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FINAL REPORT

REPORT OF THE LSPI/NASA WORKSHOP ON LUNAR BASE METHODOLOGY DEVELOPMENT

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LSPI

FINAL REPORT

REPORT OF THE LSPI/NASA WORKSHOP ON LUNAR BASE METHODOLOGY DEVELOPMENT

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SECTION ONE: INTRODUCTION

The workshop on Lunar Base Methodology Development was convened on August 26-30, 1985 by the Large Scale Programs Institute and co-sponsored by the NASA Johnson Space Center. The purpose of the workshop was to explore the feasibility of developing a computer based methodology to analyze alternative strategies for establishing and operating a lunar base. The workshop participants represented a broad-based group of NASA experts in space transportation, space power, life support, and surface infrastructure, combined with professional operations research workers and computer programmers. Previous studies have been limited by model dependent conclusions and have not provided alternative plans and recommendations for NASA planners. Furthermore, the large number of interdependent systems involved in an advanced program include interactions that are difficult to model. Although the workshop was aimed at the development of lunar base development models, sufficient flexibility may be built into the models to allow for application to additional programs (e.g., a manned Mars mission), as well as the interactions of several programs.

The workshop laid the groundwork for computer models which will assist in the design of a manned lunar base. The models, herein described, will provide the following functions for the successful conclusion of that task:

A. Strategic Planning

Models should involve identification and assessment of strategic variables such as investment schedules, production and service requirements with various mixes of objectives even when the latter are not necessarily consistent with each other--e.g., minimize delays at minimum cost and investment. Highlighting such inconsistencies along with alteration and improvement can improve the selection of optimum strategies for lunar base program design.

B. Sensitivity Analyses

By varying the assumptions of system and subsystem performance, the impact and relative importance of technological and operational alternatives may be evaluated. These analyses will expose the most effective system strategies, and will establish priorities for technology development.

C. Impact Analyses

Variations in performance parameters and system elements may be analyzed to determine the support requirements of specific elements. Suitably arranged models may be used to document and communicate the nature of the lunar base program. Such documentation should include the current status, of course, and it should also incorporate updates as the program develops. The models should also allow testing and predictions with accompanying tests of sensitivity to data to identify the degree of confidence that might be placed in the model (and the program it represents) as well as to suggest improvements in data or alternatives in model details.

D. Documentation

The models will establish a method to document and disseminate information describing the current state of development of a lunar base. This will involve documented, user friendly "executive models" which can be run on personal computers.

SECTION II: METHODOLOGY DEVELOPMENT: TOP LEVEL PHILOSOPHY

A. Strategic Planning Objectives

The principal objective is the development of computer based models that will enable NASA to effectively and efficiently examine the impacts of various long range options for future space missions which interact with the moon. The desired models should be able to provide: (1) a graphic representation of the evolution (in both time and space) of advanced space missions that may interact, (2) investment, cost, and schedule estimates for developing lunar bases, and (3) identify and highlight performance parameters against which a set of possible program goals can be compared. Such models should also provide quantitative evaluation of tradeoff possibilities so that it will be easy to analyze the effect of: (1) alternative space missions, (2) alternative lunar base objectives, (3) alternative technologies, (4) alternative elements or subsystems, and other factors such as learning, alternate priorities, and possible contacts with other programs--including international cooperation. The results of these analyses can then be used to develop long range plans for NASA. Near term impacts can be determined for space station, orbit transfer vehicle, and earth-to-orbit delivery vehicles. Recommendations may be developed for prioritization of technology developments. To accomplish all of this, a practical general purpose tool for NASA will also advance the state of the art in both modeling and in strategic planning. Hence, components of the models and techniques developed will have application to other large scale program planning activities in NASA and elsewhere.

Model development and implementation will probably need to go through several stages. A first stage will consist of defining the problem in adequate detail and initiating the assembly of data in conjunction with the NASA staff. A second stage will consist of analytical formulations accompanied by small numerical prototypes. This will permit testing and evaluation in a manner readily understood not only by the modelers but also by the planners and decisionmakers. The development of a full-scale model should be undertaken at the next stage. If substantial communication and review is incorporated into the process, implementation and placement will follow the modeling activity in a natural and easy manner. If this is not done in an adequate manner, there is likely to be a great deal of frustration and possible failure of the modeling effort.

B. Upper Level Model Description: General Characteristics

The inputs to the models will be key specific objectives of the lunar base program as well as lunar base elemental structure with parameters. The models are composed of a set of relations and functions that describe the interrelationships of each lunar base element with every other lunar base element. When solutions are found which satisfy the input objectives, cost and schedules are determined and a set of evaluation parameters are derived. An upper level flow is shown in Figure II-1a. Figure II-1b provides a description of the flow. The model must be interactive to allow many optional schedules, technologies, techniques, or design philosophies to be considered. Figure II-2 shows the flow in greater detail.

C. Matrix Interrelationships

The heart of the model is the matrix of interrelationships generalized in Figure II-3. Each cell contains three sets of functional relationships. The first set is a collection of optional functions that relate the row element to the column element. There can be several functions which are user selected (or capability for new ones to be input by the user) and which assume different technology or design philosophy. The second set of relationships are temporal data which indicate the time phasing of the elements. In general, these data are to be used for the scheduling routines. The third set of functional relationships is data or datasets for input into the cost routines. For example, Figure II-4 is a description of the contents of matrix box 5,2. When the models have completed iteration to stable and self-consistent solutions, the design points are output for the next set of calculations. Example outputs are indicated in Figures II-5, II-6, and II-7.

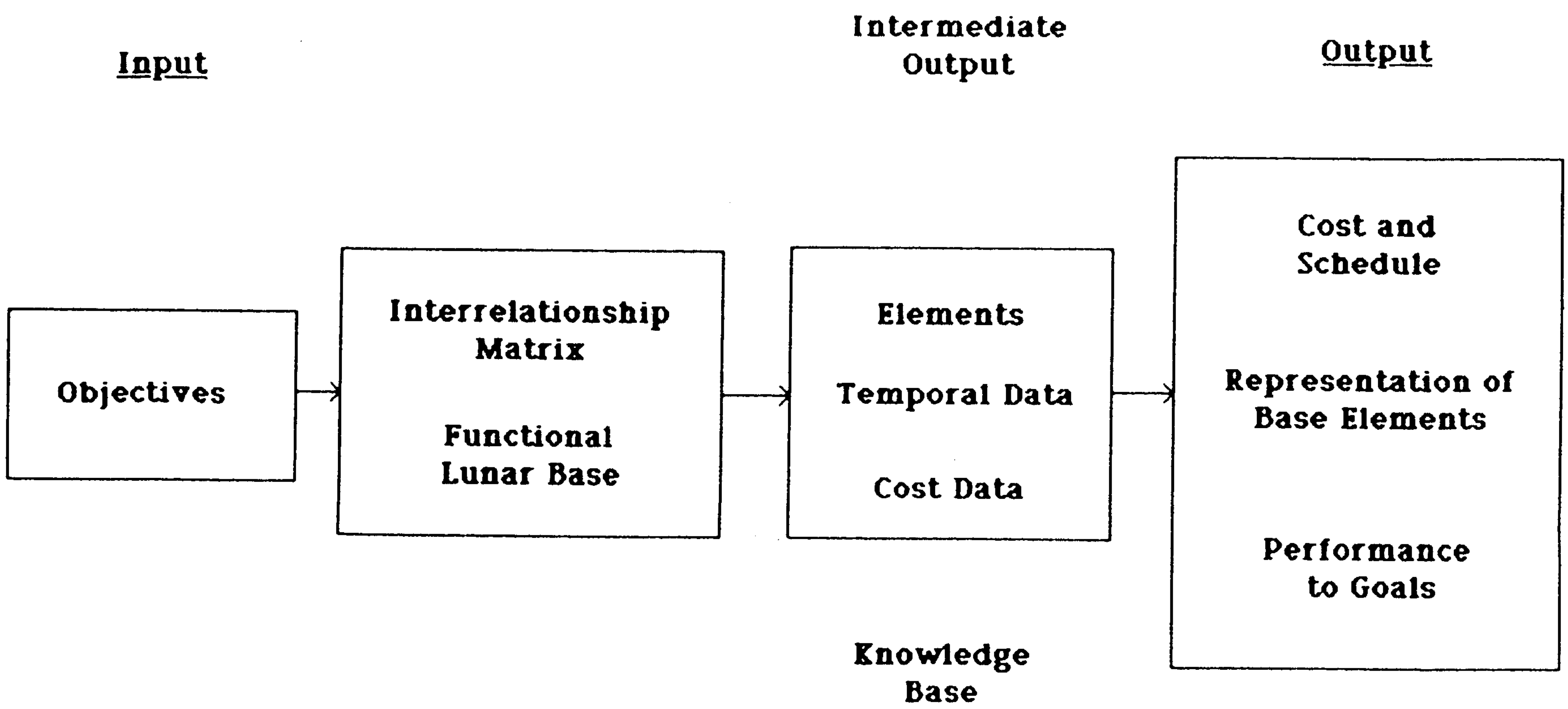


Figure II.1a. - Upper Level Flow Diagram

Input (Objectives) → Requirements → **Lunar Base Surface Elements** → Base Definition → **Output**

Input (Objectives)

- Resource Development
- Services
- Increased Knowledge of Solar System
- Generate New Technologies
- Physical Science Research
- Commercial Development
- Extraterrestrial Habitation/R&D

Lunar Base Surface Elements

- Habitats
- Surface Transport
- Power
- Space Transport
- Space Facilities
- Communications
- Mining
- Manufacturing Plants
- Experiments
- Life Science Experiments
- Material Science Labs

Output

- Cost & Schedules
- Performance To Goals
  - Comprehensive Security
  - Science
  - Economic Opportunity
  - Human Presence
  - Insipation/National Pride and Prestige
- Impacts
  - To STS
  - To SS
  - To ETO
  - To OTV
- Technology Dev. Recommendations

Figure II.1b - Upper Level Functional Description

FIGURE II-2: DETAILED MODEL FLOW

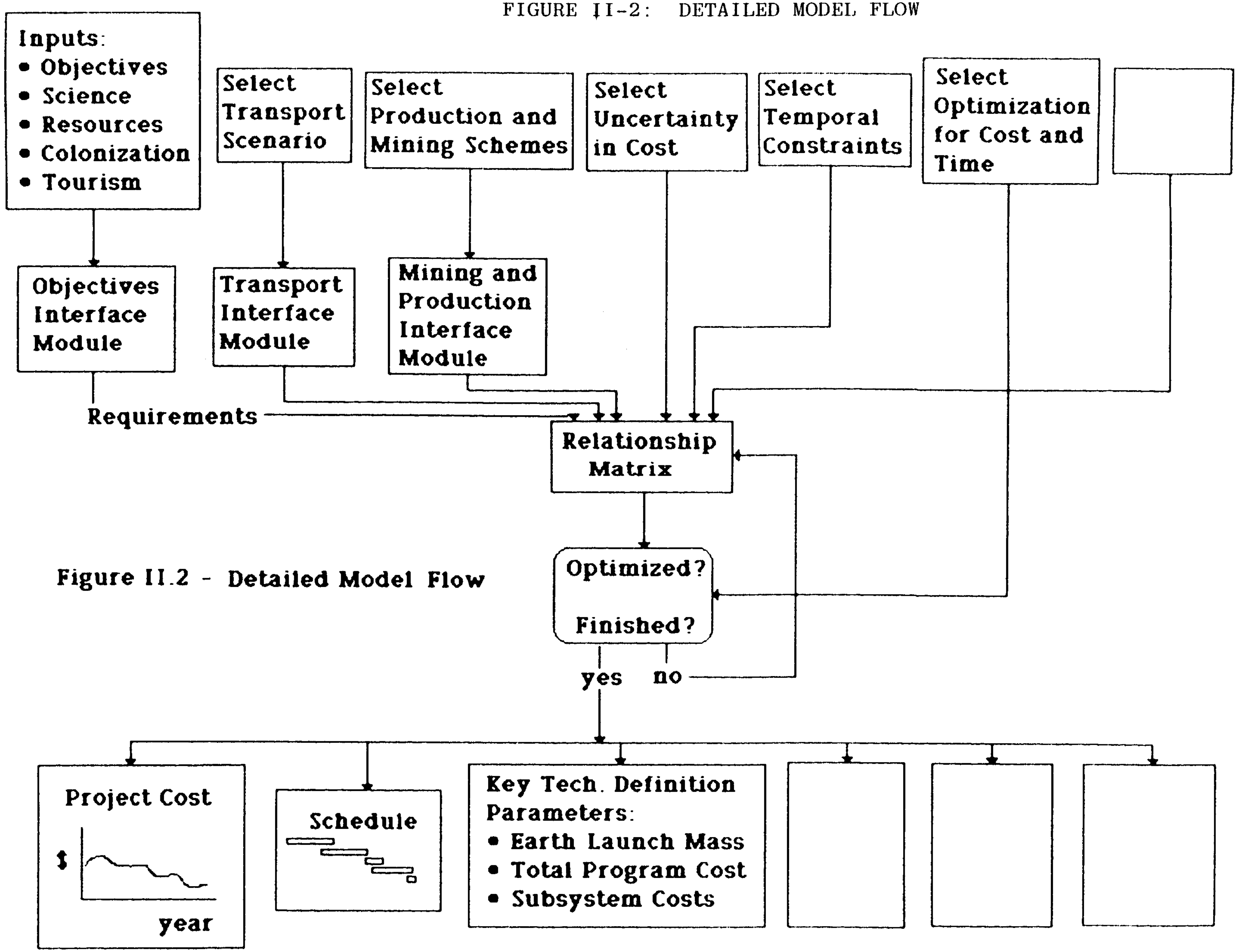
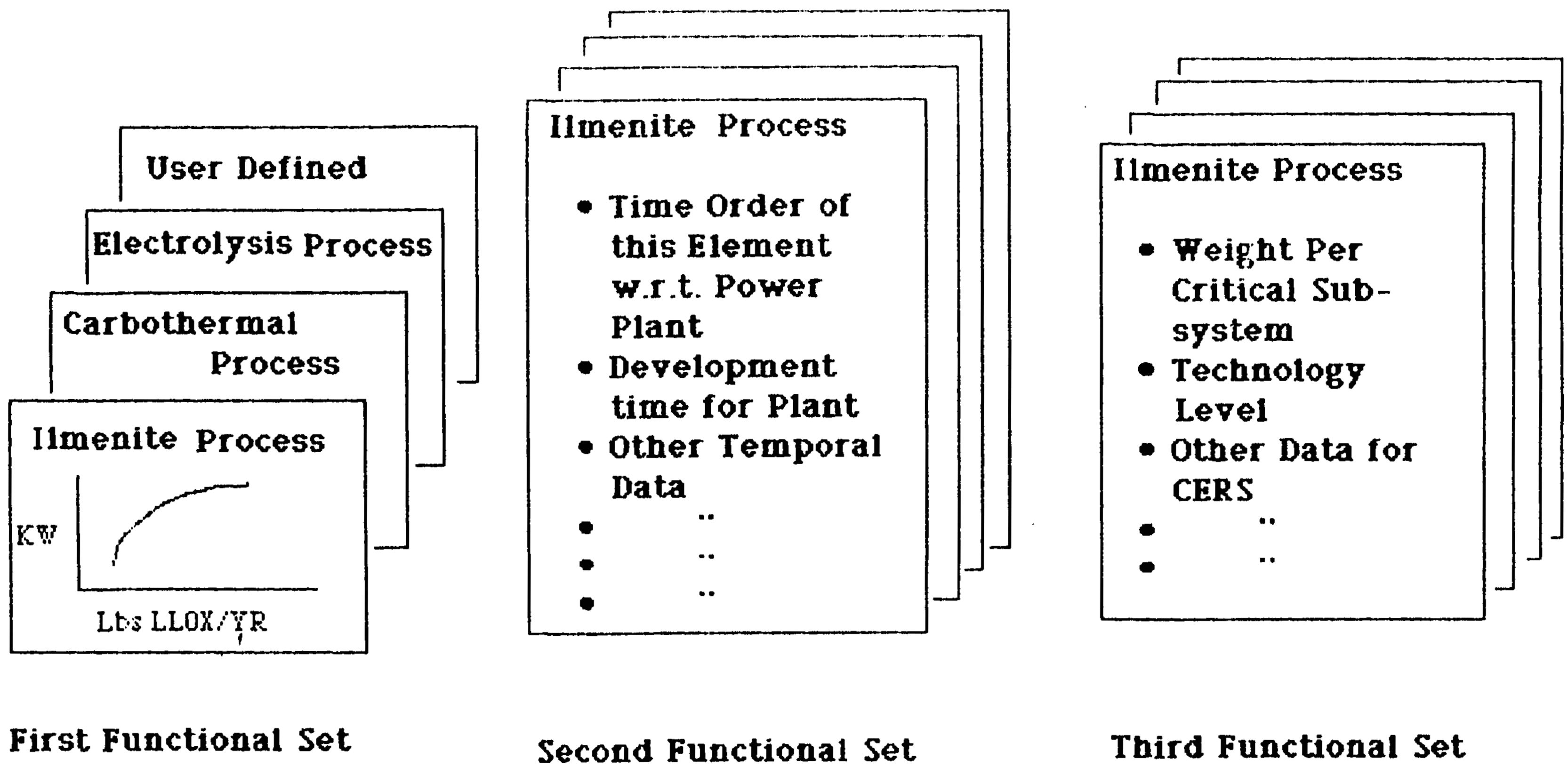


Figure II.2 - Detailed Model Flow

		HABITAT	POWER	SURF X-PORT	SPACE X-PORT	LLOX PLANT	COMMUNICATION	MINING	CONSTRUCTION EQUIPMENT	MANUFACTURING	EXPERIMENTS	LABORATORIES	OUTPUT
HABITAT	1												
POWER	2												
SURF X-PORT	3												
SPACE X-PORT	4												
LLOX PLANT	5		See Fig. 4										
COMMUNICATION	6												
MINING	7												
CONSTRUCTION EQUIPMENT	8												
MANUFACTURING	9												
EXPERIMENTS	10												
LABORATORIES	11												

