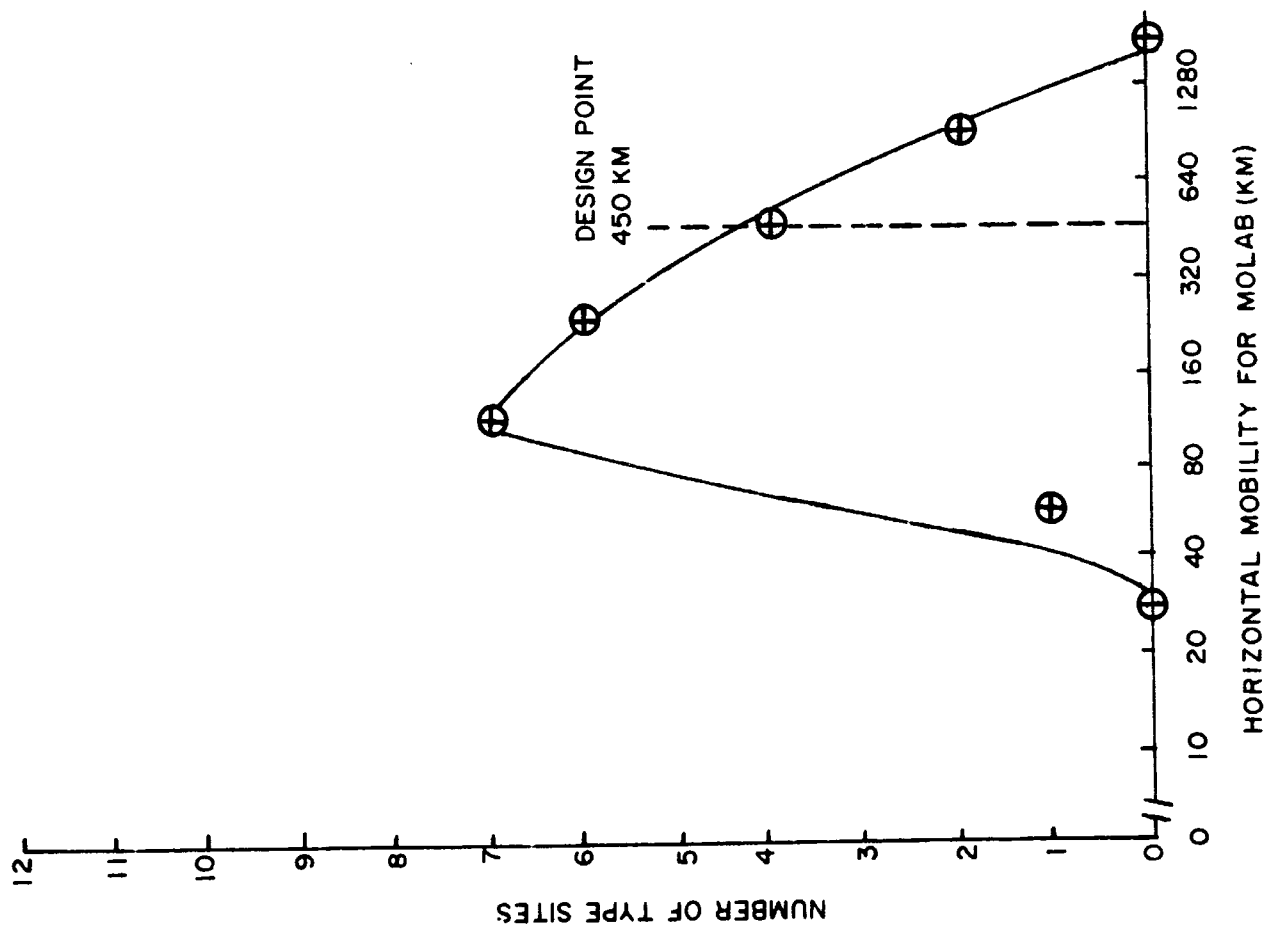


FIGURE 5. LEVEL 3 REQUIREMENT FOR MOLAB MOBILITY.

