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A Planning Logic for Exploration and Utilization of the Moon

The present paper presents a methodology for the design of a lunar exploration program. The logic is based upon (1) the recognition of the scientific objectives of lunar exploration as presently identified and (2) the critical and variable staytime requirements for lunar exploration missions. Systems ranging from orbital space flights, limited surface staytime exploration modes, and extended mobility missions to temporary stations and bases are included in the development of the analysis.

The technique is based upon the assumption that, although the program planner cannot quantify either the scientific objectives or the output of a lunar exploration program, it is nonetheless possible to employ quasianalytical techniques to derive semiclosed-form solutions to a mathematical model of a lunar exploration program. This is done by breaking down the scientific objectives and total scientific product of a lunar exploration program into percentages assigned to various exploration systems such as orbital, mobile, and fixed-base systems. Each system is designed to produce a given, assigned output of scientific product for each of the missions making up the flight program. In this manner a payload requirement (weight, volume, or power) can be developed for each mission within each system, and the experiment (and, hence, instrument) requirements can be identified as a function of the scientific questions requiring answers during the exploration program.

By appropriate manipulation of the various parameters making up the model, a series of mathematical expressions are derived which present the elements of the exploration program in a simplified analytical relationship. These expressions are plotted in various forms to depict the significance and interdependence of the variables. Some of the significant results and conclusions of the paper are:

(1) A semianalytical mathematical model of a lunar exploration program can be derived if some rather bold assumptions are made.

(2) The mathematical model can be a useful tool to the program planner in structuring and analyzing various lunar exploration systems designed to accomplish certain fixed scientific objectives.

(3) Problem areas in the development of long-range plans for total lunar exploration can be identified for management using this tool.

(4) Technology development requirements can be identified in broad terms in advance of random detailed studies of various systems and subsystem elements.

The paper concludes that if sophisticated management and organizational methods and techniques are vital to the success of space operations, they are also equally vital to successful planning for space systems and operations. Thus the approach described can be very useful in long-range lunar planning activities.

INTRODUCTION

Perhaps as a consequence of U.S. continued success in space, increased interest in lunar exploration and exploitation is developing and is being stimulated anew by the impending project Apollo, a manned landing on the Moon. Thoughtful persons, Government agencies, and industrial organizations are looking toward the Moon as an object of potentially large opportunity for mankind, that is, an opportunity for improving man's understanding of himself, his Earth-Moon environment, and the universe in general. Thus the manned Apollo landing will not mark the conclusion of another space program, but rather will mark the beginning of a period in which the full potential of the Apollo system to support lunar exploration will be realized.

Interest in lunar exploration, including means and scientific results, leads inevitably to a related interest in lunar bases even though the need and justification for lunar bases is not readily apparent. Space exploration is an expensive enterprise, and the benefits, though real, are not entirely tangible or visible. The most successful space programs are those that are motivated by a demonstrated scientific need within technical and economic constraints.

Such an imperative has not yet been firmly established for lunar bases, and though considered opinion reflects an intuitive conclusion that bases on the Moon will be a justifiable and inevitable end product of our Apollo capability, a reasonable logic for such bases has been slow in developing. The fundamental question, of course, is: How can one determine in advance of the first manned landing if a base will ultimately be necessary or even desirable later in the exploration program, when definitive scientific results upon which to support such a decision are lacking? At the same time, the planner realizes that long lead-times are necessary in order to develop mission and support equipment for a base and that those planning and design factors evolving as logical consequences of the environment should be incorporated into all stages of planning and execution of the project.

This paper is addressed to the problem of planning lunar exploration missions and programs up to and including the establishment of lunar bases. For the analysis presented here, an arbitrary time period of 20 years' active life has been chosen. Other major assumptions are presented in the paper as need for them develops. The planning problem is composed of a number of elements which interact with one another. A somewhat incomplete expression of this problem can be phrased as follows: How should a lunar exploration program comprising a number of discrete systems, each of which must accomplish a finite but indefinite amount of "science," be developed? How long should the system continue to be used, how many missions should be flown within it, and when should it be terminated or upgraded to one having greater capability? Articulated in another way, we want to maximize the efficiency of each system in the proposed program and yet anticipate the required efficiency of each system prior to obtaining a good understanding of what we want to do on the Moon and what the products of our exploratory efforts might be.

Answers to all these questions cannot be presented in this short paper, but it is intended that some insight will be provided into the type, nature, and magnitude of the problems constituting the planning process which will be of significant value during future planning and efforts, and which, if left unanswered, could result in losses of efficiency and scientific return as well as national prestige and resources.

The concepts presented in several of the illustrations were developed by the author during his association with the Missile and Space Division, General Electric Co. As such, permission to use these illustrations is gratefully acknowledged. The reader should understand that they do not represent official or even necessarily current thinking of the National Aeronautics and Space Administration and are used only as representative concepts to support the discussion herein.

WHAT IS LUNAR EXPLORATION?

Exploration can be defined in several ways, though a commonly accepted definition is the survey of new areas or regions, usually previously unexplored, with a desire to determine the environment, map or survey the terrain, and establish references for later missions or surveys. Exploration of the Antarctic regions is a good terrestrial example of this procedure. Lunar exploration differs from terrestrial exploration, however, in that visual and photographic orbital surveys will have been made to some degree prior to surface exploration. Furthermore, sophisticated scientific instruments will be used to supplement visual and photographic data and sample acquisition on the Moon. Early terrestrial explorers were limited by the scientific instruments then available. Expressed in precise terms, orbital and remote sensor surveys of the surface must be included in the term "exploration" when it is applied to the lunar case; thus, manned exploration of the lunar surface will produce fewer of the unexpected elements which marked terrestrial exploration.