FIGURE II-3. AN EXAMPLE OF THE INTERRELATIONSHIP MATRIX



Matrix Element for Row 5, LLOX Plant, and Column 2, Power Plant

Figure II.4 - Contents of Matrix Box 5,2

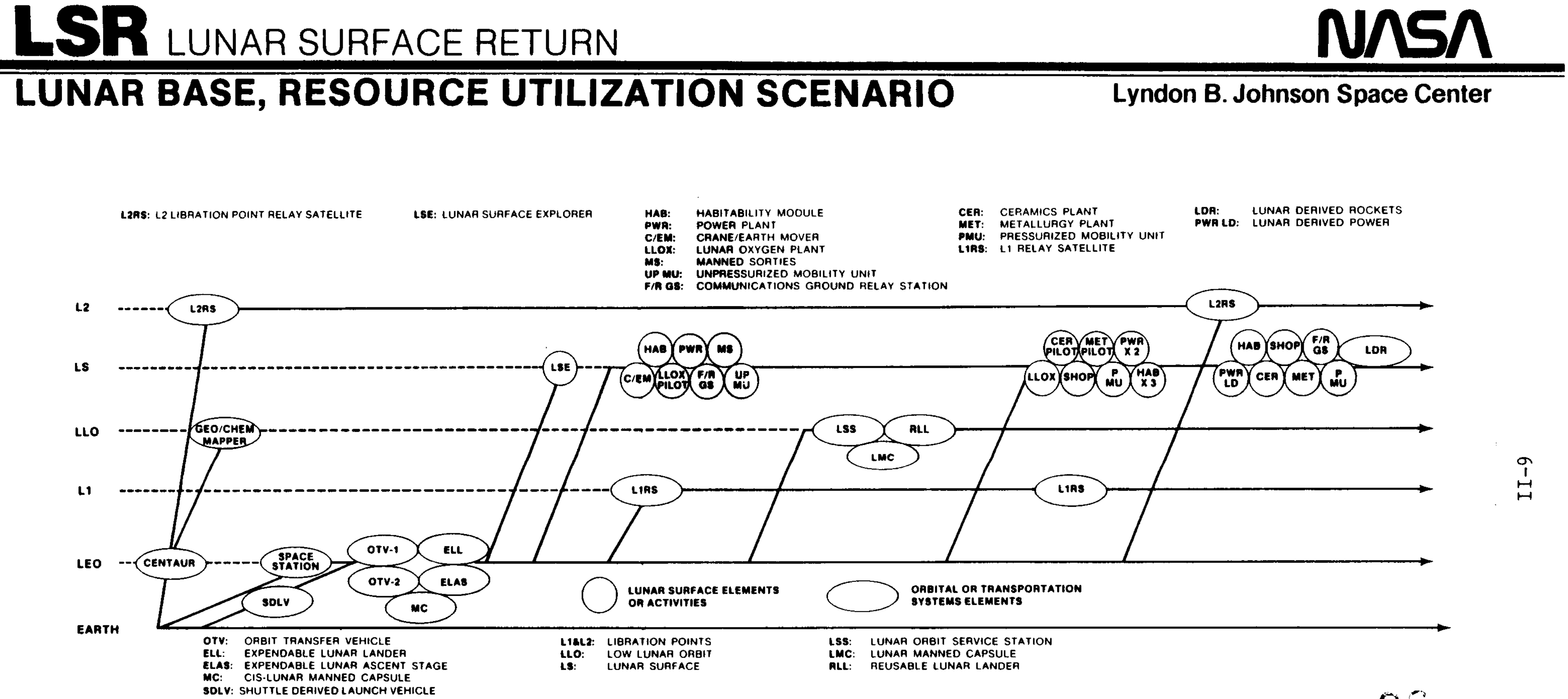


Figure II-5: Example of a Temporal and Spatial Plot of Lunar Base

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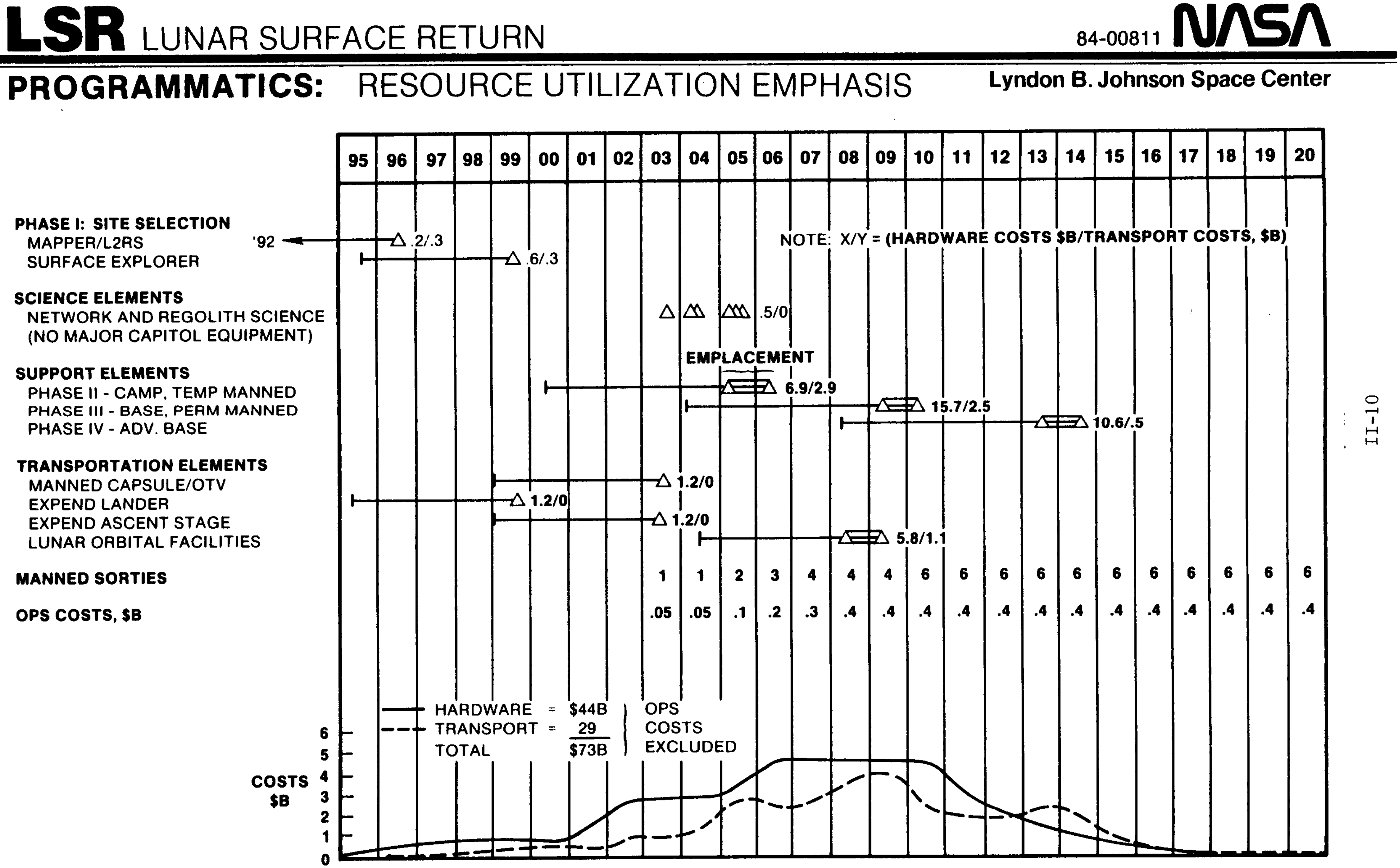


Figure II-6: Example of a Cost and Schedule Plot

MAXIMUM SIMPLE INCREMENTAL
MISSION ("TENTPOLE MISSION")

- **Earth Launch Requirements:**

  Mass = ______, Volume = ______
  Mass/Year = ______ (or a Plot)

- **Total Program Cost: $______**

- **Cost of Lunar Products**

  - **Raw Material**

    - In LEO = $/LB
    - In GEO = $/LB
    - In LI (or LLO) = $/LB

  - **Manufactured Products**

    - In LEO = $/LB
    - In GEO = $/LB
    - In LI (or LLO) = $/LB

- **Science Man Hours Available = ______**

  Cost = ______ $/Man Hour

- **Space Station Impacts**

  - Thruput: LBS, LBS/Year, or Plot
  - Number OTV's Utilized
  - EVA and IVA Man Hours

Figure II.7 - Typical Goal Performance Parameters

SECTION III: MODEL USERS, FEATURES, DESCRIPTIONS, COMPUTER IMPLEMENTATION AND MANAGEMENT

The following section describes (A) the potential user community of the proposed modeling system, (B) the user interface and model features as seen by the various sections of that community, (C) model descriptions, (D) system implementation, and (E) model management.

A. The User Community

Potential users of the lunar base model may be found at three different levels. The top level consists of program managers and their staffs who are interested in determining how the operation of one system, such as a lunar base, interacts with the operation of other potential systems, such as a manned Mars mission.

The second set of potential users consists of project managers and their staffs, outside contractors and researchers interested in analyzing various lunar base scenarios in order to meet specific mission goals and objectives.

A third set of users consists of subsystem experts, primarily outside contractors, but also NASA staff members, who are interested in analyzing different system configurations in a lunar base scenario in order to determine the value of possible technical innovations as part of the process of evaluating specific lunar base system configurations.

B. Model Features

Properties considered desirable for such models by the potential user communities are as follows:

(1) System Accessibility. The modeling system must be easily understood by the entire user community. Potential users should be able to use the model effectively and be able to learn to do so in a reasonable amount of time (e.g., no more than a day or two). It

should not be necessary for outside contractors or university researchers to buy specialized hardware or software or to hire professional programmers in order to use the modeling system and contribute to the model definition.

(2) System Flexibility. As new data are generated and as ideas on the nature of the lunar base progress, it will be necessary to add and delete system elements. The structure and parameters of the element characteristics will also change. The modeling system must be able to incorporate these changes without requiring modifications of the core of the modeling system. The model will allow flexibility in the level of detail exercised. For example, one might want to do sensitivity analyses in a limited area, keeping some model elements fixed while looking at variation in others.

(3) Self-Documenting. The modeling system must include an on-line help facility that will allow potential users to obtain the sources and to secure explanations of the relationships which are being employed within the model. For example, the definition of Mass Payback Ratio (MPR) used by the model could be called up for inspection. A brief text explanation of the inputs, outputs, and how the formulae were derived should be associated with each system element and each of the subsystems that make it up. These features are particularly important to subsystem experts who will also be using models that describe various system elements and who need a thorough understanding of underlying assumptions in order to draw conclusions and interpret the model. Other members of the user community, such as program managers, will often use the modeling system to derive summary level figures of merit. Further detail on these, too, should be available for display when requested by the user. A listing of standard output products is required.

(4) Ease of Use. Because the modeling system needs to be accessible to a wide variety of users, it must be easy to use. The model development must adhere to the basic principles of user-friendly

systems. This implies that the modeling system will be menu-driven with a heavy graphics interface. Naturally, extensive documentation (in addition to on-line help facility) will be provided.

(5) Reporting Capabilities. A number of reporting capabilities should be included in the modeling system. Output from the system will be used in final reports, proposals, and presentations to other members of the field as well as the public. This implies that output from the modeling system must take several forms. Output data in table, graph, and chart form, pictures of system configurations, and lists of the assumptions and relationships that describe the specific scenarios being studied are examples of required formats.

(6) On-line, Interactive User Interface. Users of the modeling system at upper levels will interact with the modeling system via interactive, on-line programs. This implies that execution speed must be reasonable. Overnight runs in order to calculate outputs each time a system parameter is changed are not acceptable. Some off-line modeling tools may be provided to aid reseachers in model definition. For example, persons involved in process plant research may require a separate program to aid in the definition of a base process plant. It should be possible to service such requests interactively, although further detail, when required, may be obtained through batch (overnight) operations.

(7) Identification of Areas of Uncertainty. The "behavior" of some system elements is better defined than others and some data are much less certain than other data. When uncertain data or relations are used, a mechanism should be provided to indicate the level of uncertainty involved or at least include allowable ranges which the user can specifically inspect. For example, a researcher analyzing the system configuration of the space transportation system might include other system elements in the scenario. Protective safeguards are also needed. If the calculations defined for these other elements have a large amount of uncertainty, a flag should be triggered to

alert the user that the accuracy of the output is questionable within certain ranges of values. This feature would let an expert in one system element utilize the current level of knowledge of the experts in another system element without being led astray or having to become an expert in all elements of a lunar base program.

(8) Test Cases. Previous models of lunar propellant production schemes have been developed under the supervision of the NASA Johnson Space Center by Eagle Engineering, Inc., Earth Space Operations, and others.

Figure III-1 illustrates the methodology used by Stump, et al, for a given scheme for returning propellants to LEO with input data being chosen from a variety of options and the results then subjected to a series of increasingly complex "filters" that can eliminate uneconomic schemes. First, best case and average mass payback ratios are calculated. Mass payback ratio is roughly "what you get back (propellant) over what you send out" from LEO in terms of mass. This ratio must be greater than 1.0. Following mass payback ratios, increasingly complex cost calculations are used to compare lunar launched $/Kg cost to Earth launched $/Kg. The completed model is then applied to a variety of scenarios for oxygen delivery to LEO, including some which include lunar hygrogen and advanced propulsion. The propellant production scenario can provide a test case to be used in developing and testing the model.

C. Model Descriptions

This section describes the types of models which will comprise the modeling system. The list is not meant to be exhaustive--other model types may be necessary or desirable. Model type descriptions are sketchy. Further elaboration will be provided later as the methodology matures.

Single Period Scenario Analysis Model. The purpose of this model is to support the steady state analysis of a specified lunar base system. Inputs to the model include:

1. System objectives.
2. System configuration or structure.
3. Models of systems elements.
4. System parameters.

Outputs of the model are:

1. System operation variables.
2. System performance variables.
3. System cost variables.
4. Sensitivity analyses.

A brief description of these items follow.

Inputs. System objectives must ultimately be expressed in specific numerical terms, e.g., as tons of Lunar LOX to be delivered to LEO per year. These may be input directly by the user, or may be derived from various "markets" which the system is serving, e.g., LEO servicing, LEO space station, SDI, Mars Missions, etc. System configuration or structure is a complete specification of what system elements are included in a particular study and the type of each element. System elements include the surface infrastructure, Earth launch systems, lunar launch systems, and OTV systems. In the case of Earth launch systems, element types include shuttle, SDV, or HLLV. System element models specify the input/output relations of each system element. An example is annual power consumption of lunar LOX plants as a function of annual LOX production. It is important to note that there are two levels of element models: aggregated (or simplified) and detailed. Initially, we will probably use aggregate models, consisting of a few graphs, formulas, or parameters. Detailed models go more deeply into the physics of the various devices and processes, and are much more complex. Outputs of these detailed models will be used to update the aggregate models. System parameters specify these elements in adequate numerical detail to do the required calculations. They include items such as people per habitat, power requirements or habitats and production facilities, and vehicle characteristics such as O/F ratio, specific impulse, and vehicle mass.

Outputs. System operation variables include power consumption, LLOX production, person and cargo trips/year of various vehicle types, etc. System performance variables are either a subset of system operation variables or are easily derived from them. An example is metric tons of lunar oxygen delivered to LEO, mass payback ratios, etc. Costs include transport costs, system lifetime cost, emplacement costs, etc.

Internal operation of this model is straightforward computation of system outputs from system inputs. If there are simultaneous equations, they appear to be few and should not pose a significant computational burden. Given these outputs, it is easy to perform sensitivity studies, either by performing multiple runs with different inputs or by automating this capability, e.g., by stepping a parameter through a range and displaying the resulting outputs, perhaps in graphical form.

Program Planning and Costing Model. This model is closely related to the single period scenario analysis model. Its inputs include:

1. System configuration or structure.
2. System parameters.
3. A list of activities required to create each system element. For each activity, one must specify its immediate predecessors (the activities which must be done before it can be done), its duration, and its cost. This data is sufficient to construct a PERT graph showing the time-phasing of all activities needed to construct the base.

Its outputs include resource requirements and costs for each year in the planning horizon. See Figure III-1 for a description of how the scenario analysis and planning models work together.

Goal Programming or Other Optimization Models. These models are a natural follow-on from the previous two, and use most of the same inputs. All models in this category will vary certain system parameters (which are assumed fixed in the previous two models) in order to come as close as possible to meeting one or more system goals, or to meet such goals at minimum costs, etc. In any case, the model will compute a best set of system parameters subject to certain constraints. "Best" may mean minimal cost or the constraints may relate to achieving certain levels of performance or some combination of cost and performance constraints could be specified. Alternatively, "best" may mean "minimize the sum of weighted deviations of actual system performance from stated goals." If the only things to be varied by the optimizer are system parameters, which can take on any values within stated limits, there are several optimization software systems which can be interfaced with the single period scenario analysis model that are capable of performing the optimization. Such optimization should be thought of as an automated case study capability. Instead of the model user specifying the next scenario or case to analyze, the optimizer specifies a sequence of cases (really sets of adjustable parameter values), which come closer and closer to optimizing the objectives while satisfying the constraints. There are several ways to deal with multiple, conflicting objectives: goal programming is one such approach. See figure III-2 for a description of how the scenario analysis and optimization models fit together.

Simulation of Base Operations. A simulation model would focus on the details of lunar base system operations over a relatively short period of time, e.g., several days to several weeks. Such a model would simulate all events involved in the daily life of the system, e.g., vehicle landings, orbital rendezvous, transport of lunar rock to manufacturing facilities, etc. Its purpose is to precisely analyze detailed system operation. In this way, bottlenecks can be identified, and costs can be more precisely measured. Such models are commonly used in analyzing flows of jobs through factories, vehicle traffic and queues in ports, etc. There is a wide variety of software available for such simulations, some of which runs on PC's, uses graphic displays, etc.

D. System Implementation

There are two major hardware vehicles for system implementation: personal computers (e.g., Apple Macintosh) and mainframes (e.g., VAX machines). The Macintosh provides excellent user interface and graphics capabilities, and has substantial computational capabilities, surely enough for aggregate versions of the system element models. In addition, interacting with the modeling system on a personal computer provides a level of flexibility for the user community that is highly desirable. Data may be passed between the modeling system and other analysis systems that are readily available and familiar to the user.

On the other hand, a mainframe such as the VAX would allow many users to interact with a large on-line data base. Most NASA employees have access to a network of VAX's. In addition, there is more room for growth if the modeling system ever grew substantially beyond the current expected computational levels.

On the software level, there are several alternatives for implementing the modeling system. Most of the requirements for the upper two levels of the proposed system could be easily implemented using standard decision support software such as IFPS. This software provides a high-level, English-like language for describing a model which would be more accessible to the users than a general purpose programming language (e.g., Fortran or "C"). Excellent data management, graphics, and reporting capabilities are built into such systems. In addition, IFPS has an optimization module and can incorporate user-defined Fortran subroutines. There are mainframe and personal computer versions of IFPS.

An alternative is to develop a customized software program. Such a program could be optimized (in a programming sense, not a modeling sense) to run the required equations more efficiently. By using a standard general purpose programming language such as Fortran, an extra degree of portability is added.

The disadvantage of customized software is that potential model users must either accept the model as defined or hire professional programmers to create new "subroutines" to describe their innovations. Some customized software is necessary in order to meet the user requirements as stated during this workshop. However, writing an entire modeling system from scratch may not be the most efficient use of resources. More design work is needed before a decision can be made as to which requirements are best met by custom software and which by decision support and other analysis packages.