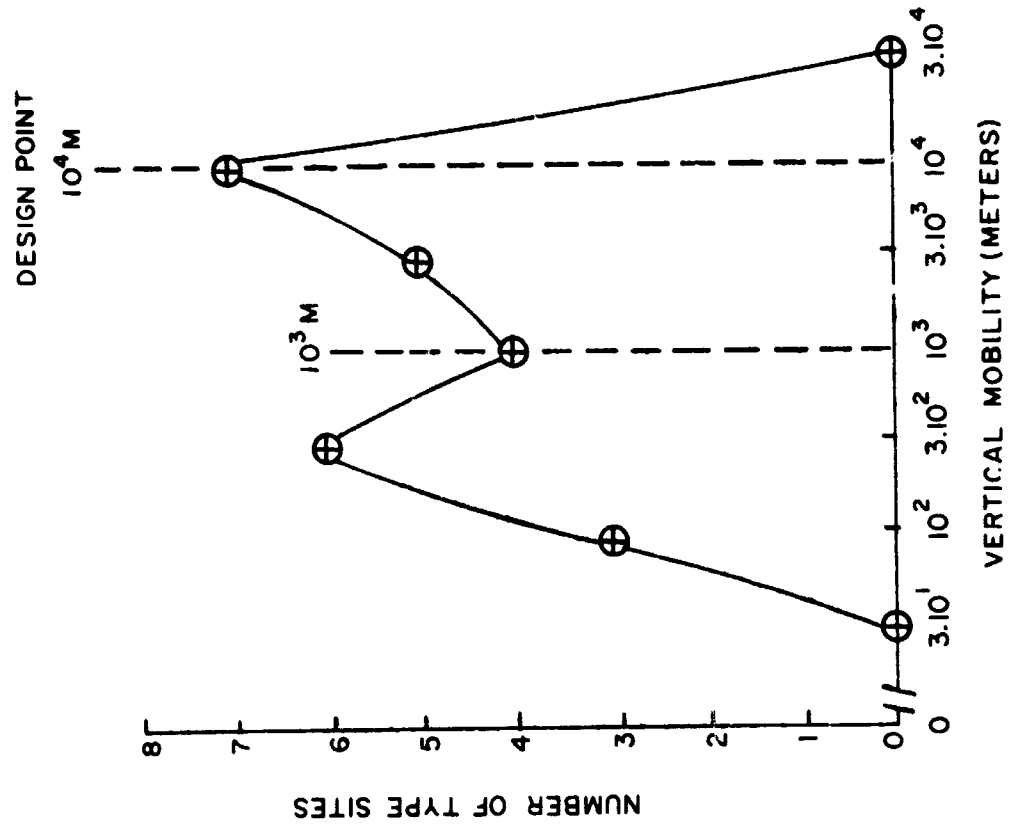


FIGURE 6. LEVEL 3 REQUIREMENT FOR VERTICAL MOBILITY.