Exploration missions involve scientific objectives which can be interpreted as:

(1) Broad, involving
  (*a*) Broad areas
  (*b*) Broad phenomena
(2) Limited, involving
  (*a*) Limited areas
  (*b*) Selected phenomena
(3) Restricted, involving
  (*a*) Specific areas
  (*b*) Specific phenomena

It is emphasized that exploration seeks to extend man's knowledge, primarily in the scientific disciplines. Thus, in order to accomplish exploration, the mission objectives should be directed toward rather well-defined scientific goals involving the testing of hypotheses, specific experiments supporting specific phenomena, and some general experiments involving interrelated phenomena or processes. Certainly one could assemble a polyglot of scientific experiments, totally unrelated and uncorrelated to any scientific goal, but such a matrix would not constitute a balanced and thoughtful program of exploration.

Science is not the only imperative for lunar exploration, however, since space exploration, in general, carries and supports other direct and indirect benefits. It is important to consider the relative importance of science in the total lunar exploration program and to understand what the other elements supporting the program and benefiting from it might be. To the degree that it is possible to define the total benefits deriving from lunar programs, it will be possible to consider them in the total context of the program and thus include them in the planning effort, if not directly at least to some degree indirectly.

The major measures of lunar program effectiveness can be considered to be its contribution to or improvement in—

(1) Scientific product
(2) Military posture
(3) Economic value
(4) Technology development
(5) National prestige

Detailed discussion of the relevance of these factors can be found in appropriate literature; for the immediate purposes it is sufficient to inquire into the question of how these factors can be quantized, and, particularly, to inquire into the magnitude of the scientific product. Informal surveys within NASA indicate that the contributions to total lunar program effectiveness by each of the above factors are approximately as given in table 1. Though it is obvious that an individual may disagree by at least ±5 percent with these indices of effectiveness, they can be used to measure system effectiveness in planning analyses.

TABLE 1.—*Relative Contributions to Program Effectiveness*

Factor	Percent contribution
Scientific product	45
Military posture	15
Economic value	10
Technology development	10
National prestige	20

We have established that scientific goals motivate lunar exploration; therefore, we can call this body of knowledge that we seek Q. The quantity Q can be considered to comprise scientific inquiry into the geologic processes on the Moon, a deeper understanding of the Earth-Moon system, and a look at questions involving the solar system or universe as a whole from the surface of the Moon. Further, since Q is defined some years in advance of the actual missions being accomplished, in particular surface missions, it can be expected that new information regarding the Moon will be derived from unmanned probes and spacecraft during this period. As a result new questions will be posed, and these will constitute an additional increment of inquiry which can be designated Δ.

For the purposes of this analysis, Q is considered to be the 15 questions posed at Woods

Hole plus the 10 additional questions posed in the MIMOSA study.[1] Since Q is not constant with time, dQ is considered to be the increase in Q with time; it should be recognized that the rate of change is probably not linear.

In the same manner, Δ reflects the scientific questions involved in disciplines other than those that are predominantly geosciences and includes astronomy, the biosciences, and physics. Again, $d\Delta$ is defined as the time rate of change of increase in Δ; $d\Delta$ is probably linear and together with Δ reflects the emphasis resulting primarily from the manned components of the lunar program.

Similarly, α and $d\alpha$ are defined as other interdisciplinary questions and research which are directed toward science performed primarily by the unmanned components of the space program.

Lastly, a term R is introduced which reflects the emphasis of lunar resources in the total program and the contribution made by lunar resources to both mission operations and scientific knowledge.

For our purposes, then, we can say that lunar exploration must produce a body of knowledge k as the scientific product of the program equal to the sum of the above subelements:

$$k = Q + dQ + \Delta + d\Delta + \alpha + d\alpha + R$$

The total lunar exploration program must in turn be supported by (1) scientific equipment and (2) mission equipment. These equipments, of course, require transportation to the Moon and involve (3) logistic systems which are also closely related to and considered a part of the total program. The sum of (1), (2), and (3) defines a general lunar exploration system.

If the foregoing is a valid assumption, then we can also assume that the accomplishment of the lunar exploration program could involve a number of rather distinct phases, each reflecting a different system or combination of mission equipments. We must recognize at the same time that the equipments involved in each system will be composed of new developments, improved versions of earlier models, and possibly hybrid combinations.

HOW CAN A LUNAR PROGRAM BE OPTIMIZED?

The analysis presented in this paper assumes a planning period of 20 years during which time the maximum number of systems which could be developed and flown is taken as five. The systems are designated by the letters L, M, N, O, and P, and each system will be designed to contribute to the total scientific product k. Figure 1 shows how these system alternatives could relate to each other in an ideal program, though it is recognized in the diagram that considerable variation and latitude in system cost, staytime, scientific scope, and time duration of use could and probably will exist.

From the foregoing variables, one can designate a simple lunar exploration program p equal to the sum of all the component systems with each performing (or contributing) a certain percent of k:

$$p = L + M + N + O + P$$

Since the components of k (Q, dQ, Δ, etc.) vary with time, k also varies and L, M, N, O, and P can be defined as operators acting on k with each extracting a certain percent of k. Thus, for time t,

$$Lk_L(t_1) = v(t_1)$$
$$Mk_M(t_2) = w(t_2)$$
$$Nk_N(t_3) = x(t_3)$$
$$Ok_O(t_4) = y(t_4)$$
$$Pk_P(t_5) = z(t_5)$$

where $t_1 = t_2 \leq t_3 \leq t_4 \leq t_5$ and v, w, x, y, and z are values strongly dependent upon the scientific and mission equipment payload capability of each system. Required in this simple case are

[1] The 15 Basic Science Questions referred to in this paper are those enunciated by the Space Science Board, National Academy of Sciences, which convened a summer study at Woods Hole during June and July 1965. Reference 1 is the report of that study and contains the 15 questions. During the conduct of a NASA study entitled "Mission Modes and System Analysis for Lunar Exploration" by the Lockheed Missiles & Space Co. (ref. 2), an additional 10 scientific questions were posed. Together, these 25 questions have been expressed as Q in this paper.