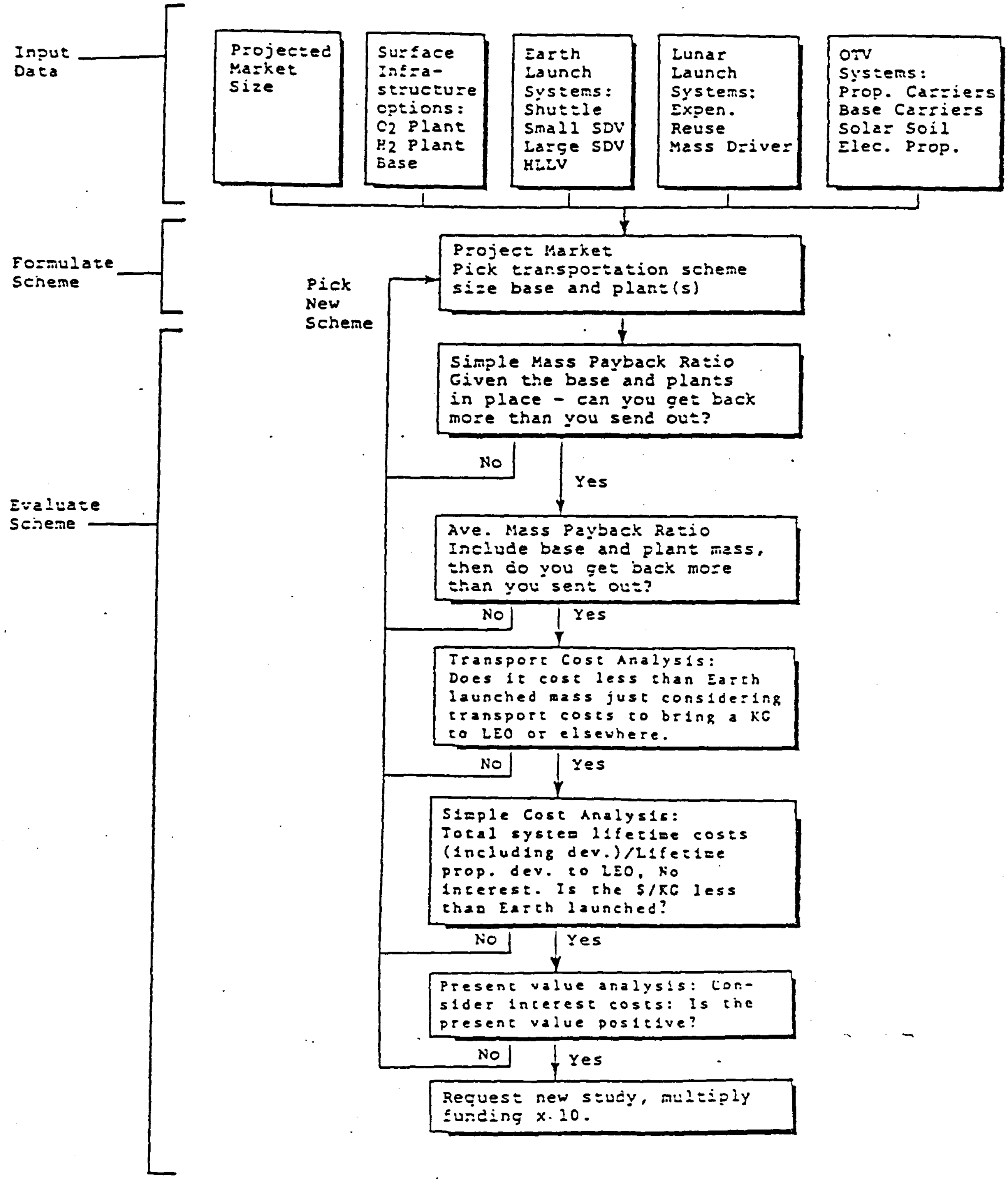
E. Model Management

When the model reaches "maturity" it should go under configuration control. Permanent modifications to the single period scenario analysis model and its associated program planning and costing model will be controlled by a NASA group. Only approved changes will be incorporated into the permanent model. Individual model components can be easily accessed and changed by interested users, but these changes will be temporary until they are thoroughly scrutinized and accepted.

In order to best manage the growth and modification of the core an in-house NASA staff member should have responsibility for participating in the modeling process. As knowledge about the lunar base grows, the types of models and the uses they are put to will grow. In-house modeling expertise could be used to insure that the models used match the requirements of their users.

It is anticipated that, as the model becomes more widely used, researchers utilizing the model will develop new data and potentially new relations, some of which may suggest changes to the model. An archival system for collecting new data, novel uses of the model, arguments for changing the model, etc. should be designed into the program at the start. Along with configuration control, this should help document the development of the model and help avoid duplicative work.

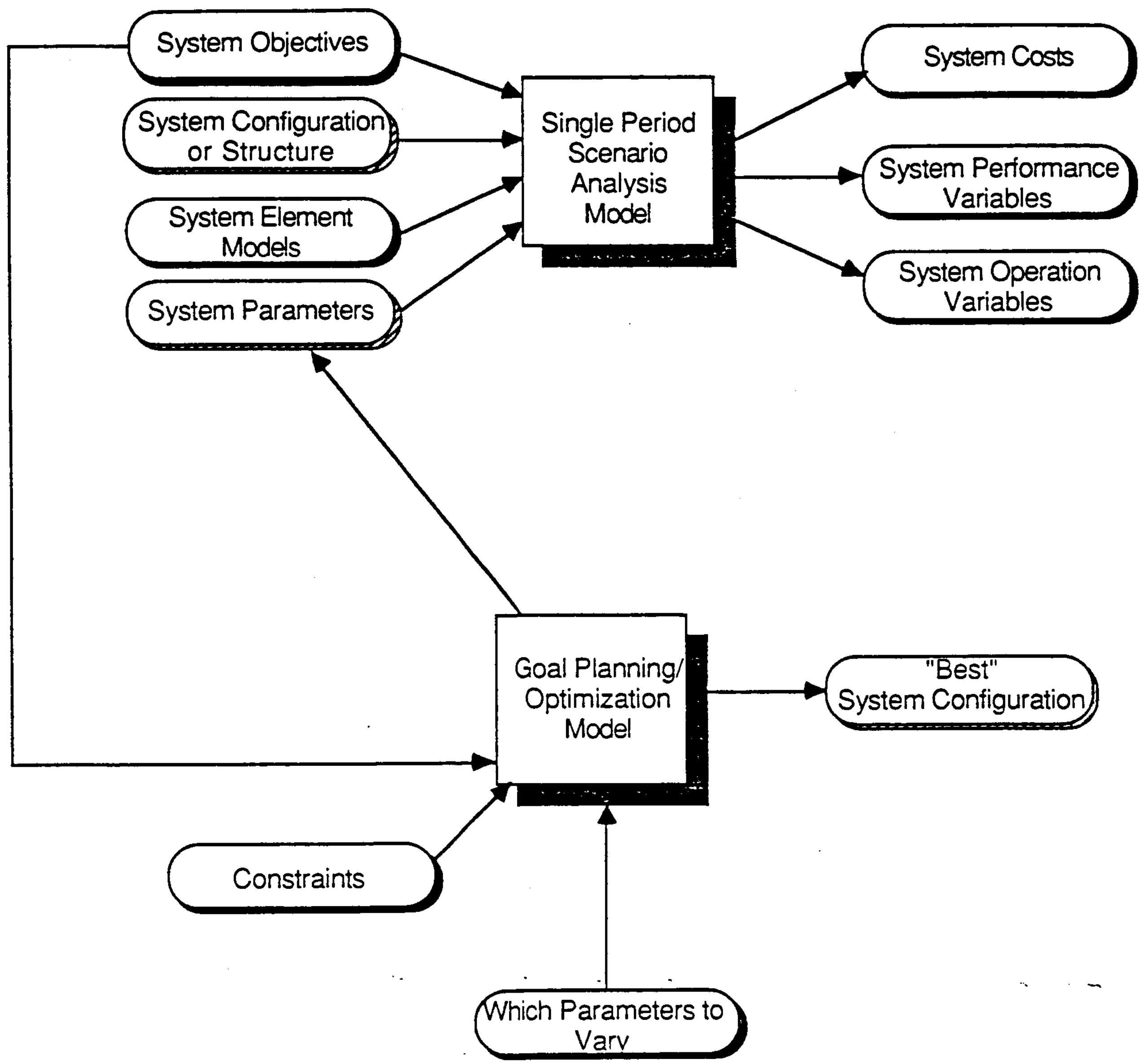
FIGURE III-1



Input Data
Projected Market Size
Surface Infra- structure options: O_2 Plant H_2 Plant Base
Earth Launch Systems: Shuttle Small SDV Large SDV HLLV
Lunar Launch Systems: Expen. Reuse Mass Driver
OTV Systems: Prop. Carriers Base Carriers Solar Soil Elec. Prop.
Formulate Scheme
Project Market Pick transportation scheme size base and plant(s)
Pick New Scheme
Evaluate Scheme
Simple Mass Payback Ratio Given the base and plants in place - can you get back more than you send out?
No
Yes
Ave. Mass Payback Ratio Include base and plant mass, then do you get back more than you sent out?
No
Yes
Transport Cost Analysis: Does it cost less than Earth launched mass just considering transport costs to bring a KG to LEO or elsewhere.
No
Yes
Simple Cost Analysis: Total system lifetime costs (including dev.)/Lifetime prop. dev. to LEO, No interest. Is the $/KG less than Earth launched?
No
Yes
Present value analysis: Consider interest costs: Is the present value positive?
No
Yes
Request new study, multiply funding x 10.

Optimization Option - Later Years
Model Relationships

FIGURE III-2



section). The overall schedule for this working group is to be approximately six months with bi-monthly meetings for the total group and more frequently, as needed, by specific sub-groups. The final meeting is expected to assess the needs for more comprehensive models and provide for any follow-on efforts.

B. Definition of Detailed Architecture

It is envisioned that the Lunar Base Model Architecture will be developed during and through the working group activities, but as a point of departure, an example architecture is suggested in figures 3 and 4. Figure 3 delineates the concept of the Executive Model, Summary Technical/Programmatic Modules and Detailed Technical/Programmatic Modules. The Executive Model with the Summary Technical/Programmatic Modules will be the basic operating system for planning and will, as an objective, be compatible with a Macintosh 512K PC or equivalent. A set of typical inputs and outputs from this Executive Model is shown in figure 4. It is the function of the working group to refine the architecture and to decide how/where the Detailed Technical/Programmatic Modules reside. A possible scheme, places Executive and Summaries in a PC and the Detailed Modules reside in a mainframe accessible via modem for detailed trades as required. As a minimum, the total program will be required to be maintained by an appropriate group or individual for the configuration control.

SECTION IV: PLAN FOR FUTURE ACTION

A. Implementing the Modeling Process

Building on the results of the Workshop on Lunar Base Methodology Development, a Lunar Base Modeling Working Group is to be formed to focus technical and strategic or programmatic models toward an overall planning model for Lunar Base development. This working group will assess the feasibility of modeling that will allow integrated lunar base planning and strategic analyses. Models should incorporate technical and programmatic (cost and schedule) modules that describe the parameters and interrelationships among transportation, base habitat, science, manufacturing, power, etc. Sensitivities to technology levels and definition uncertainties can be determined and the results can provide a focus for future studies planning and technology investment strategies.

The proposed organization of the working group is shown in figure IV-1. It is anticipated that this group will meet on a bi-monthly basis for an initial period of six months. During this period, the working group will coordinate the development of both the execution program as well as the technical and programmatic modules, and will continually assess the feasibility of progressing to more detailed model structures. The working group will bring the computer modelers and the technical-programmatic disciplines together to refine interfaces (requirements, inputs, outputs, formats, etc.).

The schedule of activities is shown in Figure IV-2. Formation of the working group is planned to be complete in late September and the first meeting will be scheduled at that time. The general meeting objectives are to assess the overall model architecture and to review proposals for the Executive Model based upon the results of the August 26-30, 1985 La Jolla Workshop. These proposals will be prepared by the computer modeling sub-group and will be accompanied by preliminary specifications for the summary modules (described in the next