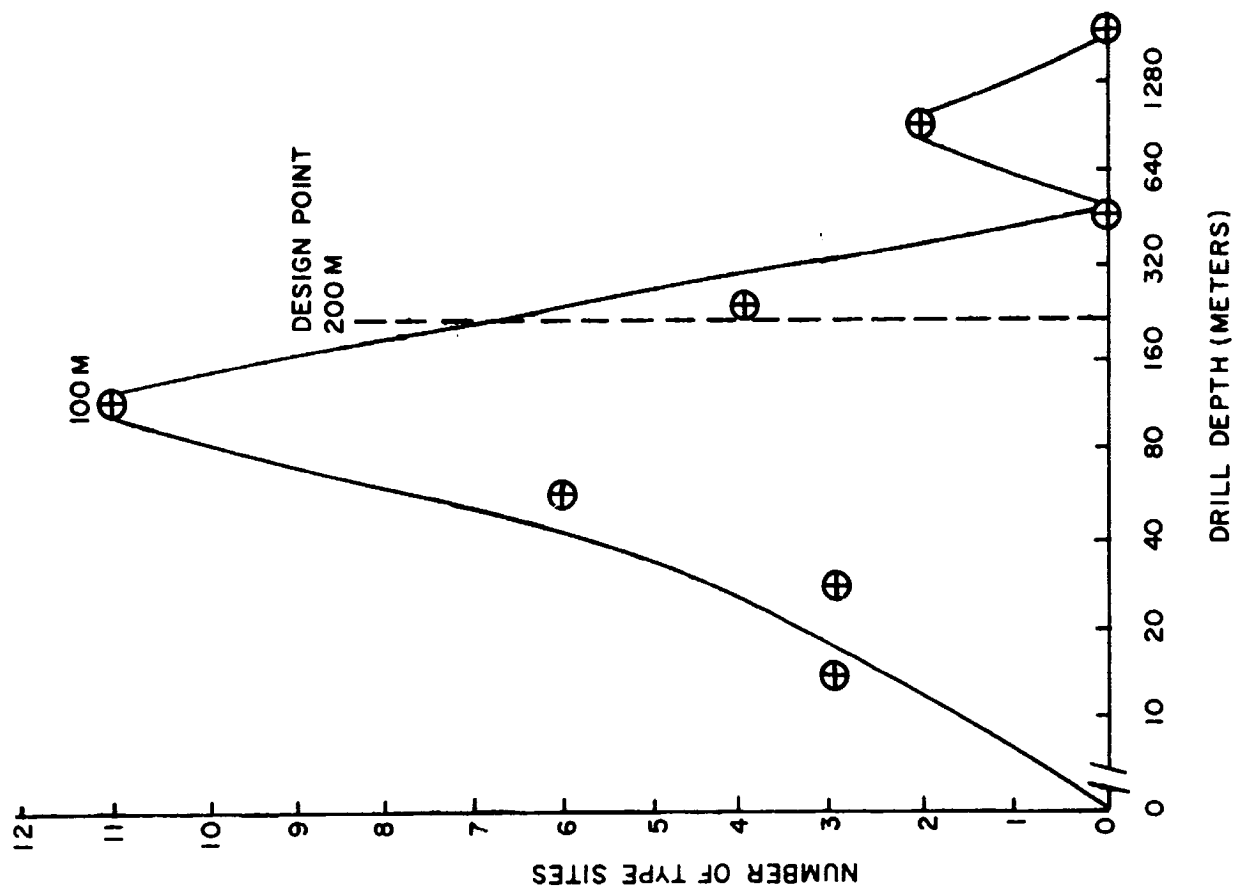


FIGURE 8. LEVEL 3 REQUIREMENT FOR DRILLING.

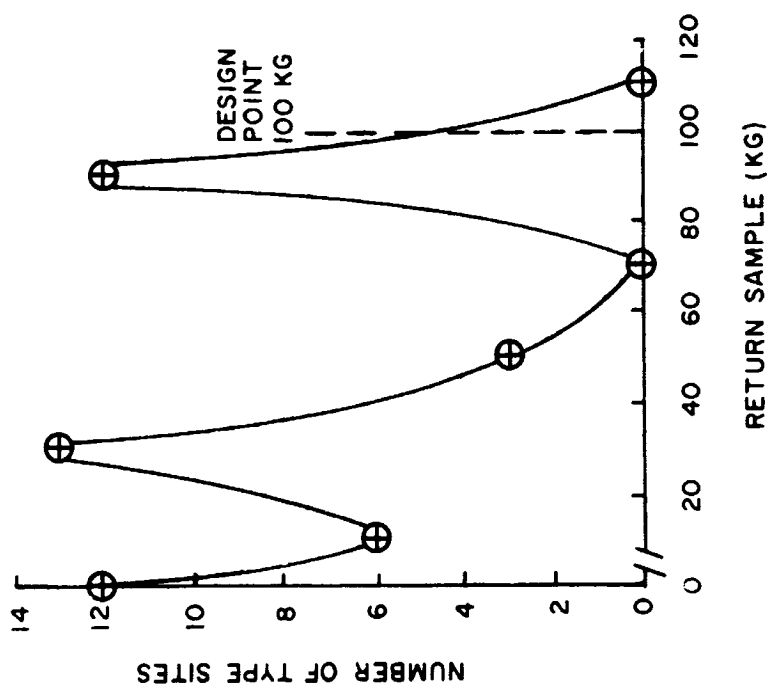


FIGURE 7. LEVEL 3 REQUIREMENT FOR SAMPLE RETURN.

and an arbitrary design point of 100 Kg has been selected.