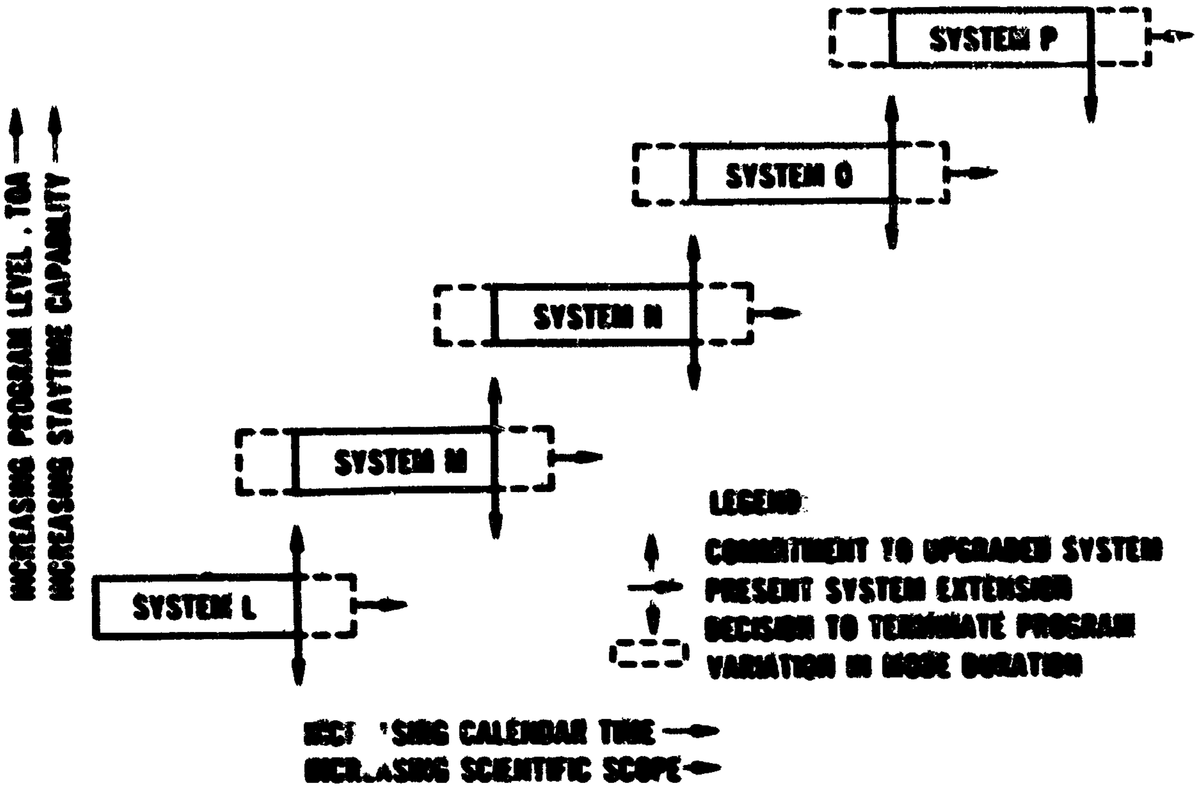


FIGURE 1.—Lunar space exploration mode alternatives.

definition of such considerations as total number of missions in each system, number of missions per year, and the mix of Q and Δ, a, and so on, in each mission.

The central problem in an analysis of this kind is to determine how the various systems should (or could) be individually optimized in terms of cost benefits (effectiveness) so that the total program, whether reflecting a period of 10, 20, or more years' duration, can be similarly optimized with respect to cost benefits. As table 1 demonstrates, the scientific product constitutes close to 50 percent of the program contribution, with the other factors making up the remaining 50 percent. The only valid approach which can be taken in advance of the manned landing is to assume that by optimizing the constituent systems and hence the total lunar program for the benefit of science, the other factors (technology, prestige, economic, and military) will also be benefited to an unknown degree which will be large though quite probably less than optimum.

By adopting this premise and stressing its essentially intuitive justification, it is possible to design a program which can be used to identify the parameters for the spacecraft, mission, payload, and landing site which bear on and influence the success or failure of the program and which serve to provide insight into the possible payload composition, including experiment and instrument requirements. Figure 1 indicates that each system should reflect an increasing level of scientific scope and staytime capability as the program progresses. These requirements will, in turn, demand increasing program budgetary levels.

In order to permit time structuring of the missions and payloads in the program, it is necessary to establish a relationship between k and the major scientific disciplines of which it is comprised. This was done by an informal survey within NASA from which table 2 was derived. By relating the time sequence of the ordered disciplines to the components comprising k, it is possible to establish a framework upon which to base a program design which includes the percent of k which must be satisfied by each system in the program and the number of missions (flights) necessary to produce the total k for each system. This has been done; the results are shown in table 3.

In this idealized analysis, several assumptions are again apparent. One, the percent k contributed by each system becomes significantly larger as each system is upgraded to a more sophisticated level of capability; and second, the payload carried per mission is capable of extracting an increasingly larger percent of k. This approach is consistent with the evolutionary growth expected in the spacecraft and launch systems during the lifetime of the program.

Studies directed toward the science to be performed on the Moon from which the definition of the elements composing k, the scientific product, were derived show that the trends indicated by table 2 are consistent with the probable course and scope of lunar science and exploration and can be used to define the systems necessary to support the scientific missions. Candidate-system concepts supporting each system are presented in the subsequent discussion.

A SYSTEM *E* POSIT

System *E* is considered to be the Apollo and unmanned spacecraft systems which perform missions whose scientific capabilities are primarily directed toward Q, the basic 15 Woods

Table 2. *Ordered Lunar Scientific Disciplines*

Scientific discipline	Subjective		Numerical	
	Value	Priority *	Value	Priority
Astronomy	Medium-low	Late	[illegible]	[illegible]
Atmospheric physics	Medium-low	Early	[illegible]	[illegible]
Biosciences	Medium-high	Early-middle	[illegible]	[illegible]
Particles and fields	Medium	Middle-late	[illegible]	[illegible]
Geology	Very high	Early-middle	[illegible]	[illegible]
Geochemistry	Very high	Early	[illegible]	[illegible]
Geodesy	Medium-high	Early	[illegible]	[illegible]
Geophysics	Very high	Early-middle	[illegible]	[illegible]

* "Priority" refers to time frame in exploration period in which major accomplishments would be anticipated.