Figure 1. Lunar Base Modeling Working Group

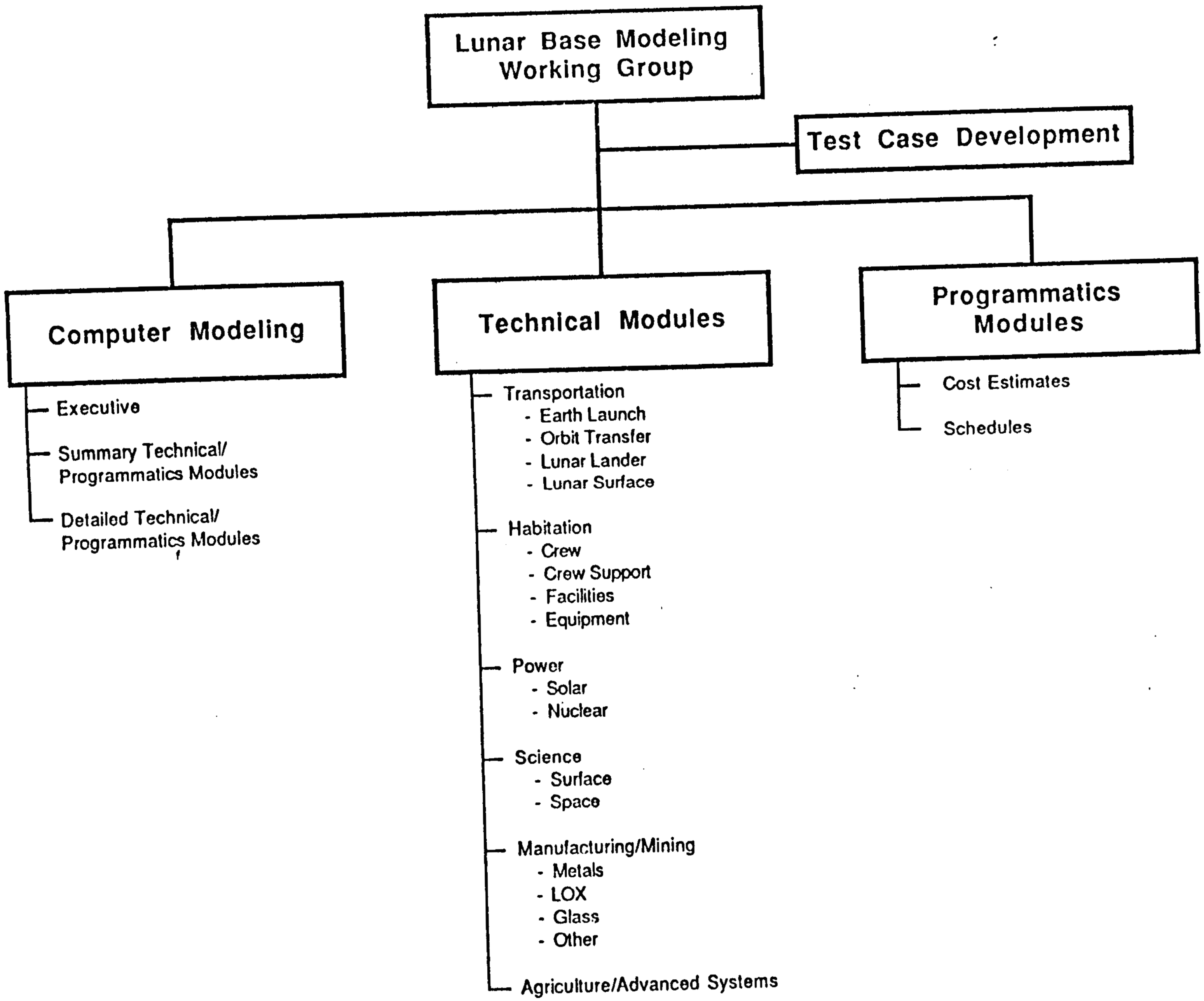


Figure 2. Lunar Base Modeling Working Group Schedule

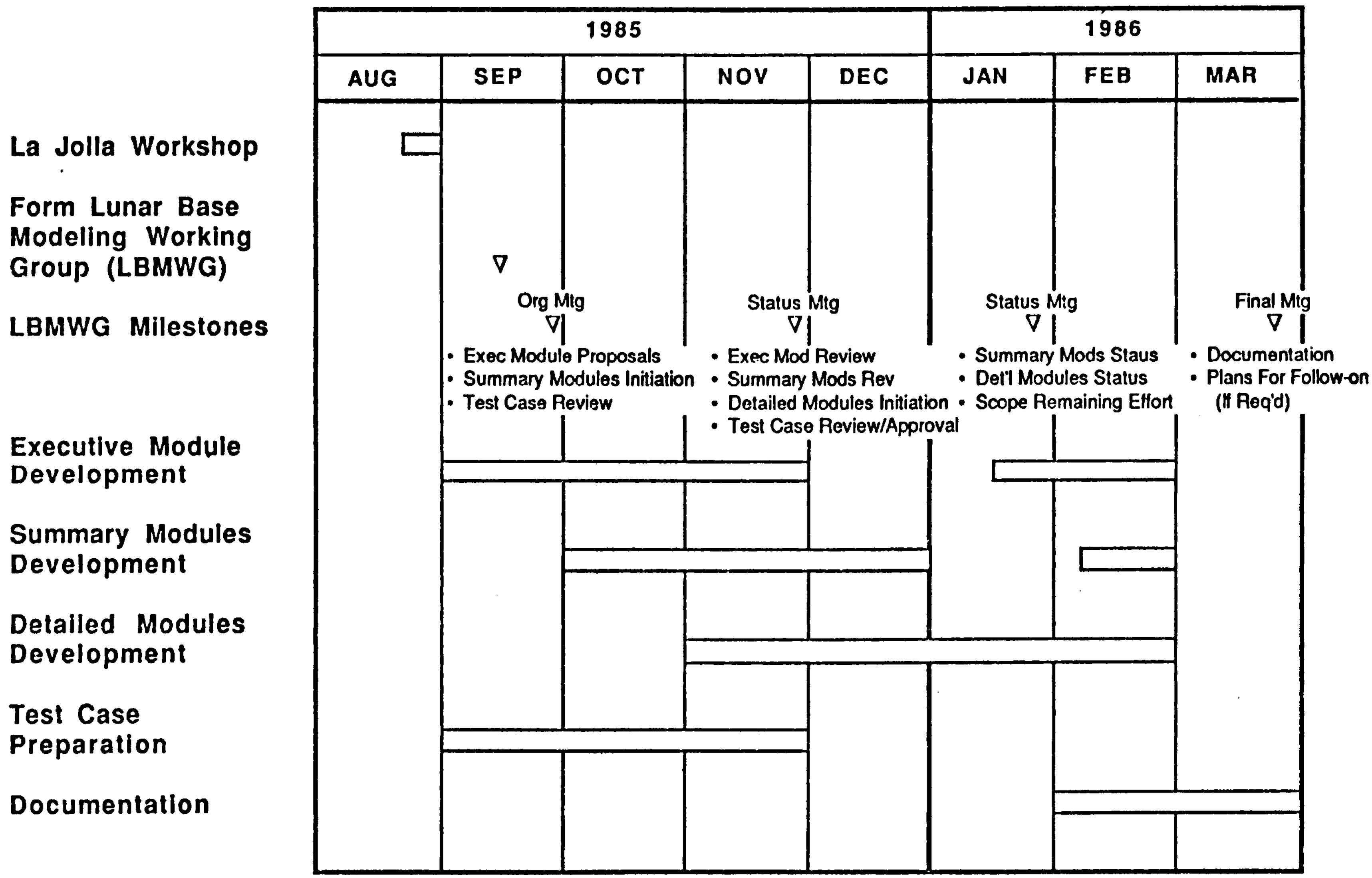


Figure 3. Lunar Base Model Architecture

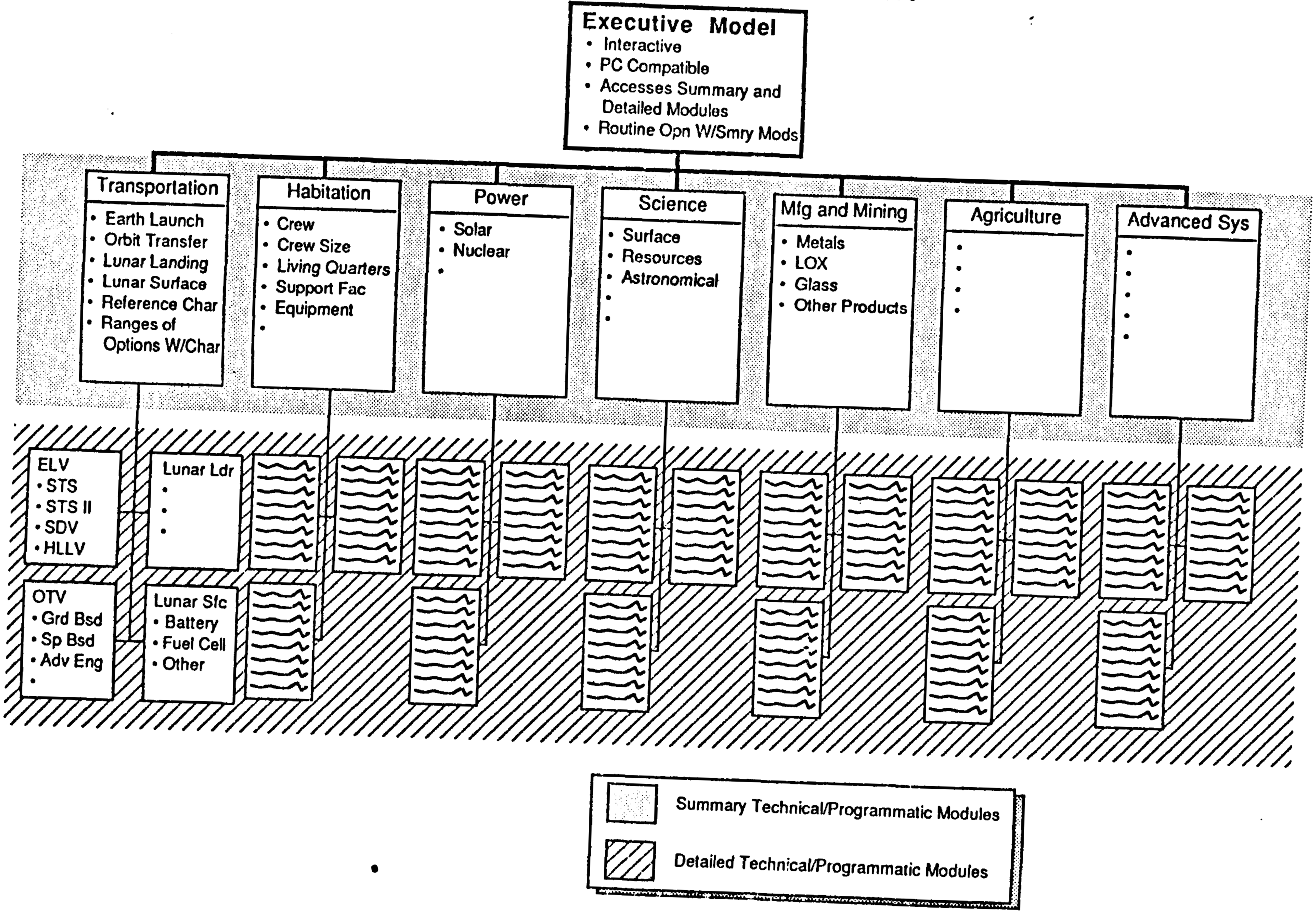


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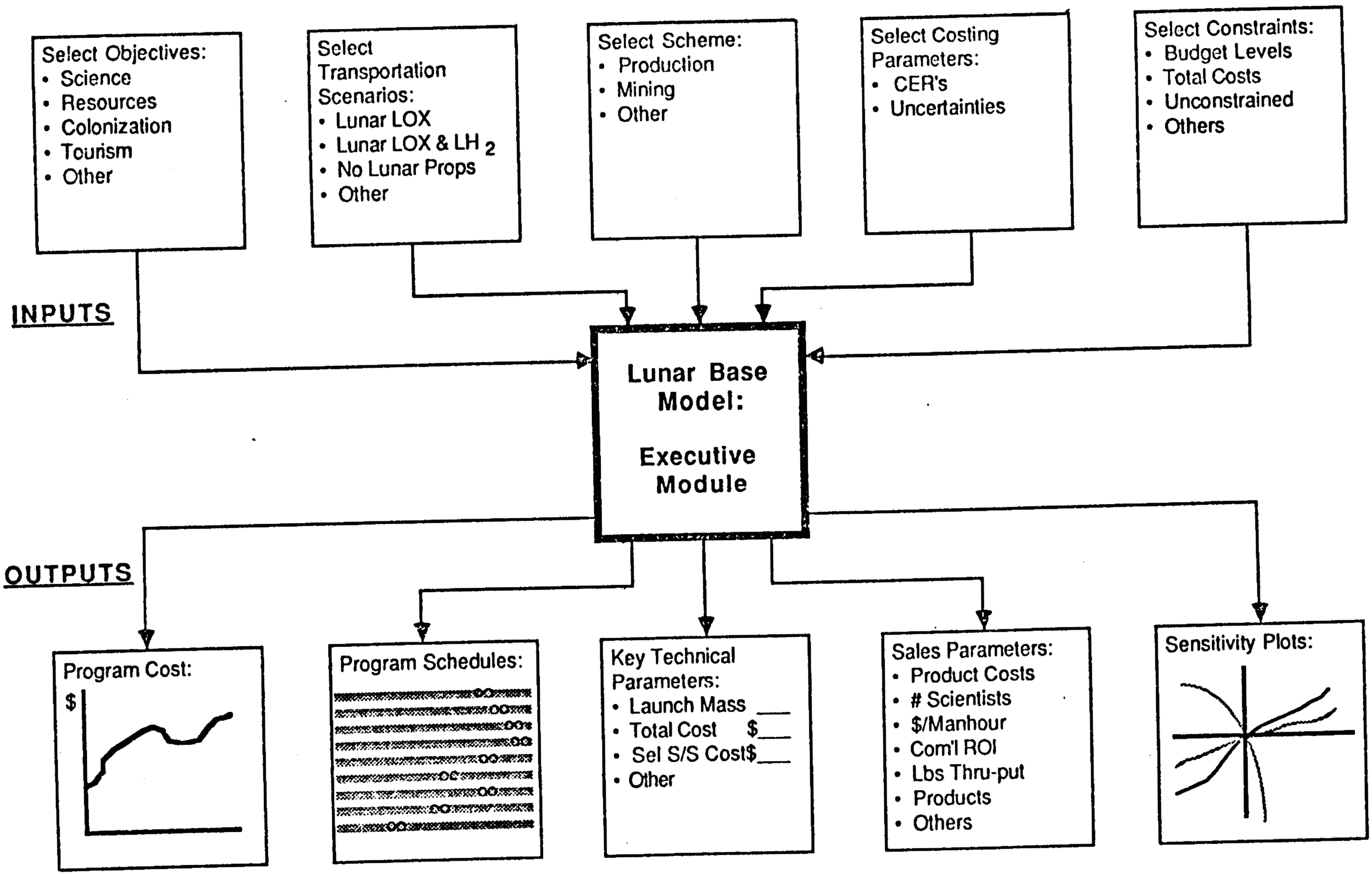
Figure 4. Lunar Base Executive Module Sample Inputs/Outputs



APPENDIX A: INTRODUCTION

The purpose of this section of the report is to identify, within the limitations of the talent and time available:

(1) The elements and sub-elements of a lunar base program; most frequently an identifiable, discrete hardware end-item.

(2) The quantifiable requirements for each sub-element which must be specified to the designer of each sub-element before beginning the concept selection and design process. Examples of such requirements are payload, range, reliability and life.

(3) The attributes of the element or sub-element which provide both a physical description of the end-item and the needs which must be supplied from outside the element in order for it to fulfill its function and meet its requirements. Examples would be the mass, volume, unit cost, and fuel consumption rate of an internal combustion engine. The fuel consumption attribute of the engine, once defined, would become a part of the requirements for the fuel supply and distribution element.

(4) The transform relationships which may be used in the modelling process for deriving first order estimates of new attribute values in response to new requirement values. An example of an attribute is the specific mass of a storage battery, expressed in the units of Kg/Watt Hour. Although many transform relationships may be a single constant, others will require a more complex algorithm which may involve multiple constants or non-linear relationships or both.

APPENDIX B: ORGANIZATION

The essence of the completed lunar base model will be the mathematical relationships linking the "requirements" to the "attributes" of the lunar base "elements" which are required to achieve a specified set of goals. Eleven candidate lunar base elements were defined early in the workshop to provide a starting point for development of such relationships. Regrouping and redefinition of these elements will be a natural outcome of further effort on the lunar base model development project. These early candidate elements are:

1. habitat
2. power
3. surface transportation
4. space transportation
5. lunar liquid oxygen plant
6. communication
7. mining
8. construction equipment
9. manufacturing
10. experiments
11. laboratories

After identification of these elements, a number of major "sub-elements" were defined for each element, to achieve the needed level-of-detail for the model. Principal "attributes" and "requirements" were then identified for each subsystem. A matrix of "transform algorithms" will ultimately be developed for each lunar base sub-element, providing the mathematical link between each requirement and each attribute of each sub-element. As shown in Figure I-1a, certain sub-element attributes that are designed to meet lunar base goals (e.g., the power required for production of liquid oxygen) will generate secondary requirements influencing the design of other sub-elements (e.g., the manpower and surface transportation requirements for establishment and maintenance of the lunar base power system. Therefore, the full identification of total requirements for each element of the lunar base will require iteration to assure that all needs are fulfilled.

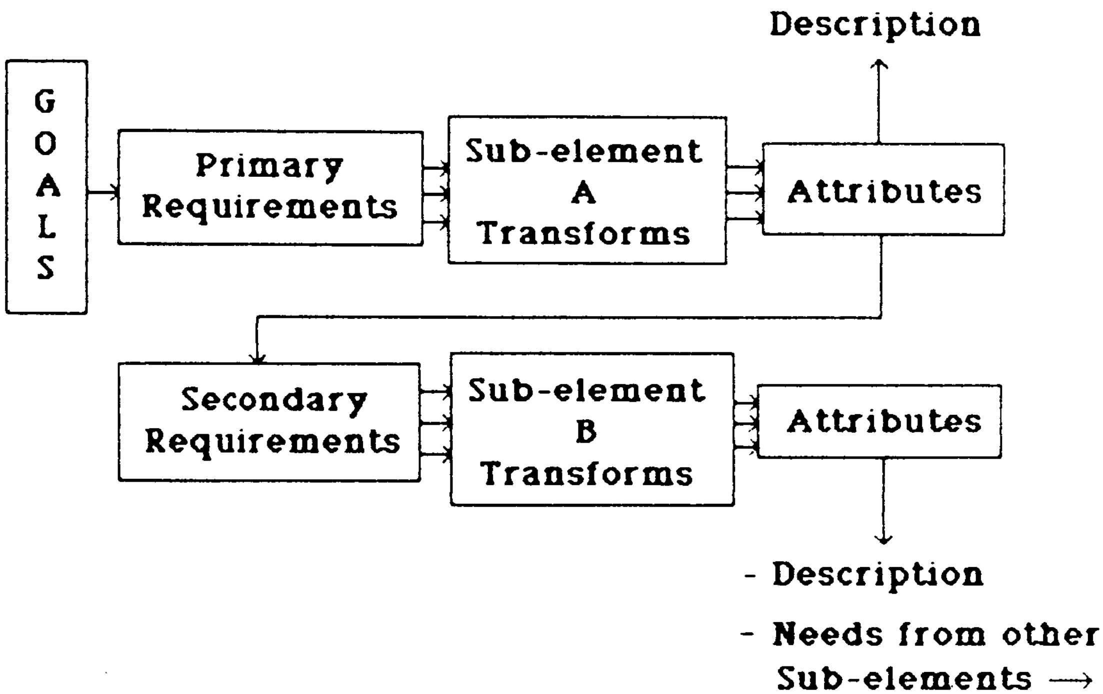


Figure B-1. Attributes of lunar base sub-elements will be defined by primary requirements for meeting lunar base goals and secondary requirements for supporting other sub-elements of the lunar base in the achievement of these goals.

APPENDIX C: SUGGESTED RE-ORGANIZATION OF LUNAR BASE ELEMENTS

Before the model architecture is established, it is recommended that further time be devoted to the top-level organization of elements to assure that:

a. All necessary elements are identified and present in the model.

b. No element is entered twice, resulting in inaccurate characterization of the overall lunar base system.

Table C-1

Lunar Base Elements

A. Lunar Surface Elements

1. Habitat
2. Power
3. Transport (surface)
4. Communications & control
5. Scientific experiments
6. Laboratories
7. Manufacturing
8. Mining
9. Construction
10. Space vehicle basing and operation

B. Lunar Orbit Elements

1. Habitat
2. Power
3. Local transport
4. Communications and control
5. Scientific experiments
6. Laboratories
7. Manufacturing
8. Propellant Storage
9.
10. Space vehicle basing & operation

C. LEO Elements

1. Habitat
2. Power
3. Local transport
4. Communications & control
5. Scientific experiments
6. Laboratories
7. Manufacturing
8. Propellant Storage Transfer
9. Other programs
10. Space vehicle basing & operation

D. Earth Surface Elements

1. Launch Facilities
2.
3.
4. Communications and Control
5.
6. Laboratories
7. Manufacturing
8.
9.
10. Space vehicle basing and operation

E. Space Transportation, Lunar Landing & Ascent

1. Expendable landers
2. Reusable landers
3. Personnel module
4. Support equipment
5. Spares

F. Space Transportation, Lunar Landing & Ascent

1. Expendable chem.
2. Reusable chem.
3. Reusable electric
4. Advanced concepts
5. Personnel module
6. Support
7. Spares

G. Launch Vehicles

1. STS-I
2. STS-II
3. SDV-I
4. SDV-II
5. HLLV
6. Priority LV
7. P/L support
8. Other support
9. Spares

APPENDIX D: INITIAL UTILIZATION

Initially, a normalization of the level-of-detail of the sub-element descriptions, requirements and attributes will be necessary. Completion of the definition of the transform algorithms will also be necessary. Much of the data on nominal estimated transform algorithms will be missing and little or no data on the necessary minimum and maximum expected values will be present.

A consistent, non-redundant numbering system must be devised to trace the requirements, attributes, and transforms through the models as they are employed.

The expected run procedure will be to employ "best estimate" statements of requirements developed individually by the person responsible for the element/sub-element.

From the initial run, the "attributes" of each sub-element will be defined and these attributes which impose incremental requirements on other sub-elements will be accumulated by sub-elements and the process completed. Criteria must be established to determine the degree of stability, or convergence necessary to declare that the model has produced a set of sub-elements which meet all requirements, both external to and internal to the lunar base. The accumulator routines will require considerable care to assure that all requirements of all sub-elements are fulfilled once and only once.

Also, it may be necessary to define influence coefficients to expedite system closure and prevent model oscillation.

APPENDIX E: MODEL GROWTH AND EXPANSION

Initial models will attempt only to provide a "snapshot" of the lunar base at it will exist at a single moment of its life cycle.

The real lunar base will, of course, require multi-year activities to establish first a transient fasthold, then a facility which can support life over an extended interval and, eventually a human community which approaches self-sufficiency and produces goods and services for export.

Multiple "snapshots" can give some indication of this pattern of growth but it is expected that refinement of the models will be necessary to permit more realism in describing the growth of the lunar base. Alternative strategies for establishing and growing a lunar base should be examined through the use of the upgraded lunar base model and some application made of optimization subroutines to improve these strategies.

An additional facet of lunar base model growth will be in the consideration of uncertainties. Certainly none of the transform algorithms will be absolutely correct nor will technology remain static. Addition of some standardized "best case" and "worst case" values will be necessary as will some indication of the distribution function across the range of uncertainty (gaussian, triangular, regular, skewed, etc.).

Finally, the completed models must accommodate off-nominal conditions which can be expected in the real world--breakdowns, failures, accidents, etc. must be modelled and their influence on the lunar base determined.

In the summer semester 1985, a case study on comparison of alternative strategies for return to the moon was carried out at the Technical University of Berlin. The study was carried out by a group of 13 graduate aerospace students and 2 assistant professors with the overall supervision of a full professor. The subject was to compare a "bare bone" strategy, an "exploration" strategy and a "utilization" strategy for return to the moon in terms of costs and benefits. For all three strategies the same set of ground rules was used for the design of the lunar base and the space transportation system. It was assumed that the lunar base will have an operational life cycle of 25 years after 10 years of development and 4-5 years of assembly. It was found that the cost of such programs, assuming crew sizes of 6, 30, and 120 people on the lunar surface will be in order of 56 to 106 billion \$1985. The overall system efficiency will be 300 to 3000 times better than the efficiency of the Apollo program in terms of spent man years on earth for one man year on the moon. In the two larger scenarios also LOX production from lunar soil to satisfy the requirements of the space transportation system was assumed.

The NASA-sponsored study, "Economic Implications of Space Resource Utilization Technologies," (EISRUT), was performed by Earth Space Operations (ESO) from December 1984 through April 1985. Michael C. Simon, ESO President, was study manager and principal author of this report. Raymond J. Gorski (ESO Vice President), Thomas L. Kessler (Executive Consultant), and Andrew H. Cutler (Consultant) were also major contributors to this study effort. The principal study objectives were to expand and refine the analyses of space resource utilization initiated during the NASA/CalSpace summer study that was conducted in La Jolla during the period of June through August 1984.

EISRUT study efforts focused on analysis of the baseline space resource utilization scenario that was developed during the CalSpace study. The objective defined in this scenario was to manufacture 1 million kg (1,000 metric tons) of liquid oxygen (LO_2) on the Moon each year, and to deliver as much of this LO_2 as possible to low Earth-orbit (LEO).

The basis for many of the analyses and trade studies conducted during the EISRUT study was the Space Resource Utilization (SRU) Cost

Model, which calculates lunar LO_2 costs parametrically as a function of fifteen key variables. While the baseline lunar LO_2 costs estimates are all subject to considerable uncertainty, the SRU Cost Model demonstrated with reasonable confidence that the cost of providing lunar LO_2 in LEO will be most heavily influenced by costs associated with logistics support for LO_2 production and delivery to LEO. Among these logistics-related costs, space transportation costs were found to be the most significant factor influencing the cost-effectiveness of providing lunar LO_2 in LEO.

An important issue related to transportation costs is the cost of providing the liquid hydrogen (LH_2) needed on the Moon to fuel the lunar OTVs used to return lunar LO_2 to LEO. At the nominal Earth-to-Moon transportation cost used in this study, the cost of providing the LH_2 required to support the baseline scenario comprises a large portion of total operations costs.

Production of LH_2 on the Moon offers the possibility of eliminating LH_2 transportation costs altogether, but the relatively scarcity of LH_2 in lunar fines raises important questions about the size and cost of the LH_2 production facilities needed to manufacture sufficient quantities of LH_2 on the Moon.