- 6.9 Drill Depth - The estimate of the drill depth is based only on estimates of the vertical dimension of the sub-surface structure of the features. Fig. 8 shows the distribution of required drill depths. The major requirement is for holes on the order of 200 meters deep.
- 6.10 Number of Drill Holes - The estimate for the number of drill holes is related to the need for profile sampling and to the surface extent of the feature. Some of the holes (10m in depth) are needed in large numbers (~100) for thermal probes. The distribution is shown in Fig. 9 for the 64% of the type sites to which it applies.
- 6.11 Trenching - Trenching is required for two reasons, 1) to provide vertical cross section information since it is unlikely that there will be natural banks and cliffs needed for these type of studies and 2) to clear off the regolith so the solid rocks can be studied. The average clearing operations are estimated to require that some 100 m^3 of material be removed. Fig. 10 shows the distribution for both regolith removal and for vertical exposure, for the 79% of type sites requiring trenching. A design point of some 2×10^3 cubic meters has been estimated.

In addition to the above scientific requirements several engineering requirements must also be considered in the final form of the matrix. These include weight, power, volume, communication, trajectory and mission constraints each of which will impact the final design of the level 3 mission capabilities. They have not

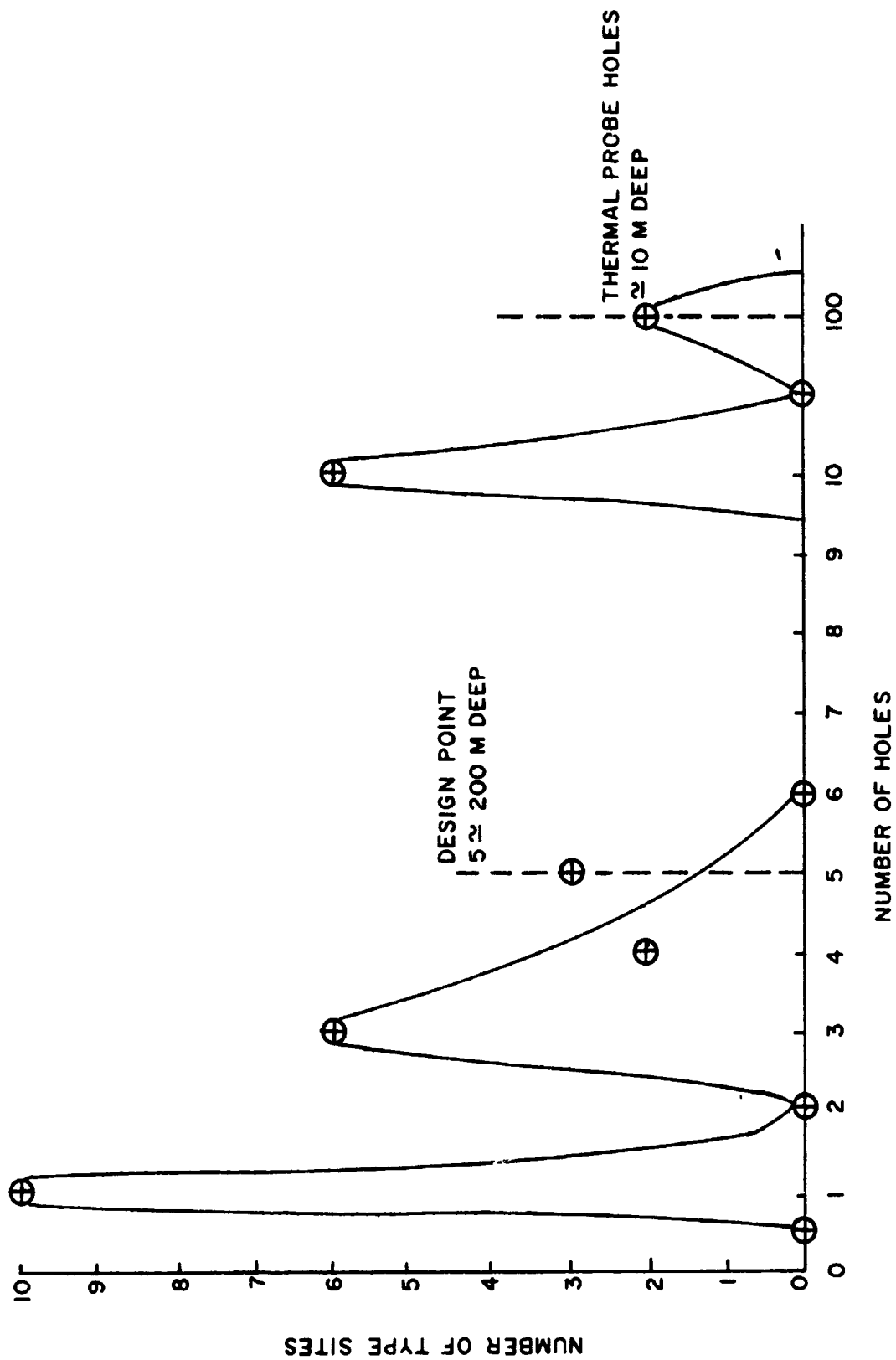


FIGURE 9. LEVEL 3 REQUIREMENT FOR DRILL HOLES

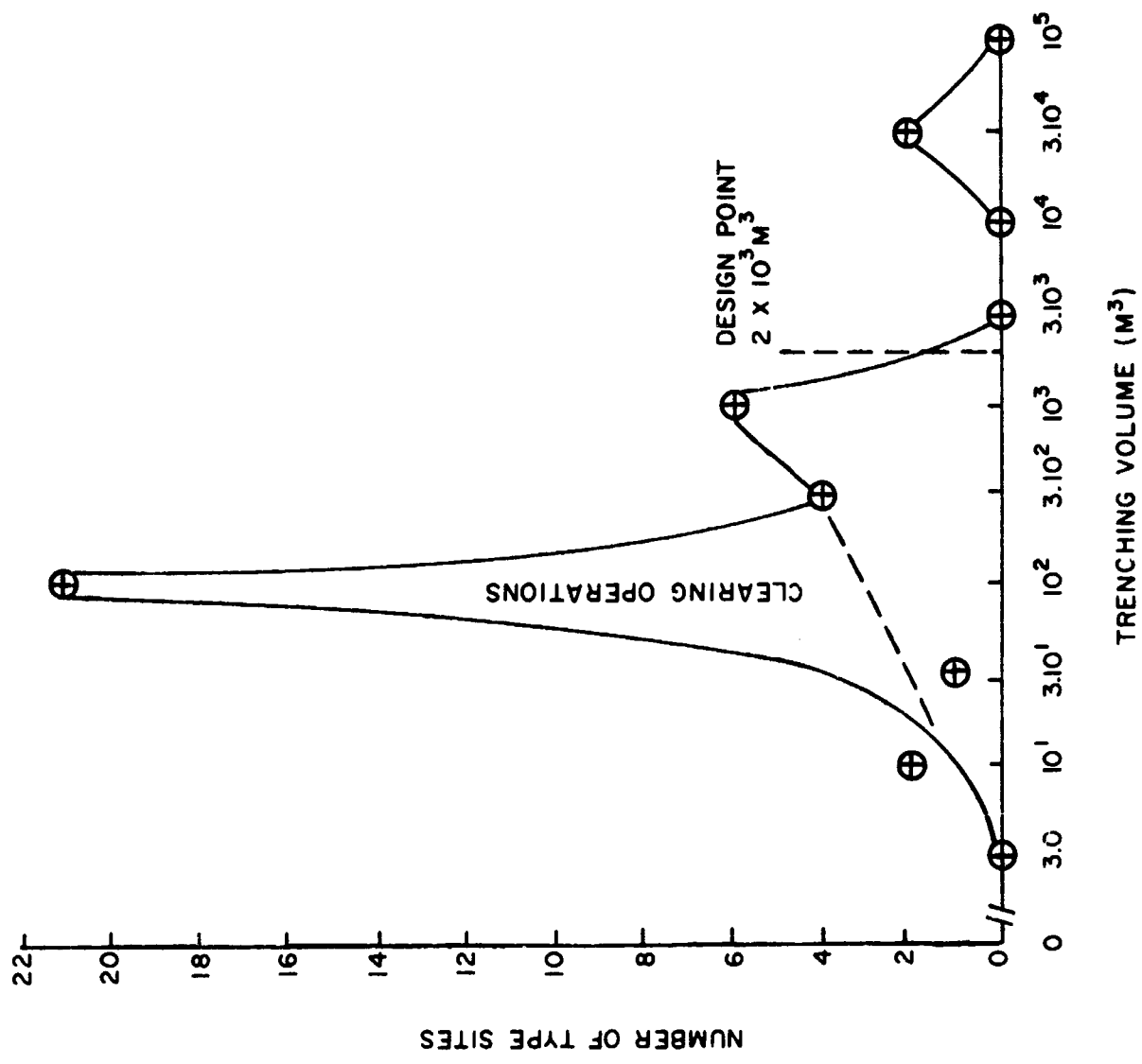


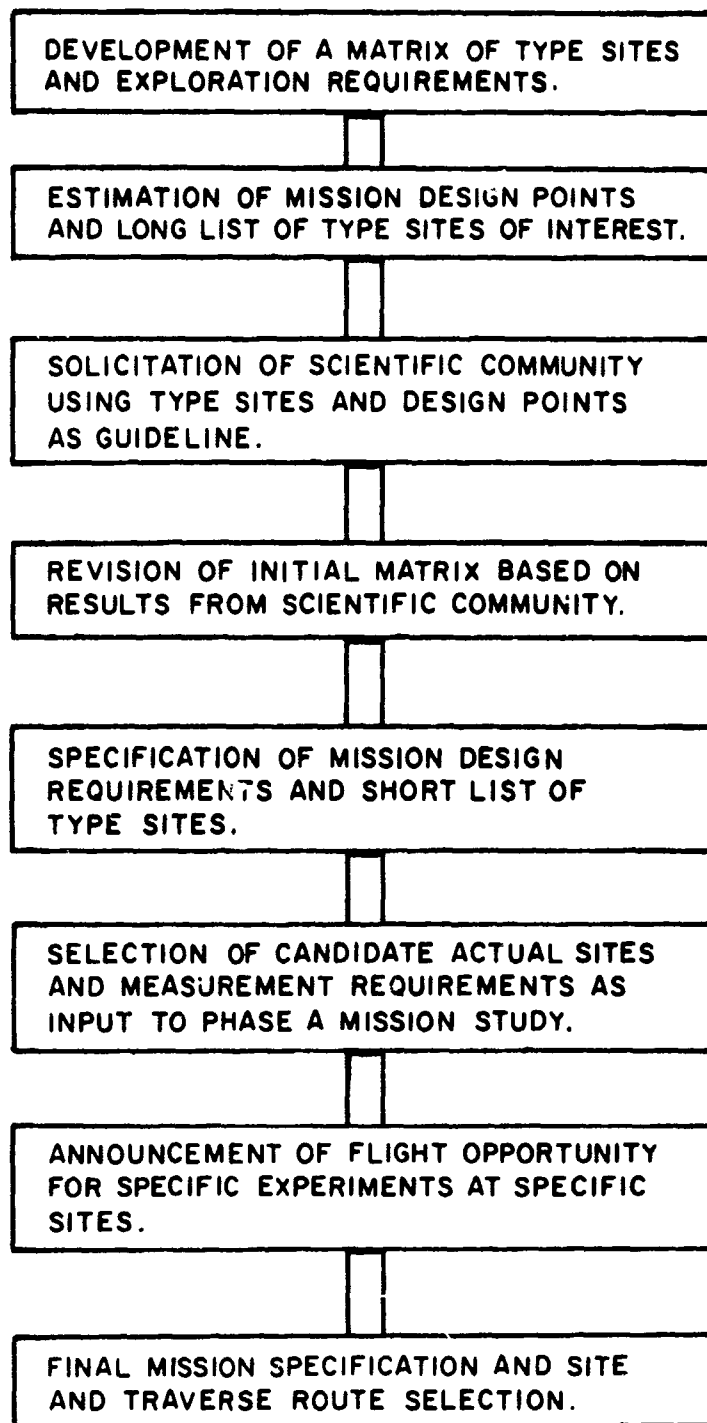
FIGURE 10. LEVEL 3 REQUIREMENT FOR TRENCHING