Table 3. *Idealized Lunar Program Analysis*

Years, cumulative	4	8	12	16	20
Years, incremental	4	4	4	4	4
System	E	M	S	O	P
System description	Apollo and unmanned	SAA	Mobile on platform	Permanent station	[illegible]
Percent k	10	12	20	25	33
Cumulative k	10	22	42	67	100
Payload per mission, percent k	2	3	5	5	11
Number of missions	5	4	4	5	3

Hole questions and the MIMOSA questions. Here, the amount of *k* capable of being produced by each mission is small (2 percent) as shown in table 3. If a total of five missions of Apollo or Apollo equivalence in the case of unmanned or manned orbiter flights is assumed, it can be expected that sample return, remote sensing, and imaging experiments will dominate the payload composition. Staytimes in this case are short, on the order of a few hours for Apollo to a few days for manned orbiter and unmanned systems.

A SYSTEM *M* POSIT

System *M* can be conceived as a logical extension of the Apollo system whose elements are composed of Apollo and Apollo derivatives. Its mission is envisioned as comprising broad surveys and exploration with time-independent experiments over widely separated areas. The percentage of *Q* covered in this mission is probably quite large, Δ is probably rather small, and the span of time over which the useful effective lifetime of *M* is extended is also as long as possible, probably several years or more. The studies conducted with *M* are directed toward an understanding of the whole body of the Moon and involve such disciplines as geology, geophysics, and geochemistry. Lunar staytimes are also probably quite short, on the order of a few days to a few weeks.

Figure 2 shows an artist's concept of such a system, which might be described as an early lunar pair. Studies show that two Saturn V launches might be required for this system; one launch would land an unmanned shelter carried by the LM truck and would be followed by another launch carrying an Apollo LM taxi which lands the astronauts on the lunar surface. Mission equipments would include a drill capable of drilling to depths of 100 feet and recovering cores for return to Earth. Also carried on the LM taxi would be a small one-man roving vehicle, currently under study, known as a local scientific survey module (LSSM). This roving vehicle would operate within a range of perhaps 5 miles beyond the initial landing point. It will be noted that the vehicle would not contain either environmental control or life-support systems. Portable backpacks are the sole provision for life support with this mobility mode.

Significant contributions to *Q* can be obtained with this system. These include advancing our understanding of the structure and internal composition of the Moon, learning more of the internal energy regime of the Moon, and studies involving the composition of the lunar surface and processes which act to alter its shape and composition. Missions conducted with this system would involve the placement of fixed instruments at specific sites where time-dependent data are desired and can be obtained by fully automatic instruments. These data might include measurements of heat flow, seismism, gravity, and atmospheric phenomena.

A SYSTEM *N* POSIT

Planning for system *N* is not as simple as for *M*, since the mission objectives and scientific studies which are required for this system are constrained by the accomplishments of *M* in terms of the amount of *Q* remaining as well as probable increased requirements of Δ on the system.

The mission objectives involve greater areal coverage and are directed toward both selected areas and rather selective phenomena for investigation. As a result, it is not unrealistic to assume that this system will involve a large mix of new developments and second-generation mission equipments. The scientific phenomena of interest during this period, visualized to extend over several years with one or more missions per year, are more time dependent and involve studies in disciplines in addition to the geoscience. These might include the biosciences and supporting studies in astronomy, for instance.

Conceptual studies indicate that this system might also involve two launches of a Saturn V booster per mission. One launch would land an unmanned mobile laboratory and would be followed by an LM taxi carrying two and possibly three astronauts to the lunar surface as shown in figure 3. An additional shelter developed for system *M* might be available as well in the event that system *N* spacecraft are landed