APPENDIX F: HABITAT

SUBELEMENT	REQUIREMENTS	ATTRIBUTES	TRANSFORMS
Environmental Control and Life Support Systems (ECLSS)	Pressure/composition control Revitalization/temp control Water management Waste management EVA servicing Support for n crewmembers X years lifetime Y% reliability No maintenance H_2O No maintenance O_2	Mass Volume Power Atmos. Pressure O_2 N_2 Water Vapor CO_2 Contaminants Atmos. temp H_2O Additional fluids Solids Total # people	(/pd = /person/day) lbs/pd ft^3/pd kw/pd % O_2 % N_2 % water vapor max. % contaminants Total per/one person
Thermal Control System	Heat rejection & generation Lifetime Reliability	Mass Volume Power Thermal/energy rate	Attribute/pd Attribute/BTU transformer Attribute/Kw consumed in habitat
Crew Systems Stateroom Hygiene Galley Housekeeping Wardroom	Provide personal living space and personal computer systems access. Provide for personal sanitary needs. Provide for food prep/cleanup. Provide for personal equipment/ clothing maintenance. Provide for recreation and entertainment.	Volume Mass Power	Attribute/pd Attribute/p
Nutrition	Provide food requirements. Provide potable water reqs. Provide adequate nutrient balance. Palatability.	Mass Volume Fats Protein Carbohydrates Minerals Vitamins	Attribute/pd
Radiation Shielding and Detection Devices	Provide radiation protection and monitoring. Reliability Advanced warning capability	REMS to: Skin Eyes Germinal Cells Blood forming organs RADS to electrons eV energy level GCR radiation Solar event radiation Mass Volume Power	Attribute/day Attribute/ft^3 of soil
Healthy Maintenance Facility	% health maintainability Patient restraint Exercise	Mass Volume Power	Attribute/likelihood of specific occurrence of disease or injury
EVA equipment	Durability Maintainability Suit consumables Donning Maintenance Lifetime	Mass Volume Power	Attribution/UR EVA

APPENDIX G: POWER SYSTEM ALTERNATIVES MODELING FOR THE LUNAR BASE SUPPORTING ELEMENTS

Discussion:

Power System Parameters - and an example explaining their use - are presented for the following Lunar Base Support Elements. Detailed models for all applicable systems are included in the Appendix.

1. Main Base Power
   Early Base (small power requirements)
   Mature Base (large power requirements)

2. Outpost Power

3. Lunar Surface Mobile Power

4. Orbit Transportation Power - Electric Propulsion Cargo Carrier - LEO to LLO.

5. Lunar Transit Vehicle Power (Manned Transit Vehicle)

6. Earth to LEO Launch Vehicle Power.

The power system alternatives considered for application to these elements are:

1. Solar Photovoltaic Power Systems with Regenerative Fuel Cells for storage.

2. Solar Thermal Dynamic Power Systems (cycle unspecified).

3. Nuclear Reactor Power (Energy Conversion System TBD).

4. Isotope Power Systems - Dynamic and Passive.

5. Regenerative fuel cells for Lunar Surface Transportation.

6. Batteries/Fuel Cells for Launch Vehicle and Lunar Transit Vehicle Power.

7. Isotope Power for Recoverable Earth-to-LEO Launch Vehicles.

The characteristics of these various power systems are presented in parameter form for those components which make up these various systems. Since the power system configuration is in many cases application/orbit dependent, the component breakdown given here is necessary until better definition of the mission is available. This is especially true of solar based systems which may be highly orbit dependent.

Also a given parameter may be application/installation dependent. As an example, a solar array fixed on the lunar surface may have a smaller (W/KG) or (W/M^2) parameter than one that has a sun-following drive. However, in this case the weight and cost of the sun-following drive must be included in the system make-up as a separate component or be explicitly included in the parameter (W/KG).

If better definition of the mission were available - LEO orbits, LLO orbits, transit orbits - lunar surface installation details - these various power system models could be significantly simplified - mainly the number of descriptive parameters for a given power system might be both simplified and reduced. This simplification will be the next step in the lunar mission model formulation.

If a given power system has components which could be manufactured on the lunar surface - as the solar cells for photovoltaic systems - the parameter expressing the weight, (KG/KW) must be omitted when determining the transport weight - i.e., that weight which must be delivered to the lunar surface from the earth. The power systems models given here were structured to be able to handle such contingencies. Also, if an additional parameter is needed but is not explicit in the various models - it would be a relatively simple task to reformulate the various models to include them - either weight, volume or cost.

The technology alternatives which comprise the various power systems will evolve from those of today, to those anticipated for the future. Example descriptions are given in the following pages for these power technologies as they evolve from the 1990's to the 20xx's.

The following two charts show the applications of the various power system concepts to the lunar base and support functions.

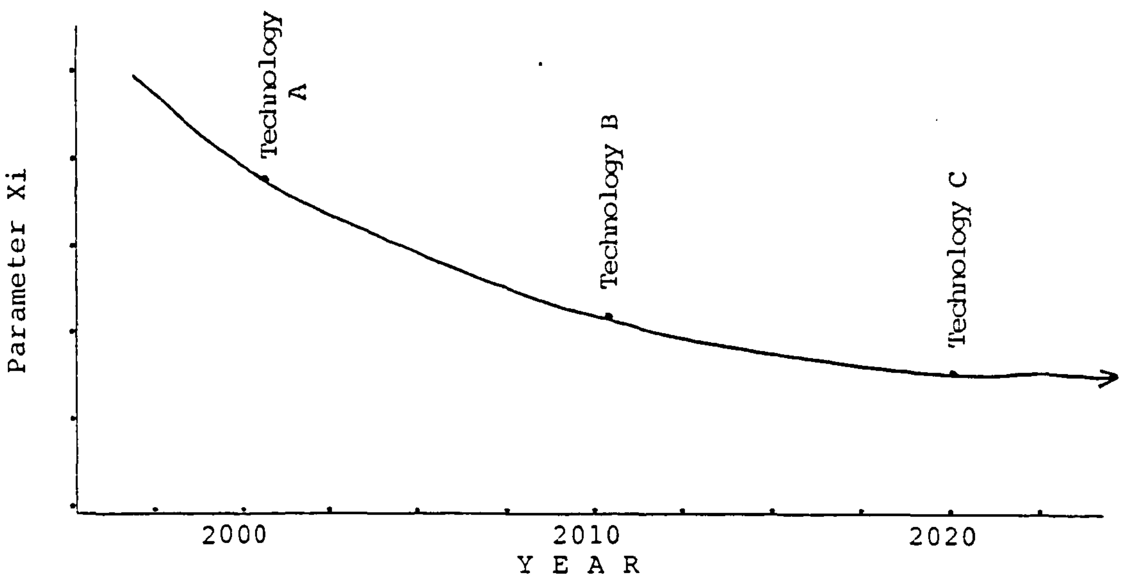
TABLE I

ELEMENT: POWER	POWER SYSTEM PARAMETERS	
SUB-ELEMENTS	SOLAR	NUCLEAR
Main Base Power		
Early Base Power (KW)	Photovoltaic Storage: Regen. fuel cell Solar thermal dynamic, (ECS-TBD)	Isotyope Dynamic: Thermo-electric, etc. Reactor, (ECS-TBD)
Mature Base Power (MW)	Photovoltaic Regen. fuel cell storage Solar thermal dynamic, (ECS-TBD)	Reactor, (ECS-TBD)
Outpost Power (KW)	Photovoltaic Storage*: Regen. fuel cell Solar thermal dynamic	Reactor Isotope Dynamic: Thermo-electric, etc.
Transportation - Construction Equip.	Regenerative fuel cells Recharged at base	
Lunar Surface (KW)	Primary fuel cells - refueled at base	
Transportation Earth Orbit to Lunar Orbit (KW) Cargo Carrier Electric Propulsion	Photovoltaic with minimum storage - Regen. fuel cells Solar Dynamic Thermal with minimum thermal storage Coast during Shadow period	Reactor
Transportation Lunar Transit Vehicle Power (Manned)	Photovoltaic - Regen. fuel cell Solar thermal dynamic Primary/secondary fuel cells/batteries (recharged at LEO/LLO	Reactor Isotope - Small vehicles
Transportation Earth to LEO OMV - Small OTV	Batteries Primary Fuel cells Primary If vehicle is recoverable - secondary systems recharged in orbit or on the earth surface may be applicable.	Isotope (If vehicle is recoverable)

* If required

Power System Parameters:

The various power energy system parameters will be given in the following format.



Note: The parameters which make up a given system must be compatible. Example: The nuclear ECS parameters - Turbine outlet temp must correspond to the radiator parameter for that max radiator temperature and turbine inlet temperature must correspond to reactor loop outlet temperature.

Modeling the Power Systems - Use of the Parameters

Explanatory Example: Solar photovoltaic power system (weights only). (Note: Detailed models of all of the applicable systems are given in the Supplement.)

The weight of a solar photovoltaic power system is the sum of the weights of the constituent parts.

1. Solar array (W/KG) (W = Power watts).

2. Regenerative fuel cell storage
   Power dependent part of storage (W/KG)
   Energy dependent part of storage (W-HRS/KG)

3. Power management and distribution (W/KG)

4. Heat rejection radiators (W/KG), also (M^3/KG)
   PMAD radiators
   Fuel cell thermal control radiators

5. Structural components - For this model we estimate this by adding up parts 1 thru 4 and multiplying by FS = 1.1 to account for structural items.

Calculation Procedure

Required input:

1. Electric power requirement - Max in orbit = P_{ELEC}

2. Efficiencies of components.

3. Orbit Data - For a solar based system, sun-shadow* times are needed and the power profiles during these phases - this is required to size the storage and solar array.
   (*Note: Detailed models of all of the applicable systems are given in the Supplement.)

4. Cost functions of components/systems.

The solar array must be sized to furnish the rated electrical power during sunlight plus charging the storage to provide the required power and energy during the shadow period.

Thus, the power in the array is (assuming the same power for both the sun and shadow period):

$$P_{ARRAY} = P_{ELECT} \left(1 + \frac{\text{Shadow Time}}{\text{Sun Time}} \frac{1}{\eta_{rt}}\right) \frac{1}{\eta_{PMAD}} = (KW)$$

Where η_{rt} is the round trip efficiency of the storage system - charging and discharging, and η_{PMAD} is the efficiency of the conversion and distribution system.

Power output of storage = P_{ELEC}/η_{PMAD}

Weight of Power Dependent part of storage (Fuel cell modules)

$$W^{POW}_{STOR} = (P_{ELEC}/\eta_{PMAD}) \;/\; (W/KG)_{STOR} = (KG)$$

Weight of the energy dependent part of storage (Tanks - reactants - piping - etc.)

$$\text{Energy Required of Storage} = \frac{(\text{Shadow Time})\, P_{ELEC}}{\eta_{PMAD} \times \eta_{DISCHARGE}} = (KW\text{-}HRS)$$

And thus the weight becomes

$$W^{EN}_{STOR} = \frac{(\text{Shadow Time})\, P_{ELEC}}{\eta_{PMAD} \times \eta_{DISCHARGE}} \;/\; (W\text{-}HRS/KG)_{STOR} = (KG)$$

Weight of the heat rejection - thermal control system - radiators - There may be two - The PMAD radiator and the fuel cell module radiator

$$W^{RAD} = \frac{P_{ELECT}}{\eta_{PMAD}} (1-\eta_{PMAD}) \;/\; \left(\frac{W}{KG}\right)_{\substack{PMAD\\RAD}} = (KG)$$

$$\text{WEIGHT OF ARRAY} = (P_{ARRAY}) \;/\; (W/KG)_{ARRAY} = (KG)$$

The weight of the storage system is made up of two parts: that dependent on the power level and that determined by the total energy delivered during the shadow phase of the mission.

$$W^{RAD}_{FUEL\ CALL} = P_{ELEC} (1-\eta_{DISCHARGE}) \;/\; \left(\frac{W}{RG}\right)_{\substack{FUEL\ CELL\\RAD}} = (KG)$$

The weight of the PMAD System is

$$W_{PMAD} = \frac{P_{ELEC}}{\eta_{PMAD}} \;/\; \left(\frac{W}{RG}\right)_{PMAD} = (KG)$$

Thus the total weight of this system is

$$\boxed{W_{PV} = (W_{ARRAY} + W^{POW}_{STOR} + W^{EN}_{STORAGE} + W^{RAD}_{FUEL\ CELL} + W^{RAD}_{PMAD} +}$$

$$\boxed{W_{PMAD})\ F.S. = (KG)}$$

The weights of the other power systems follow the same procedure. However, since they do not all consist of the same components, care must be taken to sum up the correct components.

In some cases it is also important to know the volume - regenerative fuel cells and their tankage is a major example since they may effect transportation costs and construction costs. Thus the parameter (W/M^3) or (KW/M^3) is also given. Costs - construction, transportation, and maintenance costs are also computed for each system, as appropriate.

Power System Technologies anticipated to be applicable to the lunar base support function

Reactor Power Systems

1990-2000

Liquid metal cooled reactor technology

1400°K reactor outlet temperature

Refractory alloys

Stirling - potassium Rankine cycles

Heat pipe radiator

7 year lifetime

2000-2010

Graphite core gas cooled reactor

2400°K reactor outlet temperature

Direct Brayton energy conversion

Advanced radiator technology

7 year lifetime

2010-2020

Particle bed and gas cooled reactor technology

3000°K reactor outlet temperature

Ceramic materials - superconducting alternator

Advanced radiator technology

7 year lifetime

Photovoltaic Power Systems

1990-2000 Photovoltaic array - 2 mil silicon

4-6 mil cover glass as needed

H_2-O_2 Regenerative fuel cell
Filament wound = metal lined reactant tanks

7 year lifetime

2000-2010

Photovoltaic array - 10M Galium Arsenide

4-6 mil cover glass as needed

H_2-O_2 Regenerative fuel cell
Bifunctional electodes
High strength filament wound reactant tanks
Higher efficiency catalyst for electrodes

7 year lifetime

Solar Thermal Dynamic Power Systems

1900-2000

Brayton cycle - 1120°K max. cycle temperature

LiF storage medium

Fin tube radiator

7 year lifetime

2000-2010

Brayton cycle - Stirling cycle

MgF_2 storage medium

1536°K max cycle temperature

Advanced radiator technology

7 year lifetime

TABLE II

ELEMENT: POWER	POWER SYSTEM ALTERNATIVES	
SUB-ELEMENTS	S O L A R	N U C L E A R
Main Base Power (MW)	Solar Based System Parameters (ECS) Power level (Electrical) (W/KG) These will depend (W/M^2) on type of surface installation (fixed-sun following)	Reactor System Parameters Power level (Electrical) Nuclear system parameters $(W/KG):(W/M^3)$ Shielding requirements (KG/KW_{OUTPUT})
	Power Management and Distribution (PMAD) Voltages Currents AC-DC Components parameters(W/KG) Rejection temps. Transmission lines (KG/M) Component Efficiencies Thermal Control Requirements Radiator parameters (W_R/KG) (W_R/M_1) (High and low temp. radiators) Storage System Requirements Power-Energy Requirements $(W\text{-}HRS/KG):(W\text{-}HRS/M^3):(W/KG)$ Charge-discharge efficiencies Environmental Protection Requirements Shielding - area to be protected (KG/M^2) Process Heat (Direct) Requirements-for solar thermal Thermal buss (W/KG)	Shadow Shield } Man rated 4π Shield } Instrument rated Power Management and Distribution Same as solar systems Thermal Control Requirements Same as solar systems Environmental Protection Requirements Same as solar systems Process Direct Heat Requirements Same as solar systems Additional shielding may be required for heat transfer loop (W/KG): (W/M^3)

TABLE II (CONT.)

ELEMENT: POWER	POWER SYSTEM ALTERNATIVES	
SUB-ELEMENTS	SOLAR	NUCLEAR
Main Base Power (MW) (cont.)	Cost Parameters (System) (\$/W) (Solar array, solar thermal (ECS)) (\$/M^2) Solar array, solar Concentrator (\$/W) PMAD equipment (\$/W) Thermal control eqpmt Transportation Costs (\$/KG):(\$/M^3) Support requirements: Maintenance-Construction (\$/KW) (M-HRS/YR) Requirements Maintenance shop facilities LXHXW Tools: (KG/KW) Shirtsleeve environment	Cost Parameters (System) (\$/W) Reactor (\$/KG) Shielding (\$/W) PMAD equipment (\$/W) Thermal control eqpmt (\$/M) Special Trans. lines for system isolation Transportation Costs (\$/KG):(\$/M^3) Support requirements: Construction-Maintenance (\$/KG) (M/HRS/YR) Requirements Maintenance shop facilities LXHXW Tools: KG/KW shirtsleeve environment
Early Base Power or Outpost Power	Same as main base power - but at smaller level - no process heat requirements	In addition to reactor power Radioisotope energy conversion system - same as main base parameters - but no process heat requirements
Transportation Lunar Surface Manned rover vehicles Construction vehicles	Regenerative Fuel Cell Sys. Recharged at main base Mission parameters Range Endurance/No. of occupants Speed Hill climbing profile Mission power profile Vehicle wt/roll resistance These lead to the energy power requirements fuel cell parameters (W/KG):(W-HRS/KG):(W-HRS/M^3) Heat rejection requirements (W_R/KG) Chg-discharge efficiencies	Reactor Power Systems Same as for base power sys. Except at smaller power levels with the exception of process heat requirements

TABLE II (CONT.)

ELEMENT: POWER	POWER SYSTEM PARAMETERS	
SUB-ELEMENTS	SOLAR	NUCLEAR
	Power Management and Distribution Same parameters as outpost base power Cost Parameters Same as main base requirements Requirements Power energy for charging (KW):(KW-HRS) Garage-housing-maintenance LXHXW Shirtsleeve environment Tools: (KG/KW)	Cost Parameters Same as main base requirements Requirements Garage-housing-maintenance LXHXW Shirtsleeve environment Tools: (KG/KW) Isotope Power Systems Isotope power may be practical for smaller systems. All parameters same as for outpost power system.
Transportation LEO to LLO Electric propulsion system power Solar power systems storage sized only for vehicle functions with coast during shadow perios - rendezvous with lunar descent stage	Solar Based Systems Same parameters as for base power for ECS collector Power Management and Distribution Same as for base power except very high voltage system Storage System Parameters Same as for base power systems - but sized to meet only vehicle housekeeping requirement Thermal Control Same as for base power	Reactor Power Same parameters as for base power systems

TABLE II (CONT.)

ELEMENT: POWER	POWER SYSTEM PARAMETERS	
SUB-ELEMENTS	SOLAR	NUCLEAR
	Cost Parameters Same as for base power Requirements Loading: Cargo and fuel at LEO or LLO: (M^3),(KG) Descent stage to lunar surface Maintenance at LEO	Cost Parameters Same as for base power Requirements Loading: Cargo and fuel at LEO or LLO: (M^3),(KG) Descent stage to lunar surface Maintenance at LEO
Lunar Transit Vehicle Vehicle Power	Solar Based Systems Same parameters as previous but sized to orbital requirements Fuel Cells - Parameters Primary - Refuel at LLO or LEO Secondary - Recharge at LLO or LEO (W/KG):(W-HRS/KG):(W-HRS/M^3) Charge-discharge efficiencies Heat rejection - PMAD Parameters same as for base power Batteries - Parameters Primary - Replace at LEO Secondary - Recharge at LEO or LLO (W/KG):(W-HRS/KG):(W-HRS/M^3) Charge-discharge efficiencies Heat rejection - PMAD: same as for fuel cells Cost Parameters Same as Solar based main base systems Requirements Same as for LEO to LLO system, plus (KW-HRS/TRIP) for storage charge	Reactor Power Systems Same parameters as previous Cost Parameters Same as nucelar main base system Requirements Same as for LEO to LLO system

TABLE II (CONT.)