been included in this sample matrix because of the general lack of definition of these parameters that currently exists.

7. SITE SELECTION METHODOLOGY AND CRITERIA

The selection of specific locations on the Moon at which Lunar missions will land has not been attempted in this study. That exercise must rightly be left until a mission design has been specified and the latest lunar data from all the Apollo missions is available. The more important task, which has been the subject of the study, is the identification of a methodology and selection criteria which will permit the best choice of such sites. The key to the proposed methodology is the matrix of Fig. 4. The logic is shown in Fig. 11 and is briefly as follows:

- (i) Site Selection Board, acting as a working group, generates a matrix of type sites and requirements.
- (ii) Use matrix to estimate mission design points (i.e. staytime mobility etc.) and to identify a long list of interesting type sites.
- (iii) The Site Selection Board solicits the scientific community for experiments, and the related specific site requirements using, as a guide, the type sites and mission design points from the matrix.
- (iv) The response from the scientific community is used to revise the data in the original matrix.
- (v) Analysis of the new matrix will provide for
 - a) hardened mission design points
 - b) the exclusion of type sites clearly beyond the mission design specifications
 - c) the identification of Advanced Technology and Development requirements for candidate experiments
 - d) a long list of potential sites and type sites for post Apollo missions
 - e) enough design data to perform a phase A



PROPOSED OPERATING PROCEDURE FOR SITE SELECTION BOARD.

FIGURE II.

study of mission concepts to meet the scientific requirements

- (vi) The remaining tasks are to refine the list of sites, the mission design and the experiment requirements. These steps are iterative and should await the results of the phase A study.
- (vii) After the phase A study, the scientific community should be solicited to participate in a new, more firmly specified series of missions with candidate sites specifically identified.

The specific sites which are suggested by the scientific community are to be evaluated by checking their mission needs against the capabilities of the post Apollo system. It is assumed that several specific sites will be suggested as examples of each type site and that out of these a few may require more capability than the Level 3 system can provide. Assuming that all of the suggested sites entirely satisfy the science objectives for that type site, then the specific sites requiring excessive capabilities would be rejected. The choice as to which of the remaining several specific sites is actually visited is arbitrary and thus will allow greater flexibility in accommodating the mission and trajectory constraints.

Since by the way in which the mission definition was derived, a number of missions would not require the full capabilities of the level 3 system, it should be possible to combine two or more missions into one by the proper selection of sites, i.e. if two or more type sites can be found which are sufficiently close together, then a single mission would allow both sites to be explored to the required degree. For example, a diatrema might require 5 men for 2 weeks and an exposed ring might require 4 men for 4 weeks; then a suitable area would allow both sites to be explored with one full mission to the dual site, provided that a capability of 5 men for 6 weeks was available. Alternatively, according to Table 4, the regular cone, bulbous dome and low dome each require 8 men

with 25 day staytime and a minimal traverse. Thus a double mission of 5 men each would provide, say, 10 men for 90 days with enough traverse to go between the three features even if they were ~ 400 km apart. A suitable site could be found in the Marius Hills.

At the point at which the mission can be defined and a specific site selected, the experimental payload should be opened up to accept as many other experiments as possible. The so-called "experiments of opportunity", although not used to define the mission, must be included on the actual flights.