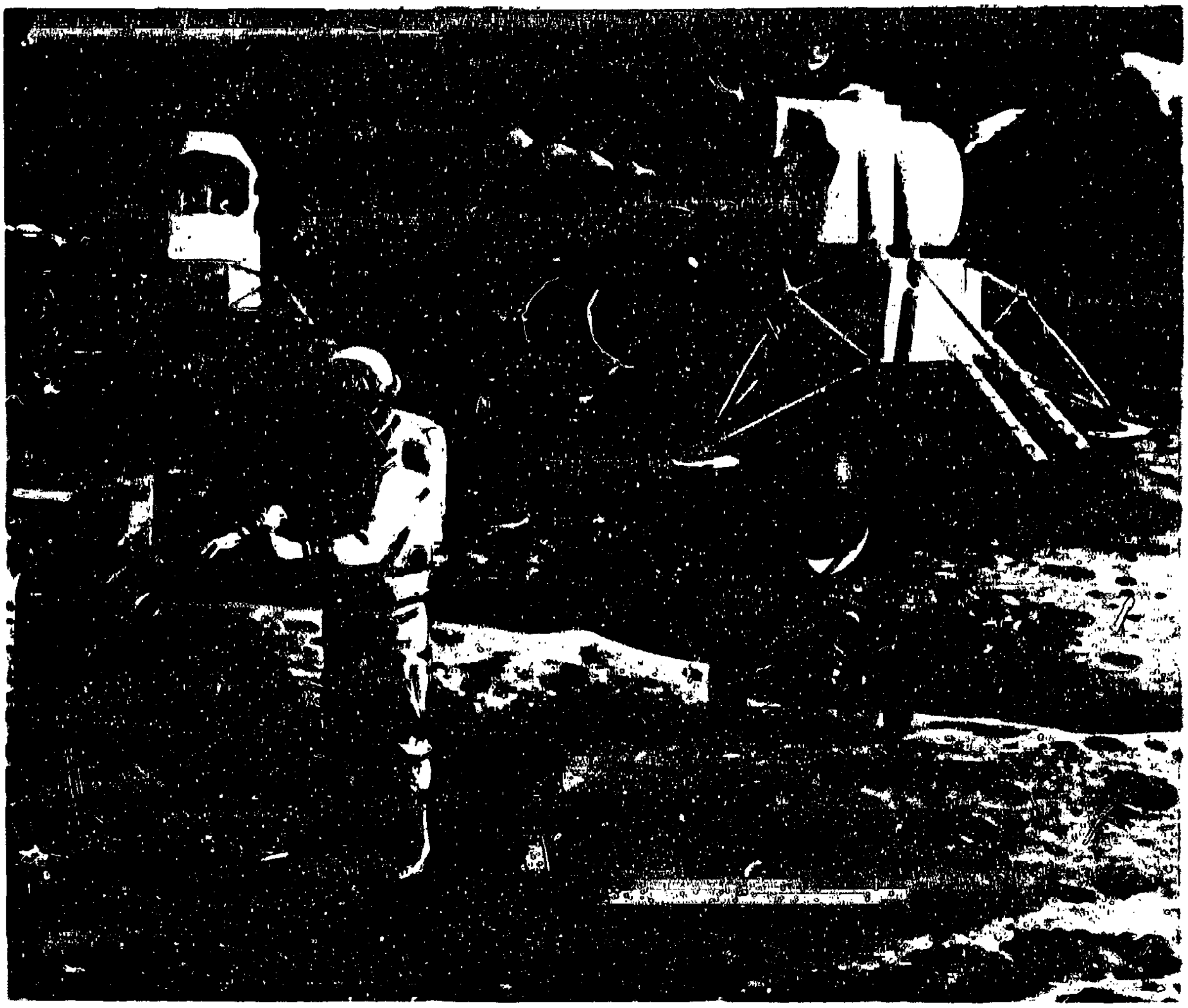


FIGURE 2.—Artist's concept of system *M*.

near a site explored briefly during the lifetime of system *M*. In this case we might be thinking in terms of staytimes of several weeks to several months, during which the mobile laboratory would make extended traverses over the lunar surface. In addition to conducting scientific studies and emplacing scientific equipment, the team would also conduct engineering experiments *in situ* to determine the requirements for more permanent base facilities and to obtain data upon which to base the design of these facilities.

During the lifetime of system *N*, one could reasonably expect that requirements for astronomy and biomedical research would be identified, as would possible lunar resources, and applied science and engineering research needs.

A SYSTEM *O* POSIT

By the time the requirements for system *O* have been identified, the major early requirements involved in *Q* will have been largely satisfied and a rather comprehensive understanding of the Moon, the relationship of the Earth-Moon system, and the history and evolutionary events in the Moon's progression to its present form will have been obtained. Thus the major scientific objectives of this

FIGURE 3.—Artist's concept of system N.

system are associated with more restricted areas involving specific sites and specific phenomena which are associated with very time-dependent studies. The scientific experimentation includes a large remaining percentage of Q and a larger percentage of Δ and $d\Delta$ which include small percentages of astronomy and biomedical experiments. In addition, lunar resources R first investigated by system N are given increasing emphasis. These requirements derive from the conclusions reached from k up to this time. Even though systems M and N could be extended and uprated, they are inefficient and inadequate to support the expanded scientific program at this point. As a result, the development of a system composed entirely of newly developed components is needed.

A concept for this system is shown in figure 4. In the left background is a shelter-laboratory for four to six men which has been landed directly on the lunar surface from Earth, and was followed by an improved personnel delivery system lander which transported the astronauts to the site. The manned delivery system might be either direct flight or lunar orbit rendezvous (LOR) depending upon the results of studies currently underway. Later cargo trips have provided additional scientific and mission equipment and an expandable shelter