ELEMENT: POWER	POWER SYSTEM PARAMETERS	
SUB-ELEMENTS	SOLAR	NUCLEAR
Earth to LEO Short duration power for launch vehicles	Batteries/Fuel cells Primary Same parameters as above	
OMV or Small OTV		

TABLE II
(cont)

INPUT REQUIREMENTS	POWER SYSTEM PARAMETERS	
	SOLAR	NUCLEAR
Power Levels	Base Habitat power/energy requirements Procesing: Power/energy requirements Thermal Electrical These must be given for both sun and shadow periods to size the power and energy storage systems Transportation Power profiles energy requirements to size power and storage systems	Base Same as for solar systems to establish power system power requirements, plus transmission line lengths for isolation shielding requirements man rated instrument rated Habitat protection Transportation Same as for solar systems to establish power levels plus any special shielding or isolation requirements
Costs	Costs for both system and transportation must be given for each parameter. Also cost uncertainties for each parameter would be desirable.	Same as for solar systems

SUPPLEMENT TO APPENDIX G: POWER SYSTEM MODELS FOR SUB-ELEMENT APPLICATIONS

Detailed models of the alternative power systems are given here. It is intended that this supplement be a "stand alone" document for the programmer and those who prepare the input.

POWER SYSTEMS ALTERNATIVES MODELS

- SUB-ELEMENT: Main Base Power (Early Base).

Options: Solar photovoltaic power systems
Solar thermal dynamic power systems
Nuclear (reactor) power systems
Isotope power (RTG's). (small bases)

Input Requirements:

a) power profiles, sun period, shadow period — P_{elec} (KW)

b) thermal process heat requirements $(KW)_T$

c) base installation parameters - transmission line distances. $(KM)_T$

NOTE: No process heat requirements may be specified for solar photovoltaic systems. Process heat requirements are assumed applicable to high temperature systems only.

TABLE IA

SOLAR PHOTOVOLTAIC SYSTEMS

Components	Systems Param.	Cost Param.
Energy Conversion Syst.	$(KW/KG)_{SA}$	$(\$/KW)_{SA}$
Solar array assembly	$(KW/M^2)_{SA}$	
Solar array assembly		
Pow. Man. and Distribution		
PMAD equipment	$(KW/KG)_{PM}$	$(\$/KW)_{PM}$
Transmission lines	$(KG/KM)_{PM}$	$(\$/KM)_{PM}$
PMAD efficiency	η_{PM}	
Thermal Control System		
Fuel cell radiator	$(KW_R/KG)^1_R : (KG/M^2)^2_R$	$(\$/M^2)^1_{RAD}$
PMAD radiator	$(KW_R/KG)^2_R : (KG/M^2)^2_R$	$(\$/M^2)^1_{RAD}$
Stoarge System (Reg.F.C.)		
Fuel cell pow. module	$(KW/KG)_{F.C.}$	$(\$/KW)_{F.C.}$
Reactants, tankage	$(KW\text{-}HRS/KG)_{F.C.}$	$(\$/KW\text{-}HR)_{F.C.}$
Reactants, tankage	$(KW\text{-}HRS/M^3)_{F.C.}$	
Round trip efficiency	η_{RT}	
Discharge efficiency	η_{DIS}	
Transportation		
PU system (wt related)		$(\$/KG)_{PV}$
PU system (vol. related)		$(\$/M^3)_{PV}$
Support, Construct, Maint.		
Site Preparation		$(\$/M^2)_{PV}$
Maintenance support		$(M\text{-}HRS/YR)_{PV}$
Tools/spares, equip.	$(KG/KW)_{PV}$	

PHOTOVOLTAIC POWER SYSTEM MASS MODEL

$$* \quad W_{PV}\ (KG) = \Bigg\{ \left[P_{ELEC}^{SUN} + P_{ELEC}^{SHAD} \left(\frac{\text{SHADOW TIME}}{\text{SUN TIME}} \right) \frac{1}{\eta_{RT}} \right] \frac{1}{\eta_{PM}} \Big/ \left(\frac{KW}{KG} \right)_{SA}$$

$$+ \frac{P_{ELEC}^{SHAD}}{\eta_{PM}} \Big/ \left(\frac{KW}{KG} \right)_{FC} + \frac{\text{SHADOW TIME} \times P_{ELEC}^{SHAD}}{\eta_{PM} \times \eta_{DIS}} \Big/ \left(\frac{KW\text{-}HRS}{KG} \right)_{FC}$$

$$+ \frac{P_{ELEC}^{MAX}}{\eta_{PM}} (1-\eta_{PM}) \left(\frac{KW_R}{KG} \right)_R^2 + \frac{P_{ELEC}^{SHAD}}{\eta_{PM}} \frac{(1-\eta_{DIS})}{} \Big/ \left(\frac{KW_R}{KG} \right)_R^1$$

$$+ \frac{P_{ELEC}^{MAX}}{\eta_{PM}} \Big/ \left(\frac{KW}{KG} \right)_{PM} + KM_T \times \left(\frac{KG}{KM} \right)_{PM} + P_{ELEC}^{MAX} \left(\frac{KG}{KW} \right)_P \Bigg\} \times 1.10$$

THE FACTOR 1.10 IS INCLUDED TO INCLUDE STRUCTURAL ITEMS NOT DETAILED IN THE MODEL.

PHOTOVOLTAIC SYSTEMS COST MODEL

SYSTEMS COSTS

$$* \quad C_{PV}^{S}\ (\$) = \Bigg\{ \left[P_{ELEC}^{SUN} + P_{ELEC}^{SHAD} \left(\frac{\text{SHADOW TIME}}{\text{SUN TIME}} \right) \frac{1}{\eta_{RT}} \right] \frac{1}{\eta_{PM}} \times \left(\frac{\$}{KW} \right)_{SA}$$

$$+ \frac{P_{ELEC}^{MAX}}{\eta_{PM}} \times \left(\frac{\$}{KW} \right)_{FC} + \frac{\text{SHADOW TIME} \times P_{ELEC}^{SHAD}}{\eta_{PM} \times \eta_{DIS}} \times \left(\frac{\$}{KW\text{-}HR} \right)_{FC}$$

$$+ \left\{ \left[\frac{P_{ELEC}^{MAX}}{\eta_{PM}} (1-\eta_{PM}) \Big/ \left(\frac{KW_R}{KG} \right)_R^2 \right] \Big/ \left(\frac{KG}{M^2} \right)_R^1 \right\} \times \left(\frac{\$}{M^2} \right)_{RAD}^1$$

$$+ \left\{ \left[\frac{P_{ELEC}^{SHAD}}{\eta_{PM}} \frac{(1-\eta_{DIS})}{} \Big/ \left(\frac{KW_R}{KG} \right)_R^2 \right] \Big/ \left(\frac{KG^2}{M^2} \right)_R \right\} \times \left(\frac{\$}{M^2} \right)_{RAD} + \frac{P_{ELEC}^{MAX}}{\eta_{PM}} \Big/ \left(\frac{\$}{KW} \right)_{PM}$$

$$+ KM_T \times \left(\frac{\$}{KM} \right)_{PM} \Bigg\} \times 1.10$$

TRANSPORTATION COSTS

$$* \quad C_{PV}^{TRANS} \ (\$) = W_{PV} (KG) \times (\$/KG)_{PV}$$

SUPPORT COSTS - SITE PREPARATION

$$* \quad C_{PV}^{SITE} \ (\$) = \left[\left\{ P_{ELEC}^{SUN} + P_{ELEC}^{SHAD} \left(\frac{\text{SHADOW TIME}}{\text{SUN TIME}} \right) \frac{1}{\eta_{RT}} \right\} \frac{1}{\eta_{PM}} \Big/ \left(\frac{KW}{M^2} \right)_{SA} \right] X \left(\frac{\$}{M^2} \right)_{PV}$$

MAINTENANCE COSTS

$$* \quad C_{MAINT}^{PV} \ (\$) = (\$/M\text{-}HR)_{PV} \ X \ \left(\frac{M\text{-}HRS}{YR} \right)_{PV}$$

SITE REQUIREMENTS

$$* \quad AREA \ (M^2) = 1.25 \left[P_{ELEC}^{SUN} + P_{ELEC}^{SHADOW} \left(\frac{\text{SHADOW TIME}}{\text{SUN TIME}} \right) \frac{1}{\eta_{RT}} \right] \frac{1}{\eta_{PM}}$$

TABLE IB
SOLAR THERMAL DYNAMIC SYSTEMS

COMPONENTS	SYST'S PARAM'S	COST PERAM'S.
Energy conversion system		
Conversion equipment	$(KW/KG)_{ST}$	$(\$/KW)_{ST}$
Concentrator	$(KW/KG)^1_{ST}$: $(KG/M^2)_{ST}$	$(\$/M^2)_{ST}$
ECS efficiency	η_{ST}	
Pow. Man. and Distribution		
PMAD equipment	$(KW/KG)_{PM}$	$(\$/KW)_{PM}$
Transmission lines	$(KG/KM)_{PM}$	$(\$/KM)_{PM}$
PMAD efficiency	η_{PM}	
Thermal Control System		
ECS radiator	$(KW_R/KG)^1_R : (KG/M^2)^1_R$	$(\$/M^2)^1_{RAD}$
PMAD radiator	$(KW_R/KG)^2_R : (KG/M^2)^2_R$	$(\$/M^2)^2_{RAD}$
Thermal Storage System		
Storage medium-rec'v'r	$(KW\text{-}HRS/KG)_{ST}$	$(\$/KG)$
Storage medium-rec'v'r	$(KW\text{-}HRS/M^3)_{ST}$	$(\$/KW\text{-}HRS)_{ST}$
Receiver efficiency	η_{REC}	
Process Heat Subsystem		
Thermal busses	$(KW/KG)_{Buss}$	$(\$/KG)_{Buss}$
Transportation		
System costs		$(\$/KG)^1_{ST}$
Support, Construct, Maint.		
Site preparation		$(\$/M^2)^1_{ST}$
Maint. support		$(M\text{-}HRS/YR)_{ST}$
Tools/spares/equip.	$(KG/KW)^1_{ST}$	

Physical Constant: Solar Flux = 1.37 KW/M^2 (At 1 AU)

SOLAR THERMAL DYNAMIC SYSTEM MASS MODEL

$$
\begin{aligned}
\bullet\quad W_{ST}(KG) = \Bigg[& \left\{ \left(P^{SUN}_{ELEC} + P^{SHAD}_{ELEC} \left(\frac{\text{SHADOW TIME}}{\text{SUN TIME}} \right) \frac{1}{\eta_{REC}} \right) \right\} \frac{1}{\eta_{PM}} \times \frac{1}{1.37} \times \frac{1}{\eta_{ST}} \Big/ \left(\frac{KG}{M^2} \right)_{ST} \\
& + \frac{P^{MAX}_{ELEC}}{\eta_{PM}} \Big/ \left(\frac{KW}{KG} \right)_{ST} + \frac{\text{SHADOW TIME} \times P^{SHAD}_{ELEC}}{\eta_{PM} \times \eta_{REC} \times \eta_{ST}} \Big/ \left(\frac{KW\text{-}HRS}{KG} \right)_{ST} \\
& + \frac{P^{MAX}_{ELEC}}{\eta_{PM}} \left(1-\eta_{PM} \right) \Big/ \left(\frac{KW_R}{KG} \right)^{2}_{R} + \frac{P^{MAX}_{ELEC}}{\eta_{PM}} \frac{\left(1-\eta_{ST} \right)}{\eta_{ST}} \Big/ \left(\frac{KW_R}{KG} \right)^{1}_{R} \\
& + \frac{P^{MAX}_{ELEC}}{\eta_{PM}} \Big/ \left(\frac{KW}{KG} \right)_{PM} + KM_T \times \left(\frac{KG}{KM} \right)_{PM} + KW_T \left(\frac{KW}{KG} \right)_{BUS} + P^{MAX}_{ELEC} \left(\frac{KG}{KW} \right)^{1}_{ST} \Bigg] \times 1.10
\end{aligned}
$$

SOLAR THERMAL DYNAMIC COST MODEL

$$
\bullet \quad C_{ST}^{S}(\$) = \Bigg[\left\{ P_{ELEC}^{SUN} + P_{ELEC}^{SHAD} \left(\frac{\text{SHADOW TIME}}{\text{SUN TIME}} \right) \frac{1}{\eta_{REC}} \right\} \frac{1}{\eta_{PM} \times \eta_{ST}} \times \frac{1}{1.37} \times \left(\frac{\$}{M^2} \right)_{ST}
$$

$$
+ \frac{P_{ELEC}^{MAX}}{\eta_{PM}} \times \left(\frac{\$}{KW} \right)_{ST} + \frac{\text{SHADOW TIME} \times P_{ELEC}^{SHAD}}{\eta_{PM} \times \eta_{REC} \times \eta_{ST}} \times \left(\frac{\$}{KW\text{-}HR} \right)_{ST}
$$

$$
+ \left\{ \left[\frac{P_{ELEC}^{MAX}}{\eta_{PM}} (1-\eta_{PM}) \Big/ \left(\frac{KW}{KG} \right)_R^2 \right] \Big/ \left(\frac{KG}{M^2} \right)_R^2 \right\} \times \left(\frac{\$}{M^2} \right)_R +
$$

$$
\left\{ \left[\frac{P_{ELEC}^{MAX}}{\eta_{PM}} \frac{(1-\eta_{ST})}{\eta_{ST}} \Big/ \left(\frac{KW}{KG} \right)_R^1 \right] \Big/ \left(\frac{KG}{M^2} \right)_R^1 \right\} \times \left(\frac{\$}{M^2} \right)_R + \frac{P_{ELEC}^{MAX}}{\eta_{PM}}
$$

$$
\times \left(\frac{\$}{KW} \right)_{PM} + KM_T \times \left(\frac{\$}{KM} \right)_{PM} + KW_T \times \left(\frac{KG}{KW} \right)_{BUSS} \times \left(\frac{\$}{KG} \right)_{BUSS} \Bigg] \times 1.10
$$

TRANSPORTATION COSTS

- $C_{ST}^{TRANS}(\$) = W_{ST}(KG) \times (\$/KG)_{ST}$

SUPPORT COSTS - SITE PREPARATION

- $C_{ST}^{SITE}(\$) = \frac{1}{M_{ST}} \left\{ P_{ELEC}^{SUN} + P_{ELEC}^{SHAD} \left(\frac{\text{SHADOW TIME}}{\text{SUN TIME}}\right) \frac{1}{\eta_{REC}} \right\} \frac{1}{\eta_{PM}} \times \frac{1}{1.37} \times \left(\frac{\$}{M_2}\right)_{ST}^{1}$

MAINTENANCE COSTS

- $C_{MAINT}^{ST}(\$) = (\$/M\text{-}HR) \times (M\text{-}HRS/YR)_{ST}$

SITE REQUIREMENTS

- $AREA(M^2) = \frac{1.5}{\eta_{ST}} \left[P_{ELEC}^{SUN} + P_{ELEC}^{SHAD} \left(\frac{\text{SHADOW TIME}}{\text{SUN TIME}}\right) \frac{1}{\eta_{RC}} \right] \frac{1}{\eta_{PM}} \times \frac{1}{\eta_{ST}}$

TABLE IC

NUCLEAR (REACTOR) SYSTEMS

COMPONENTS	SYST'M'S PARAM.	COST PARAM.
Reactor Power System		
Includes, ECS, radiator, Etc.	$(KW/KG)_{NR}$	$(\$/KW)_{NR}$
ECS Efficiency	η_{NR}	
Pow. Man. and Districution		
PMAD Equipment	$(KW/KG)_{PM}$	$(\$/KW)_{PM}$
Transmission Lines	$(KG/KM)_{PM}$	$(\$/KM)_{PM}$
PMAD Efficiency	η_{PM}	
Thermal Control System		
ECS Radiator	$(KW_R/KG)_R:(KG/M^2)_R$	
Process Heat Subsystem		
Thermal Buss	$(KW/KG)_{Buss}$	$(\$/KG)_{Buss}$
Special Shielding	$(KG)_{NR}$	$(\$/KG)_{Shield}$
Transportation		$(\$/KG)_{NR}$
Support, Maint, Constr.		
Site Preparation (Surf)		$(\$/M^2)_{NR}$
Site Prep. (Shielding)	$(M^3)_{NR}$	$(\$/M^3)_{NR}$
Maint Support		$(M\text{-}HRS/YR)_{NR}$
Tools, Spares-Equip.	$(KG/KW)_{NR}$	

NUCLEAR SYSTEMS (REACTOR) WEIGHT MODEL

$$W_{NR}\ (KG) = \left\{ P_{ELEC} \times \left(\frac{KW}{KG}\right)_{NR} + \frac{P_{ELEC}}{\eta_{PM}} \times \left(\frac{KW}{KG}\right)_{PM} + \text{SPECIAL SHIELD (KG)} + KM_T \left(\frac{KG}{KM}\right)_{PM} + P_{ELEC} \times \left(\frac{KG}{KW}\right)_{NT} \right\} \times 1.3$$

NUCLEAR SYSTEMS (REACTOR) COST MODEL

SYSTEMS COSTS

$$C^S_{NR}\ (\$) = \left\{ P_{ELEC} \times \left(\frac{\$}{KW}\right)_{NR} + \frac{P_{ELEC}}{\eta_{PM}} \times \left(\frac{\$}{KW}\right)_{MP} + \text{SPECIAL SHIELD} \times \left(\frac{\$}{KG}\right)_{Shield} + KM_T \times \left(\frac{\$}{KM}\right)_{PM} \right. \times 1.10$$

TRANSPORTATION COSTS

$$C^T_{NR}\ (\$) = W_{NR}(KG) \times (\$/KG)_{NR}$$

SUPPORT COSTS - SITE PREPARATION

$$C^{SITE}_{NR} = \left[\frac{P_{ELEC}}{\eta_{NR}} (1-\eta_{NR}) / \left(\frac{KW}{KG}\right)_R \right] \Big/ \left(\frac{KG}{M^2}\right)_R \times \left(\frac{\$}{M^2}\right)_{NR} + (M^3)_{NR} \times (\$/M^3)_{NR}$$

MAINTENANCE COSTS

$$C^{NR}_{MAIN}\ (\$) = (\$/M\text{-}HR)_{NR} \times (M\text{-}HRS/YR)_{NR}$$

SITE REQUIREMENTS

$$AREA\ (M^2) = 2X \left\{ \frac{P_{ELEC}}{\eta_{NR}} (1-\eta_{NR}) \Big/ \left(\frac{KW}{KG}\right)_R \right\} \Big/ \left(\frac{KG}{M^2}\right)_R$$

TABLE ID

ISOTOPE POWER SYSTEMS

COMPONENTS	SYSTEMS PARAM.	COST PARAM.
Energy Conversion System		
RTG	$(KW/KG)_{ISO}$	$(\$/KW)_{ISO}$
Pow. Man. and Distribution		
PMAD Equip.	$(KW/KG)_{PM}$	$(\$/KW)_{PM}$
Transmission Lines	$(KG/KM)_{PM}$	$(\$/KM)_{PM}$
PMAD Efficiency	η_{PM}	
Transportation		$(\$/KW)^{1}_{ISO}$
Support, Constr.-Maint.		
Site Preparation	K(Factor)	$(\$/M^2)_{ISO}$
Maint Support		$(M\text{-}HRS/YR)_{ISO}$
Tools, Spares, Equip.	$(KG/KW)_{ISO}$	

ISOTOPE POWER SYSTEMS MASS MODEL

- $$W_{ISO}(KG) = \left\{ P_{ELECT} \Big/ \left(\frac{KW}{KG}\right)_{ISO} + \frac{P_{ELEC}}{\eta_{PM}} \Big/ \left(\frac{KW}{KG}\right)_{PM} + KM_T \times \left(\frac{KG}{KM}\right)_{PM} + P_{ELEC} \times \left(\frac{KG}{KW}\right)_{ISO} \right\} \times 1.10$$

- ISOTOPE POWER SYSTEMS COST MODEL

SYSTEM COSTS:

- $$C_{ISO}(\$) = 1.10 \left\{ P_{ELEC} \times \left(\frac{\$}{KW}\right)_{ISO} + \frac{P_{ELEC}}{\eta_{PM}} \times \left(\frac{\$}{KW}\right)_{PM} + KM_T \times \left(\frac{\$}{KM}\right)_{PM} \right\}$$

TRANSPORTATION COSTS:

- $$C^T_{ISO}(\$) = W_{ISO}(KG) \times (\$/KG)_{ISO}$$

SUPPORT COSTS - SITE PREPARATION

- $$C^{SITE}_{ISO}(\$) = K \times (\$/M^2)$$

MAINTENANCE COSTS

- $$C^{ISO}_{MAINT} = (\$/M\text{-}HR) \times (M\text{-}HRS/YR)_{ISO}$$

SITE REQUIREMENTS

- $AREA(M^2) = K$ (to be specified)

SUBELEMENT: Main Base Power (Mature Base)

Options: Solar photovoltaic power systems
Solar thermal dynamic power systems
Nuclear (reactor) power systems

Input Requirements

Same as main base (early) requirements

Power System Models

Same as main base (early) requirements

SUBELEMENT: Outpost Power

Options: Solar photovoltaic power systems
Solar thermal dynamic power systems
Nuclear (reactor) power systems
Isotope power systems (small outposts)

Input Requirements

Same as main base (early) requirements

Power Systems Models

Same as main base (early) requirements

SUBELEMENT: TRANSPORTATION - CONSTRUCTION EQUIPMENT - LUNAR SURFACE

OPTIONS: Regenerative fuel cells - recharged at base
Primary fuel cells - fueled at base

Input Requirements:

a) Vehicle weight (earth referenced). (KG) may have to iterate on weight after determining power system weight to ensure that all equipment is included. (This is fully loaded vehicle weight.)

b) Power profiles - for all but propulsive power (KW vs. time).