In addition to the methodology described above, it is important to identify the criteria by which judgements are made at each of the steps or decision points. Table 5 contains a total of thirty such criteria that have been identified in the site selection analysis and they fall into six major groups.

The first group of criteria relates to the scientific priority which should be attached to the type sites. The criteria relate to the worth of the results if the type site is adequately explored. In this context the importance of both the expected and the unexpected results must be considered.

The group relating to measurement requirements is included to ensure that an adequate understanding has been obtained of what it will take to investigate the type site. The measurement requirements range from the staytime to a definition of the experimental payload that must be included in the mission.

The third group requires an identification of the mission capability that must be available at the type site. This capability has to be traded off against the measurement requirements to ensure that the mission concept is adequate. It is proposed that the mission design points discussed in the methodology above be used as the basis for specifying the mission capability where no hard mission design is available.

The next group of criteria relates to the translation of type sites into actual locations on the Moon. The important criteria must specify the location of the site and how well it

TABLE 5. CRITERIA FOR SITE SELECTION

- ESTABLISHMENT OF SCIENTIFIC PRIORITY OF TYPE SITES:
 - 1) level of exploration
 - 2) expected results
 - 3) contribution to understanding of Moon
 - 4) significance of unexpected results.
- DEFINITION OF EXPLORATION REQUIREMENTS AT TYPE SITES:
 - 5) staytime
 - 6) number of men (including specialists)
 - 7) mobility requirements
 - 8) sample analysis or return
 - 9) drilling and trenching requirements
 - 10) lunar time of day
 - 11) experimental payload.
- SPECIFICATION OF REQUIRED CAPABILITY
 - 12) range for each measurement requirement
 - 13) nominal design point for each parameter
 - 14) subsystem support requirements (power, data handling, communications, etc.).
- IDENTIFICATION OF SPECIFIC EXAMPLES OF TYPE SITES
 - 15) longitude
 - 16) latitude
 - 17) area of interest at site
 - 18) complexity of site
 - 19) ambiguity of data interpretation
 - 20) closeness to other type sites.
- ENGINEERING FEASIBILITY
 - 21) trajectory compatibility (landing, launch, rendezvous)
 - 22) weight class of payload
 - 23) compatibility with anticipated logistic systems
 - 24) safety
 - 25) mission schedule and availability
 - 26) cost
 - 27) photo reconnaissance of site.
- AVAILABILITY OF SCIENTIFIC SUPPORT
 - 28) principle investigators
 - 29) flight ready experiments
 - 30) astronaut (specialist) availability.

meets the type site requirement. Normally more than one location would be selected for the more interesting type site.

The above criteria are basic to the selection and evaluation of candidate sites but it is the phase A study which establishes the mission and engineering feasibility. These criteria must embrace all aspects of the mission from trajectory compatibility to site reconnaissance.

Finally, given a feasible mission to a selected site it is essential to verify the scientific support for the desired investigations. In particular, the availability of trained astronaut/scientists is crucial to level 3 exploration.

The above criteria are separate from but not independent of the methodology. It is useful to consider the methodology as identifying, in a logical manner, the key decision points in the process of site selection. The criteria represent the considerations and trade off parameters on which the decisions are based.

8. CONCLUSIONS

The preceding methodology and criteria provide a number of essential ingredients in the post Apollo mission design and site selection process. First, it takes full cognizance of the very close coupling between the mission capability and the site selection. It provides that they be defined and refined iteratively and cohesively. It insists that the basic mission concepts and requirements be derived from the viewpoint of the scientific exploration of the Moon. However all other objectives are introduced in the final stages as "objectives of opportunity" and as such will play an important role in maximizing the value of the missions. Perhaps most important of all, is that it requires genuine advanced planning of the post Apollo program using the best information available at the time. It enforces a careful definition of what has to be achieved in the program and systematically and logically obtains and analysis the necessary

inputs from the scientific community and from the phase A mission analysts.

The methodology as developed here is exemplary. It can and should be modified to fit the specific conditions which will exist at the time it has to be implemented. Nevertheless it is felt that the basic criteria and essential steps will remain and that there is enough supporting analysis in this report to permit its modification.