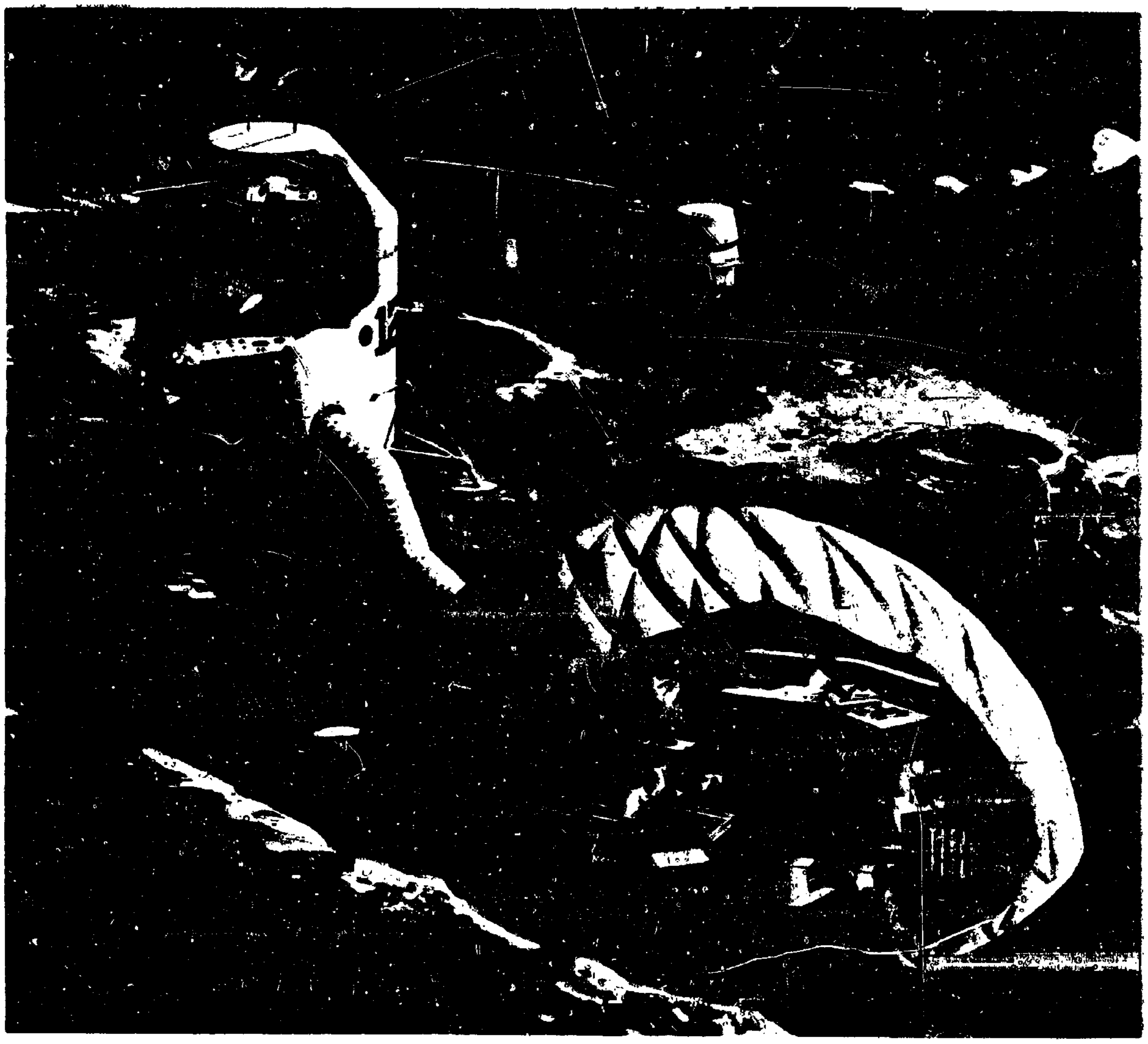


FIGURE 4.—Artist's concept of system *O*.

and maintenance module. Since preceding missions have established that the development of a lunar-base facility at this location is an economically and scientifically worthwhile project, eventual buildup to a large base facility has begun. Stations of this type are envisioned to become practical after development of an efficient unmanned method of landing large payloads directly on the surface. This is considered to be an elementary form of a lunar base. As can be seen, requirements have dictated that it be developed. These requirements are strongly dependent upon man's participation in the effective accomplishment of the mission tasks. Further, these tasks during this phase are strongly time dependent, are varied in scope and complexity, and are relatively immune to preprograming. A fixed base at this site is indicated where man can exploit his advantage on the Moon.

A SYSTEM *P* POSIT

As the requirements for surface staytimes promulgated by increasing emphasis on Δ (astronomy, biosciences, physics) and dΔ in-

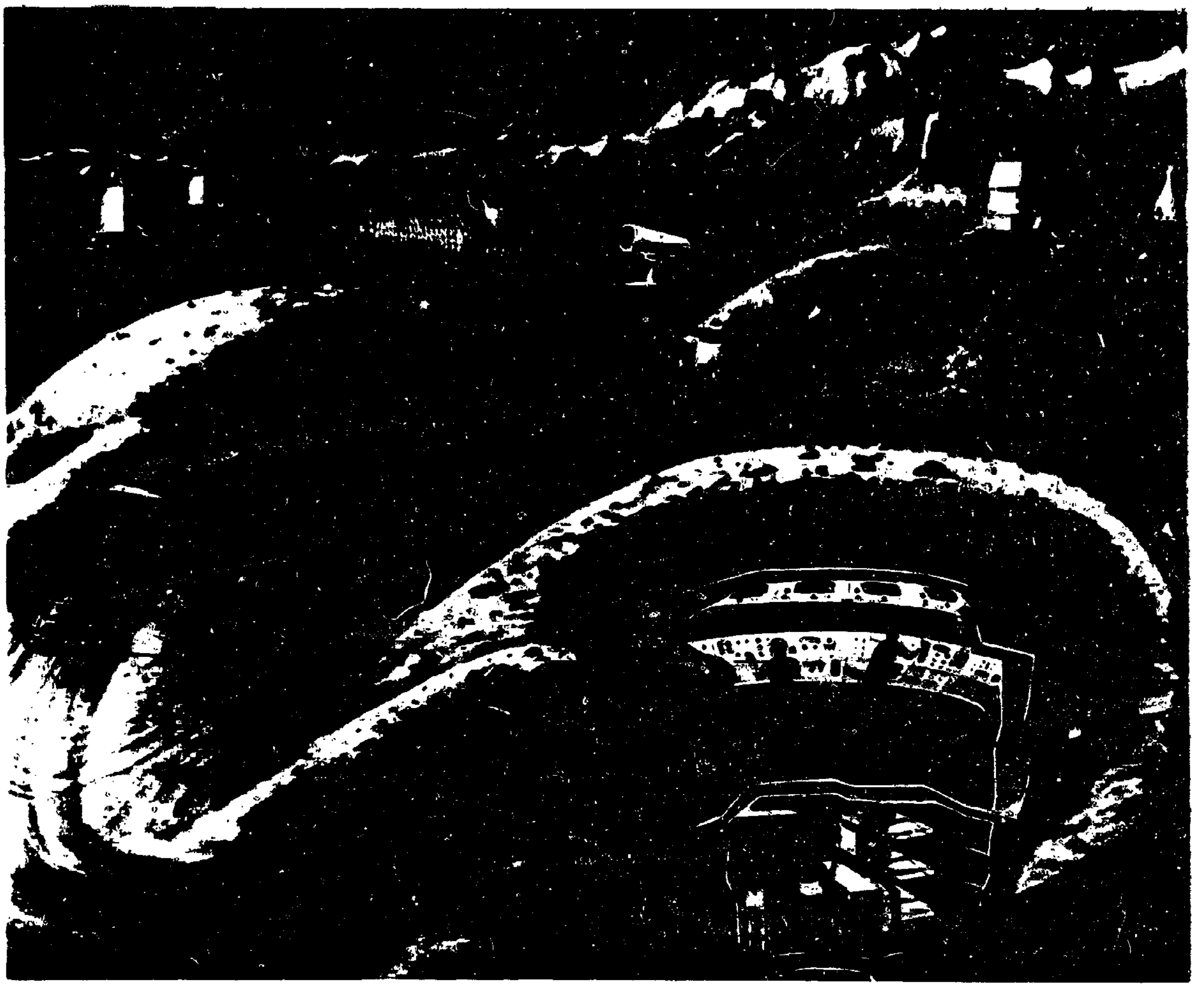


FIGURE 5.—Artist's concept of system *P*.

crease, long-range planning must include studies of concepts similar to that shown in figure 5. This large semipermanent base can accommodate 12 men for periods of a year or more. Furthermore, requirements for exploitation of lunar resources may by this time have been identified, with a parallel impact on increased surface operations capability, staytimes, and manpower levels. At the present time it is difficult to anticipate the evolutionary trend of spacecraft systems which might support a lunar base or to anticipate to what degree there might be new or modified versions of precursor systems.