   Environmental system power
   On board experiments power
   Housekeeping power
   Working Power - crane - etc.

c) Range (KM)

d) Vehicle Velocity (KM/HR)

e) Slope climbing requirements

   Angle of slope (α)
   % of total range on required slope: K_S

NOTE: Some of these inputs may not be required for all cases depending on function, i.e., "lunar winnebago," tractor, crane, etc.

TABLE IIA

FUEL CELL POWER SYSTEMS FOR LUNAR SURFACE TRANSPORTATION

COMPONENT	SYSTEM PARAM.	COST PARAM.
Energy Conversion System		
Fuel Cell Power Module	$(KW/KG)_{FC}$	$(\$/KW)_{FC}$
Reactants-Tankage	$(KW\text{-}HRS/KG)_{FC}$	$(\$/KW\text{-}HR)_{FC}$
Discharge Efficiency	η_{DIS}	
Power Man. and Distribution		
PMAD Equipment	$(KW/KG)_{PM}$	$(\$/KW)_{PM}$
Efficiency	η_{PM}	
Thermal Control System		
PMAD Radiator	$(KW_R/KG)^1_R$: $(KG/M^2)^1_R$	$(\$/M^2)^1_R$
Fuel Cell Radiator	$(KW_R/KG)^2_R$	$(\$/M^2)^2_R$
Transportation		$(\$/KG)_{FC}$
Support, Constr.-Maint.		
Maint Support		$(M\text{-}HRS/YR)_{FC}$
Tools/Spares-Equip	$(KG/KW)_{FC}$	

The first step is to calculate the energy - KW-HRS per mission - and the power requirements - This will size the system. To do this we must assume a lunar surface rolling resistance - α = .32 (lunar gravity = 1/6 earth gravity).

ENERGY REQUIREMENTS

To overcome rolling resistance.

$$E_1(\text{KW-HRS}) = W(\text{KG}) \times \text{RANGE (KM)} \times 1.48 \times 10^{-4}$$

To overcome change in potential energy due to slope climbing.

$$E_2(\text{KW-HRS}) = W(\text{KG}) \times \text{RANGE (KM)} \times \left(K_S \text{TAN}\,\alpha\right) \times 4.62 \times 10^{-4}$$

Plus we must add the energy (KW-HRS) requirement from the power profiles. Thus the energy requirements are

$$E_{TOT}(\text{KW-HRS}) = E_1 + E_2 + E(\text{POWER PROFILES}) \times 1.5 \text{ (MARGIN)}$$

POWER REQUIREMENTS

To overcome rolling resistance at V(KM/HR)

$$P_1(\text{KW}) = W(\text{KG}) \times V(\text{KM/HR}) \times 1.48 \times 10^{-4}$$

To overcome rate of increase in potential energy during slope climbing phase.

$$P_2(\text{KW}) = W(\text{KG}) \times V(\text{KM/HR}) \times \left(\text{TAN}\,\alpha\right) 4.62 \times 10^{-4}$$

Plus we must add the power from the power profiles to determine the max required power. It must be kept in mind that these are not always all additive. E.G. We must take the max requirement - vehicle moving - vehicle stationary.

$$P_{TOT}^{MAX} = \text{Max Combination Of } P_1 + P_2 + E \text{ (Power Profiles)}.$$

FUEL CELL POWER SYSTEM MASS MODEL

- $$W_{FC}(KG) = \left\{ \left(\frac{P^{MAX}_{TOT}}{\eta_{PM}} \right) \Big/ \left(\frac{KW}{KG} \right)_{FC} + \frac{E_{TOT}}{\eta_{DIS}} \Big/ \left(\frac{KW\text{-}HRS}{KG} \right)_{FC} + \right.$$

$$+ \frac{P^{MAX}_{TOT}}{\eta_{PM}} \Big/ \left(\frac{KW}{KG} \right)_{PM} + \frac{P^{MAX}_{TOT}}{\eta_{PM}} (1-\eta_{DIS}) \Big/ \left(\frac{KW}{KG} \right)^2_R$$

$$\left. + \frac{P^{MAX}_{TOT}}{\eta_{PM}} (1-\eta_{PM}) \Big/ \left(\frac{KW}{KG} \right)^2_R + P^{MAX}_{TOT} \times \frac{(KG)}{(KW)}_{FC} \right\} \times 1.10$$

FUEL CELLS SYSTEMS COST MODEL

- SYSTEMS COST
  - $$C^S_{FC} (\$) = \frac{P^{MAX}_{TOT}}{\eta_{PM}} \times \left(\frac{\$}{KW} \right)_{FC} + \frac{E_{TOT}}{\eta_{DIS}} \left(\frac{\$}{KW\text{-}HR} \right) + \frac{P^{MAX}_{TOT}}{\eta_{PM}} \left(\frac{(\$)}{KW} \right)_{PM}$$

$$+ \left[\left\{ \frac{P^{MAX}_{TOT}}{\eta_{PM}} (1-\eta_{DIS}) \Big/ \left(\frac{KW_R}{KG} \right)^2_R \Big/ \left(\frac{KG}{M} \right)^2_R \right) \left(\frac{\$}{M^2} \right)^2_R\right.$$

$$\left. + \left[\left\{ \frac{P^{MAX}_{TOT}}{\eta_{PM}} (1-\eta_{MP}) \Big/ \left(\frac{KW_R}{KG} \right)^1_R \Big/ \left(\frac{KG}{M^2} \right)^2_R \right] \left(\frac{\$}{M^2} \right)^2_R \right\} \times 1.10$$

- TRANSPORTATION COSTS
  - $C^T_{FC} (\$) = W_{FC}(KG) \times (\$/KG)_{FC}$

- MAINTENANCE COSTS
  - $C^{FC}_{MAINT} = (\$/M\text{-}HR) \times (M\text{-}HR)/YR)$

O SUB-ELEMENT: TRANSPORTATION - LEO TO LLO. (ELECTRIC PROPULSION)

Options: Solar photovoltaic power systems
Solar thermal dynamic power systems
Nuclear (reactor) power systems

* Input Requirements

Same as main base sub-element requirements (no need for thermal buss).

* Power Systems Models

Same as main base sub-element requirements (delete thermal buss item).

Isotope power not applicable there (MW).

O SUB-ELEMENT: TRANSPORTATION: MANNED LUNAR TRANSIT VEHICLE

Options: Solar photovoltaic power systems
Solar thermal dynamic power systems
Nuclear (reactor) power systems
Isotope power systems (small vehicles).

* Input Requirements

Same as main base sub-element requirements (no need for thermal buss).

* Power Systems Models

Same as main base sub-element requirements (delete thermal buss).

O SUB-ELEMENT: TRANSPORTATION: EARTH TO LEO OMV OR SMALL OTV

Options: For nonrecoverable vehicles
- Primary batteries
- Primary fuel cells

For recoverable vehicles
- Secondary batteries
- Secondary fuel cells
- Isotope (RTG) power

* Input Requirements

Power profile for mission(s).

* Power systems models

Same as for transit vehicle power (manned) for the fuel cell and isotope power systems.

BATTERY POWER SYSTEMS

TABLE IIIA

COMPONENT	SYSTEM PARAM.	COST PARAM.
Batteries	$(KW\text{-}HRS/KG)_B$	$(\$/KW\text{-}HR)_B$
Pow. Management and Distrib.		
PMAD Equipment	$(KW/KG)_{PM}$	$(\$/KW)_{PM}$
PMAD η_{PM}	η_{PM}	
Transportation		$(\$/KG)_{BAT}$
Maintenance		$(\$/M\text{-}HR)_{BAT}$

BATTERY POWER SYSTEM MASS MODEL

- $W_{BAT}(KG) = ENERGY/(KW\text{-}HRS)/KG)_{BAT} + \frac{Pow}{\eta_{PM}} \Big/ \left(\frac{KW}{KG}\right)_{PM}$

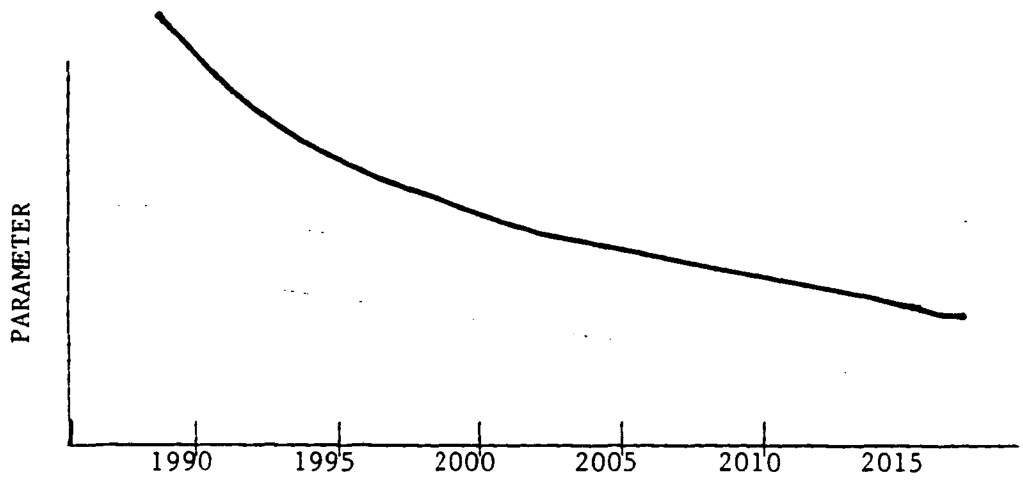
BATTERY POWER SYSTEMS COST MODEL

- SYSTEM COSTS
  - $C^{S}_{BAT}(\$) = ENERGY \times (\$/KW\text{-}HR) + \frac{POW}{\eta_{PM}} \times \left(\frac{\$}{KW}\right)$
- TRANSPORTATION COSTS
  - $C^{T}_{BAT} = W^{S}_{BAT}(KG) \times (\$/KG)_{BAT}$
- MAINTENANCE
  - $C^{BAT}_{MAINT}(\$) = (M\text{-}HRS/YR) \times (\$/M\text{-}HR)$

APPENDIX

SUMMARY:

The numerical data, (values), for the systems and cost parameters which are presented in tabular form for each of the alternative power systems will be given in the form; (where possible),



However, some parameters such as the allocation for tools, spares, etc., $(KG/KW)_{xx}$ will be presented only as a specific value for each power system.

APPENDIX H: Element: Surface Transportation/Construction Equipment

Subelements: Transport vehicles, working vehicles, traffic routes, energy storage and distribution systems, traffic control systems

Subelement A: Transport vehicles

Requirements

Passenger transportation demand (pas-km/y)
Cargo transportation demand (Mg-km/y)
Heaviest piece of payload (Mg)
Max. no. of persons to be transported together (n)
Required action radius (km)
Desired life-time (Y)
Desired reliability (%)
Desired life support to be given to driver/passengers (pas-h)
Number of transports to be performed $(\frac{n}{d})$
Degree of automatization (%)
Vehicle speed (km/h)

Attributes

Vehicle unloaded mass	(Mg)
Vehicle power consumption	(KW)
Vehicle length	(m)
Vehicle height	(m)
Vehicle weight	(m)
Propulsion system (electric, combustion, etc.)	
Mass of energy storage	(Mg)
Structural materials	
Min. operational units	(n)
Maintenance and repair factor (pers•h/oper.h)	
Spare parts consumption	(%/Y)
Development cost	($,MY)
Cost per unit	($,MY)
Operational cost	($/KM•Mg)
Propellant assumption	(Kg/Mg KM)

Subelement B: Working Vehicles

Requirements		Attributes	
soil to be excavated	(Mg/Y)	vehicle unloaded mass	(Mg)
mass to be moved around	(Mg·Km/Y)	vehicle power consumption	(KW)
heaviest piece to be moved	(Mg)	vehicle length	(m)
max height of piece	(m)	vehicle height	(m)
max dia. of piece	(m)	vehicle width	(m)
life-time	(Y)	propellant consumption	(Kg/h)
reliability	(%)	mass of energy storage	(Mg)
desired life support for driver	(pers.h)	min. operational units	(n)
number of actions to be performed	(n/Y)	maint. or repair factor	(Mg/opt)
volume of soil being excavated	(M^3/Y)	spare part consumption	(%/Y)
degree of automatiazation	(%)	development cost	($)
no. of tasks to be done simultaneously	(n)	operational cost	($)
vehicle speed	(Km/h)	propulsion system	
		structural materials	

Subelement C: Traffic Routes

Requirements		Attributes	
length of route network	(Km)	installed mass	(Mg)
traffic speed	(Km/h)	width of tracts	(m)
number of transports	(n/d)	manpower to build	(man·h/m)
vehicle width	(m)	maintenance factor	(man·h/y·km)
		cost of routes	($)

Subelement D: Energy Storage and Distribution

Requirements		Attributes	
kind of powerplant (solar, nuclear, chemical)		mass of installed powerlines	(Mg)
vehicle propulsion system	( )	power dissipation	(KW)
vehicle power consumption	(KW)	input power	(KW)
vehicle action radius	(Km)	PCU mass	(Mg)
length of routes network	(Km)	manpower to operate	(man)
degree of automatization	(%)	dev. cost	($)
		install. cost	($)
		operation cost	($/Y)

Subelement E: Traffic Control System

Requirements		Attributes	
no. of daily transports	(n)	mass of control center	(Mg)
degree of automatization	(%)	power demand	(KW)
reliability	(%)	development cost	($)
		unit/install.cost	($)
		operation cost	($/Y)

Element 3 - <u>Transforms for subelement A:</u>

$$A3A1 = (C_1 + C_2 + R3A4) * R3A3^{E1}$$

$$A3A2 = C_3 \; (R3A3 + A3A1) * R3A11$$

$$A3A7 = C_4 * A3A2 * R3A5/R3A11$$

$$A3A9 = (R^3A1 * 0.75MT + R3A2) \;/\; (2920 * (R3A3 * R3A11))$$

$$A3A10 = C_5 \;/\; R3A7 + C_6 * R3A6 + (1 - R3A10) * C_7$$

$$A3A11 = C_7 * R3A7 * R3A10 \;/\; R3A6$$

$$A3A12 = C_8 * A3A1^{E2}$$

$$A3A12 = C_9 * A3A1^{E3}$$

$$\begin{aligned} A3A14 = {} & C_{10} * A3A15 + C11 * A3A2/(R3A3 * R3A11) \\ & + A3A11 * A3A14 \;/\; (R3A1 * 0.15 + R3A2) \\ & + A3A10 * 2920 * C_{12} \;/\; (R3A1 * 0.15 + R3A2) \end{aligned}$$

$$A3A15 = f\;(A3A6)$$

nomenclature: A4B9

Attribute Requirement

No. of element

Letter of subelement

No. of attribute or requirement

$$C_3 \left[\frac{kw \cdot h}{Mg \cdot km}\right], \quad C_4 \left[\frac{Mg}{kw \cdot h}\right], \quad C_5 \left[\frac{Man \cdot h}{h \text{ of ops.}}\right]$$

$$C_6 \left[\frac{Man \cdot h}{h \text{ of ops.} \cdot Y}\right], \quad C_7 \left[\frac{Man \cdot h}{h \text{ of ops.}}\right], \quad C_{10} \left[\$/kg\right]$$

$$C_{11} \left[\$/kwh\right], \quad C_{12} \left[\$/man \cdot h \text{ on moon}\right]$$

Element 3 - Transforms for sub-element B:

$A3B1 = C_{13} * R3B3^{E4}$

$A3B2 = C_3 (R3B3 + A3B1) * R3A13$

$A3B6 = f(A3B14)$

$A3B7 = C_4 * A3B2 * 8h$

$A3B8 = (R3B2 + 0.1 * R3B7) * R3B12/(2920 * R3B3 * R3B13)$

$A3B9 = C_{14}/R3B7 + C_6 * R3B6 + (1-R3B11) * C_7$

$A3B10 = C_{15} * R3B7 * R3B11/R3B6$

$A3B11 = C_{16} * A3B1^{E5}$

$A3B12 = C17 * A3B1^{E6}$

$$A3B13 = C_{10} * A3B6 + C_{11} * A3B2/(R3B3 * R3B13) + A3B10 * A3B13/(R3B1 * 0.1KM + R3B2) + A3B9 * 2920 * C_{12}/(R3B1 * 0.1KM + R3B2)$$

$C_{14} \left[\frac{\text{man}\cdot\text{h}}{\text{h of ops.}}\right]$, $C_{15} \left[\frac{\text{man}\cdot\text{h}}{\text{h of ops.}}\right]$

Element 3 - <u>Sub-element C:</u>

$A3C1 = C_{23} * R3C1$

$A3C2 = C_{18} * R3C4$

$A3C3 = C_{19} * C_{23} + C_{20} * R3C2 * C_{21} * A3C2$

$A3C4 = C_{22} * A3C3$

$A3C5 = C_{12} * A3C3 * R3C1$

$C_{19}\left[\frac{man \cdot h}{Mg}\right]$, $C_{20}\left[\frac{1}{km/h}\right]$, $C_{22}\left[\frac{\%}{Y}\right]$, $C_{23}\left[\frac{Mg}{km}\right]$

Element 3 - <u>Sub-element D</u>:

$A3D1 = C_{24} * R3D5$

$A3D2 = R3D3 * (1-C_{25})$

$A3D3 = R3D3/C_{25}$

$A3D4 = C_{26} * A3D3^{E7}$

$A3D5 = C_{27} * A3D3/R3C6$

$A3D6 = C_{28} * A3D4^{E8}$

$A3D7 = C_{29} * C_{17}\ (A3D1 + A3D4)$

$A3D8 = A3D5 * C_{30}$

$C_{24} \left[\frac{Mg}{Km\ route}\right]$, $C_{26} \left[\frac{Mg}{KW}\right]$, $C_{29} \left[\frac{Man \cdot h}{Mg}\right]$

$C_{27} \left[\frac{man}{kw}\right]$, $C_{28} \left[\frac{\$}{Mg}\right]$, $C_{30} \left[\$/man \cdot y \text{ on moon}\right]$

Element 3 - <u>Sub-element E:</u>

$A3E1 = R3E1 * C_{31} * R3E2/R3E3$

$A3E2 = R3E1 * C_{32} * R3E2$

$A3E3 = C_{33} * A3E1^{E9} * C_{30}$

$A3E4 = C_{34} * A3E1^{E10} * C_{30}$

$A3E5 = (1 - R3E2) * R3E3 * R3E1 * C_{35} * C_{30}$

$C_{37} \left[\frac{\text{Mg}}{\text{No. of transports}} \right]$ $C_{32} \left[\frac{\text{KW}}{\text{No. of transports}} \right]$

$C_{33} \left[\frac{\text{man} \cdot \text{y}}{\text{Mg}} \right]$ $C_{34} \left[\frac{\text{man} \cdot \text{y}}{\text{Mg}} \right]$

$C_{35} \left[\frac{\text{man}}{\text{No. of transports}} \right]$

APPENDIX I: Space Transportation System Modeling for the Lunar Base and Supporting Functions

Introduction:

Space transportation elements will play a major role in the definition and operation of the Lunar Base infrastructure.