MISSION PAYLOAD COMPOSITION

As pointed out earlier in this paper, the final step in the analysis is to determine, in terms of the factors making up *k*, the scientific product, the payload composition for each mission which supports systems *L*, *M*, *N*, *O*, and *P*. For the purposes of this analysis, which is an example only, the subdivision of these factors shown in table 4 has been adopted.

If the assumed composition of *k* is known, the individual payload composition can be defined. In the example used in this paper, this was done on an iterative basis by using a simple proce-

TABLE 4.—*Percentage Composition of* k

Component	Percent composition
Q	46
dQ	6
Δ	22
dΔ	7
α	7
dα	2
R	10

dure. The procedure was based on the expectation that, within each system, the early science would extend and expand that which had preceded it and that science conducted toward the planned useful end of the same system would support more sophisticated systems and science to follow. From a total program standpoint, the priorities of table 2 were followed.

The results are displayed in table 5, where the components of k making up each mission are presented. Note the attempt to introduce more complex science (in terms of k components) during the last phases of each system and the emphasis away from Q late in the program. These expected results are based on the indicated assumptions for the analysis. Having these data at hand makes it possible to plot a graph of the scientific accomplishment of each system in terms of percent of k and its components. Such a gr’’ph is shown in figure 6. Notice the emphasis on Q and dQ, the basic scientific questions. This graph demonstrates in a visual way the original premise of this paper, namely, that the logic for the ultimate system, a lunar base (system P), appears at this time to be related solely to the needs of scientific mission objectives which cannot be met by any other system. From a solely scientific view, a lunar base is a requirement only if it is determined

TABLE 5.—*Mission Science Payload Composition*

Variable	System *L*	System *M*	System *N*	System *O*	System *P*
Components of k:					
Q	8	8	10	12	8
dQ	---	---	2	3	1
Δ	1	2	3	4	12
dΔ	---	---	1	2	4
α	1	2	2	1	1
dα	---	---	1	1	---
R	---	---	1	2	7
Percent k per system	10	12	20	25	33
Number of missions	5	4	4	5	3

Variable	*L*	*L*	*L*	*L*	*L*	*M*	*M*	*M*	*M*	*N*	*N*	*N*	*N*	*O*	*O*	*O*	*O*	*O*	*P*	*P*	*P*
Q per mission	2	2	2	1	1	3	3	1	1	3	2	3	2	1	3	3	2	3	2	3	3
dQ per mission	--	--	---	1	---	---	---	1	1	---	1	---	1	1	1	1	---	---	1	---	---
Δ per mission	---	---	---	---	1	---	---	1	1	1	1	1	---	1	1	1	1	---	4	4	4
dΔ per mission	---	---	---	---	---	---	---	---	---	---	---	---	1	---	---	---	1	1	2	1	1
α per mission	---	---	---	---	---	---	---	---	---	1	1	---	---	1	---	---	---	---	1	---	---
dα per mission	---	---	---	---	---	---	---	---	---	---	---	1	---	1	---	---	---	---	1	3	3
R per mission	---	---	---	---	---	---	---	---	---	---	---	---	1	---	---	---	1	1	---	---	---
Total k per mission	2	2	2	2	2	3	3	3	3	5	5	5	5	5	5	5	5	5	11	11	11

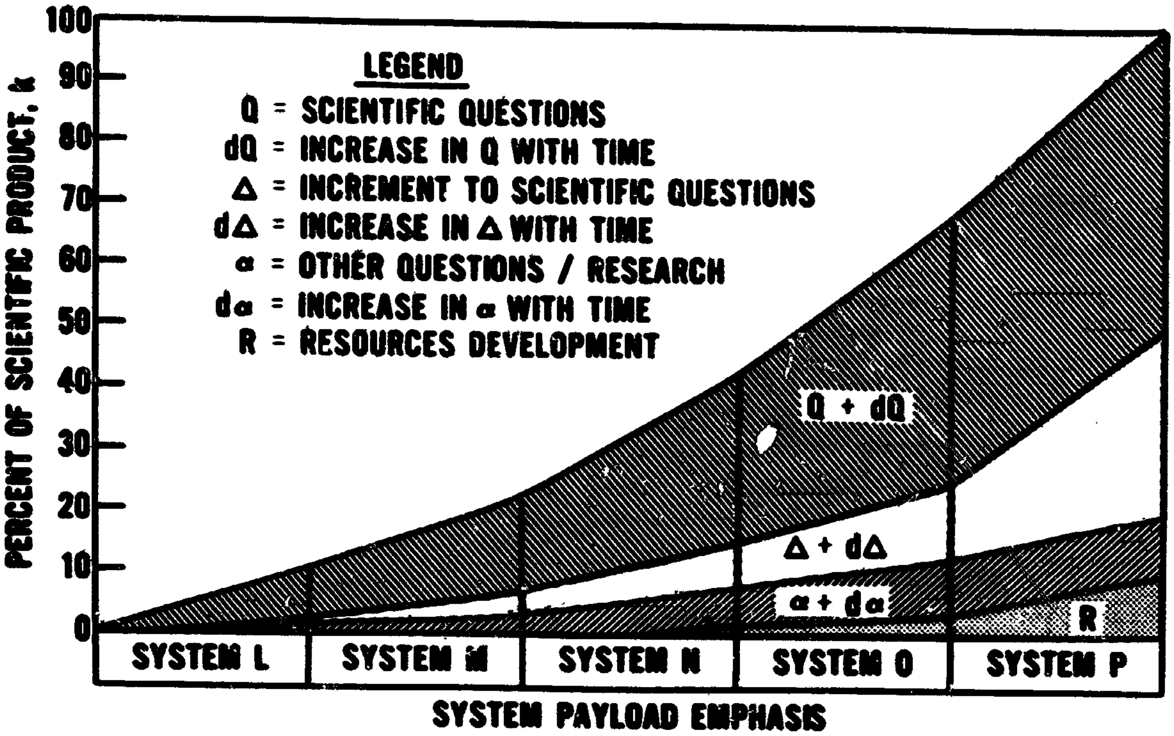


FIGURE 6.—Lunar exploration mode science capability.

that long staytimes at some point on the lunar surface are required to accomplish complex research involving man, time-dependent phenomena, and very sophisticated mission and experiment equipments. It is premature to attempt to define the operational requirements for the base and no attempt has been made in this analysis to do so. If we can sustain the conclusion, however, that a semipermanent base reflects considerably greater scientific contribution, we can at the same time stress that its contribution to technology development is correspondingly greater than that of most other spacecraft systems supporting lunar science and exploration. Many subsystems are involved in the development of a base which may or may not be characteristic of other modes of exploration. Among these are power generation and transmission, communication, and data management.

Power requirements for a base are expected to be much higher than those for systems similar to *N* and *O*. They will probably be met most efficiently by nuclear systems, though missions up to several months or even a year could be supported by solar thermoelectric and solar thermionic power units.

Requirements for communications and data transmission will be very extensive, since the missions will certainly involve links beyond the line of sight. Thus ground and space-based repeaters and groundwave propagation techniques will probably be employed. Since the communication and data systems required for base operations are directly and importantly related to the missions to be performed, the requirements for them must be established on the basis of an integrated exploration and exploitation system. Thus, they must be designed to permit expansion and modification to reflect growth from early systems to the more advanced bases. Furthermore, the load levels will be determined directly by the scientific equipments, both type and number, the data output from them, and the degree of automation of the experiments. Data recording, storage, and transmission, or, in sum, the data management problem looms as one which will require much study and definition in the period of preparation for a base.

SUMMARY AND CONCLUSIONS

An analysis of this kind does not solve problems so much as it serves to make problems more visible. Several of these problems are discussed in the following paragraphs.

The fact that a mission may have to be aborted at any time after its initiation must be recognized. This requires that the more important experiments should be scheduled and flown as early as possible, if all other constraints and considerations are equal. Again, a situation in which the experiment-conducting phase of the mission must be terminated prematurely is a real possibility. In either case, the impact on the program would be either an attempt to repeat the mission, to cancel the payload (and hence its potential contribution to *k*), or to carry over the payload to subsequent systems in the program. For example, assume a mission failure for one mission in each of systems *L*, *M*, and *N*. If the carryover mode is followed, it derives from figure 2 that a cumulative payload carryover of 10 percent *k* must be designed into systems *O* and *P* to accommodate the loss.

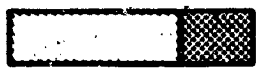
Another vexing problem involves the composition of experiments and instruments in each payload and a determination of what each might contribute to the components of *k*. Expressed in another way, we must determine the experiments and their related instruments which support the science related to *Q*, Δ, *R*, and so on. Again, which experiments and instruments have commonality and what are the common elements? Implications of these considerations on the spacecraft subsystems and on data management are evident.

These problems notwithstanding, a program of systems and missions must be planned and selected together with payloads, experiments, and instruments. This requires that the qualitative objectives of the scientific community be quantified and divided down to a level at which engineering alternatives can be determined and evaluated. Evidently the scientific community will eventually be required to exercise its collective judgment at a more precise level than that of the basic scientific questions. The process of development of a program plan attempts to relate the requirements on the program to the means by which they are accomplished. Considerable study within NASA has produced a much clearer understanding of the means than it has of the specific requirements (as opposed to general requirements), with the result that optimization of the system elements has not been possible. It is evident that, in optimizing for science, mission definition, and payload definition which impact on the systems design must progress much more rapidly than the current trend supposes.

A further remark should be addressed to the components of *k*, the scientific product of lunar exploration. At the present time the component *Q* and the influence of these questions in terms of experiments and instruments is quite well understood, as is the time ordering of the experiments continued in *Q*. This is not true for the other components which relate to such disciplines as astronomy, biosciences, physics, and so forth. Since they, too, will provide a contribution to *k* (approximately 50 percent according to table 4), they must be defined sufficiently well in terms of basic questions, experiments, and instruments to permit their timely incorporation into the payloads so that their anticipated *k* value can be extracted from both the individual systems and the total program.

How these other components might impact on the program is displayed by table 6. Note that even during phase I of a total program period, a number of experiments, operations, and engineering tests must be performed to support both operations and science during later phases. Unless the requirements in disciplines such as astronomy and bioscience are defined early in the planning period and incorporated into the early phases of the operational period, those activities required to support more involved and complex missions later in the program will not be done and

TABLE 6.—*Lunar Science Program Trends*

Component	Scientific-economic benefits	Socio-humanistic benefits	Scientific benefits
Phase	I—Early	II—Intermediate	III—Optimum
Major emphasis	Geosciences	Biosciences	Astrosciences
Disciplines	Geological Geophysical Geochemical	Biological Biomedical Physiological	Astronomy Applied science Engineering science
Experimentation program.	 Phase I support Phase II support Phase III support	 Phase II support Phase III support	 Phase III support
Purpose	Directed toward understanding Earth-Moon system	Directed toward understanding man	Directed toward understanding man's environment

delays, possible fractional payloads, and suboptimum utilization of the spacecraft systems will result. That the simple version of a lunar exploration planning logic presented here is only one of many possible forms and directions which the exploration of the Moon may take is acknowledged. Those interested in participating in this type of analysis may wish to insert their own numbers into the mission variables and may also choose to define the systems in a variety of alternate ways. One caution should be expressed, however: The plan should be structured to permit maximum effective utilization of the Apollo system derivatives and should be consistent with sound scientific objectives and reasonable measures of cost effectiveness.

Last, it must be emphasized that the analysis presented here is empirical in nature. It is hoped that it will prove possible to develop a generalized closed-form mathematical program planning model having application to programs other than lunar exploration.

If sophisticated management and organizational methods and techniques are vital to the success of space operations, they are also equally vital to successful planning for space systems and operations. Thus the approach described can be very useful in long-range planning activities such as lunar exploration and orbital space stations.

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