These space transportation elements include launch vehicles (earth to LEO), Orbital Transfer Vehicles (LEO to GEO, LEO to LLO), and Lander vehicles (LLO to LS).

The launch vehicles to be modeled in the Lunar Base Model fall into three major categories: 1) the existing Space Transportation System (STS); 2) Shuttle - Derived Launch Vehicle (SDV); and 3) Heavy Lift Launch Vehicles. The payload-to-orbit capability of the three launch vehicle systems increases from 1) to 3) respectively.

The SDV is viewed as an extension of the STS in that certain STS elements will be utilized, as for example SSME's and Solid Rocket Boosters (SRB's). (In this example, the SDV SRB's may use 5-segment filament-wound case SRB's as compared to the STS 4-segment steel case SRB's.)

The HLLV is seen as a new development, with only limited use of existing STS subsystems. The HLLV is also expected to provide the greatest payload to orbit at the lowest cost per Kg.

The OTV will be used to initially deliver the lunar base elements from the LEO space station to Low Lunar Orbit, at which time they will be placed on the lunar surface using a lander vehicle. OTV's will provide manned transportation as well as logistics support for the lunar base, and will carry lunar derived products, such as Lunar LO_2, back to the space station.

It has been shown in recent studies (ESO and Eagle Eng.) that the OTV has a major impact on the economics of a lunar base. Low-cost OTV operations must be achieved if lunar produced LO_2 is ever to compete with LO_2 delivered to LEO in the SDV.

Because of the importance of the OTV in the Lunar Base Scenario and the extreme sensitivity of Lunar Base economics with respect to OTV operations costs, special attention must be given the OTV when attempting to model it in the overall lunar base scenario.

It is highly probable that no single launch vehicle or OTV design concept will satisfy all the mission requirements that a lunar base will impose. Rather, a family of launch vehicle and OTV candidate concepts will be generated which have unique characteristics and capabilities. As an example, the OTV might initially use chemical propulsion, but as mission requirements intensify, consideration of electric or nuclear propulsion will allow the user to examine the effects of perturbing OTV subsystem elements (i.e., propulsion system) on the total Lunar Base Scenario.

The approach we will take in setting the groundwork for model development is to analyze the role of each "sub-element" of Space Transportation. Examples of space transportation sub-elements include the Lunar Vehicle (STS, SDV, HLLV), the OTVs, OMV, and the lander vehicles. The role of each sub-element in element Space Transportation will be evaluated, including sub-element interrelationships. The space transportation element, being one element in a large lunar base matrix, will then be related to all other applicable elements through a Transform Relationship.

In this manner, the impact of a variation in sub-element characteristics can be evaluated by determining its impact on other elements in the Lunar Base Model.

For example, a variation in OTV propulsion system specific inpulse, Isp will affect the sub-element "OTV" by changing its mission propellant requirements. This, however, will also affect other elements of the Lunar Base Model, such as lunar base LO_2 production rates, which would thereby influence the mining requirements, etc.

This impact must be iterated within the model and made available to the user as an output.

The method used to establish the framework for Space Transportation element model identification is to specify all sub-elements of the Space Transportation element. For each sub-element, the external requirements imposed upon the sub-element are defined. As example of a requirement imposed upon the OTV is a mission that requires 80,000 Kg of payload to be delivered from the space station to Low Lunar Orbit.

Due to the requirements, the OTV must possess various attributes. This would include size of the OTV, which would in turn effect is cost, etc.

The link between the requirements and the sub-element attributes are the Transform Relations. The transform relations define element and sub-element attributes. They also relate the various elements within the Lunar Base Model element matrix. Also, it is obvious that a sub-element attribute may become a requirement for another element or sub-element.

Transportation System Sub-elements

* Earth to LEO launches

  - STS
  - Shuttle derived vehicles
  - New development heavy lift launch vehicles

*Earth to lunar orbit transfer systems

  - Small two stage cryogenic aerobraked OTVs
  - Large single stage cryogenic aerobraked OTVs
  - Large propellant carrier cryogenic aerobraked OTVs
    Load oxygen only in lunar orbit
    Load oxygen and hydrogen in lunar orbit
  - Electric propulsion OTVs
    Nuclear power, oxygen propellant
    Nuclear power, other propellant
  - Nuclear thermal propulsion (NERVA)
  - Solar sail OTV
  - OMV
  - Tethers

*Earth to Mars orbit transfer vehicles

  - Conjunction class, all cryogenic vehicles
  - Opposition class, all cryogenic vehicles
  - Opposition class, all cryogenic aerobraked vehicles
  - NERVA vehicles
  - Nuclear electric vehicles
  - Soalr sail OTV

*Earth to asteroid transfer vehicles

  - All cryogenic
  - Nuclear electric
  - NERVA
  - Solar sail

*Lunar orbit to lunar surface

- -Small expendable cryogenic lander
- -Small expendable cryogenic ascent vehicle
- -Reusable, single stage lander for propellant transfer, lunar surface and maintained, all propellants loaded on lunar surface or only oxygen loaded
- -Reusable, single stage lander for propellant transfer, LEO based, hydrogen loaded in LEO and oxygen loaded on the lunar surface or all propellants loaded on lunar surface
- -Reusable lander, LLO based and serviced loading either oxygen only or oxygen and hydrogen on the lunar surface
- -Single stage LEO to lunar surface vehicle, reloading with propellants in lunar orbit
- -Single stage, reusable or expendable, LEO to lunar surface vehicles, loading all propellants on the lunar surface or in LEO

*Facility elements

- -Earth surface additional launch facilities
- -Space station additional propellant storage, maintenance, crew quarters, and special equipment required
- -Low lunar orbit vehicle maintenance and propellant storage and transfer equipment required

General Requirements

*Payload requirements

- -mass inbound/down, Kg
- -mass outbound/up, Kg
- -volume inbound/down, M^3
- -volume outbound/up, M^3
- -diameter inbound/down, M
- -diameter outbound/up, M
- -maximum temp., °K

-minimum temp., °K

-maximum vibratory loading, g^2/cps

-maximum acoustic loading, db, min

-maximum longitudinal accel., gs

-maximum transverse accel., gs

-maximum lateral accel., gs

*Launch success probability, %

Crew size

-up

-down

*Number of passengers

-up

-down

*Life support duration, hours

*Timeline

-time on surface, days/mission

-time in lunar orbit, days/mission

-time in LEO, days/mission

*Number of missions required

*Number of dockings/rendezvous required

*Engine parameters

-Isp, sec

-mixture ratio (O/F)

*Orbital mechanics requirements

-departure orbit apogee (KM)

-departure orbit perigee (KM)

-departure orbit inclination (deg.)

-intermediate orbit apogee (KM)

-intermediate orbit perigee (KM)
-intermediate orbit inclination (deg.)
-destination orbit apogee (KM)
-destination orbit perigee (KM)
-destination orbit inclination (deg.)
-midcourse correction ΔV, m/sec
-other maneuvering req. ΔV; m/sec

GENERAL ATTRIBUTES

Subsystem	Mass Kg	DDT&E millions$	Lifetime #missions	Maint. Manhours per mission hrs	Unit Cost million$	OPS Cost per mis. million$	MTBF #missions	No. Units Req.	Life Cycle Cost millions$
-Main propulsion									
engine(s)									
tankage									
pump(s)									
-RCS (inert)									
-Structure									
cargo pad									
landing gear									
crew component									
other									
-GN&C									
-Communications									
-Data management									
-Electrical power									
-Hydraulic power									
-Life support									
dry mass									
consumables									
-Crew systems									
suits									
other									
-Total (dry)									

GENERAL ATTRIBUTES (Cont.)

	Loaded in LEO	Loaded on LS	Loaded in LLO	Total Capacity
*Fluid mass, Kg				
main propulsion, oxidizer, Kg	*	*	*	*
main propulsion, fuel, Kg	*	*	*	*
RCS oxidizer, KG	*	*	*	*
RCS fuel, Kg	*	*	*	*
*Life support consumables				
oxygen, Kg	*	*	*	*
scrubbers, Kg	*	*	*	*
water, Kg	*	*	*	*
food, Kg	*	*	*	*

*Vehicle total wet mass and time history of vehicle mass, Kg

*Main engine parameters
  expansion ratio
  chamber pressure, PSIA
  no. of engines
  thrust per engine, Newtson

*Assembly in LEO parameters
  no. of shuttle of other vehicle loads to bring up dry mass
  manhours EVA and IVA to assemble in LEO
  special equipment in LEO req. to assemble

Disposal method for vehicle at end of lifetime

TETHERS

SUBELEMENTS

Vehicle attachment

Tether

Reel

Control System

REQUIREMENTS

Net Momentum Transfer Required

Equivalent Delta Vee

Release orbit restrictions

Available tether materials properties

Thermal and Aerodynamic regime

Gravity Gradient regime

Frequence of Operations

Vehicle Mass

Transport Node mass

Ultraviolet and atomic oxygen environment

ATTRIBUTES

Reel mass

Tether mass

Tip mass

Reel power requirements

Tether life

Tether handling requirements

Final vehicle and transport node orbits

Required transport node mass

Transport node momentum change

Transport node operational constraints

ELECTRIC MOMENTUM GENERATION

SUBELEMENTS

Electric thruster

Power Source

Propellant source (except for electrodynamic tethers)

REQUIREMENTS

Momentum required

Momentum loss due to other systems

Acceptable orbit variations

Transport node mass

Thruster and power systems performance

ATTRIBUTES

System mass - thruster and power system <u>or</u> marginal increase in power system

Duty cycle

Propellant requirements

Maintenance requirements

Orbital elements vs. time

Transport node operational constraints

APPENDIX J: EXAMPLE ESTIMATE OF LUNAR OXYGEN PRODUCTION PLANT MASS

ELECTROLYSIS OF MOLTEN SLAG: A crude mass estimate for a plant to electrolyze molten slags derived from lunar minerals can be made as follows:

Oxygen production via slag electrolysis proceeds as follows. Regolith is mined, and a specific feedstock (e.g., ilmenite) is concentrated by beneficiation. The feed material (minus tailings) is slowly introduced into the electrolysis cell where it dissolves in the liquid slag. The slag flows through the electrolysis cell and is discharged after sufficient amount of electrolysis. The Ferrotitanium product is also discharged periodically. Hot oxygen is cooled and sent to a liquifier for condensation and storage.

Thermodynamic data indicate that platinum may be adequately resistant to oxidation to be used as anode material.

It has been assumed that an iron bearing material is electrolyzed, as iron is more easily reduced than any other abundant lunar element. The mineral of choice is ilmenite, since it yields a fluid and conductive slag.

The electrolysis is carried out so as to consume half the iron, so that the residual slag will have an adequately low liquid temperature to be tapped, and so that no second phase can form from siliceous impurities in the feed. This means that a net 5.41% of the input feed is converted to oxygen.

If 1000 metric tons per year of oxygen are to be produced, 18,500 tons of ilmenite are required per year. If 5 to 15% of the mined soil is recoverable ilmenite, 1.23×10^5 to 3.75×10^5 tons of soil must be mined per year. Mining and beneficiation plant mass requirements are estimated 9.0 to 18.0 tons per year at 90% duty cycle or 20.3 to 40.5 tons at 40% duty cycle. These estimates are derived as follows:

Assuming a 10 cm slag bath depth at 1500°C and using known diffusion constants and conductivities, the optimum current density for energy efficient oxygen production is about 0.5 A/cm_2. This leads to a power efficiency of about 30%, and a required anode area of about 76 m^2 to produce 1000 tons of oxygen per year at 40% duty cycle. Using 190 watt per kg power, this gives 23 tons of powerplant to produce the oxygen from the slag.

Assuming the anode is composed of platinum 1cm thick or so, it has a mass of about 10 tons (and a present market value of about $110,000,000). The anode passes about 380 kiloamps, so the conductor to it must have a cross section of about .1 m^2, a a mass of about 1 ton per meter. If the plant is situated in the center of the power generating area, the equivalent conduction distance is about 40 meters. Thus, there are about 40 tons of wires in the plant.

The electrolysis unit must be in a pressure can about 10 meters across. Sizing this can to hold 1 psi with a safety factor of 10 indicates it will be less than 10 tons, so the mass will be taken as 10 tons. An additional 10 tons of refractory lining to protect the pressure container from the slag bath will be necessary.

Oxygen liquification is described in prior work, and is not discussed here since it is somewhat dependent on reliquification requirements for storage. The mass of the storage facility is dependent on the frequency of oxygen delivery, so it is not given and may be most conveniently described by making it a part of the transportation system.

This is a rough estimate of plant mass (inclusive of power system but exclusive of oxygen liquification and storage) is 113 to 133 tons delivered to the lunar surface.

Lunar Hydrogyn Extraction

There is a certain amount of solar wind implanted hydrogen in lunar soils. It is possible to extract this by heating the soils. There have been some hydrogen desorption vs. heating rate studies by Gibson _et al_. at JSC, which can be used to develop preliminary engineering data on a system to extract lunar hydrogen from the regolith.

There are two kinds of hydrogen in the lunar soil grains; surface correlated hydrogen which is related on heating to 500-700°C, and bulk hydrogen which is released on melting the sample. The ratio of these is about 1:1, although significant variation is present. Significant surface correlated hydrogen has been found in all lunar samples specifically examined for it. Surface correlated hydrogen becomes depleted with depth in the lunar regolith.

Gibson reports that lunar soil must be heated to 700°C in vacuo for approximately an hour with no significant hydrogen loss. Little hydrogen is released below 500° C so initial heating can be done with concentrated solar radiation. Heating from 500 to 700° must be carried out in the process vessel in order to contain the hydrogen evolved. The heat must be supplied electrically by induction heating due to the insulating nature of the regolith. This determines the process heat demand. The material must be held for 1 to 2 hours in the process vessel. This determines the vessel size.

The modeling should evaluate whether it is more economical to only recover the surface correlated hydrogen than to recover all of the hydrogen because this minimizes the electrical heat demand. Recovering all of the hydrogen present would approximately halve the amount of soil required.

A discussion of plant mass estimates for hydrogen production are given below. Solar power is assumed due to the extreme penalty of not being able to use direct solar preheating.

Recovering 50 ppm of hydrogen from the lunar soil, a reasonable value from the literature data, a baseline plant makes 80 tons of hydrogen per year. The heat demands are 80 MW of concentrated sunlight and 31 MW of electricity (70 and 90% efficiency in heating) while the sun is up. These are used to heat 9600 tons of soil per hour.

An upper limit for plant mass has 100 tons of mining equipment (Gertsch, Space Manufacturing 6), 25 tons of solar heaters, 300 tons of solar electrical generating capacity, 31 tons of RF power converters, and 100 tons of process vessel and associated equipment. This gives a total mass of 556 tons.

An advanced design plant has 50 tons of mining equipment (assuming 50% weight savings on redesign), 10 tons of solar heat, 80 tons of electrical heat (assuming higher specific power and lower temperature rise), 15 tons of induction power supply, and 50 tons of process vessel for a total mass of 205 tons.

An optimistic advanced plant may have 30 tons of miner, 10 tons of solar heat, 60 tons of electrical power supply, 12 tons of induction heater and 30 tons of process vessel. This plant design is based on finding an area of the regolith which is significantly enhanced in hydrogen content. It may also be possible to concentrate hydrogen by concentrating soil components which are enriched over the average abundance.

(APPENDIX J CONTINUED)

PERFORMANCE UNCERTAINTY

The performance, production costs, operating costs, and development costs of any item or system which does not yet exist are uncertain to some extent. There is great variability in the extent of uncertainty associated with different items. These statements are obvious. It is less obvious how to address cost and performance uncertainty in any modeling process.

Accounting for performance uncertainty accurately is very difficult. One simple approach is to make the expected uncertainty inversely proportional to the number of like items which have been made in the past and to the amount of effort (perhaps as measured by dollars) which has been expended on development or design studies for the item in question.

Using these criteria, vehicle performance is extremely well understood (1% uncertainty), power system performance is reasonably well understood (5% uncertainty), habitat and life support performance are a bit uncertain (25% uncertainty) and manufacturing plant performance is poorly understood (100% or more uncertainty).

Performance uncertainty grows as the item under consideration becomes farther removed in time or in technological sophistication from the present state of the art. Thus an advanced cryogenic engine has lower performance uncertainty than an electric thruster.

Any modeling system developed to study a lunar base must account for these uncertainties. It would be desirable for the model to perform sensitivity analyses over the range of expected uncertainty in any system parameter. Thus, sensitivity to engine I_{sp} variation would be calculated over a few seconds, while sensitivity to hydrogen plant mass would be calculated over 50 or 100 tons.

APPENDIX K: COMMUNICATIONS, COMMAND, AND CONTROL

SUBELEMENT	REQUIREMENTS	ATTRIBUTES	TRANSFORMS
On-Orbit	Provide high-resol-	Transmission	Attribute/
Command module	ution imagery	rates	KW
TDRS	Provide survey		
Survey/	Earth-moon tracking	Operation rates	
science	and relay		
TDRS-HALO		Memory Storage	
satellite	Maintain Mission		
	Control/document-	Mass	
Surface	ation	Vol.	
Mission		Power	
Operations	Maintain Ground		
Center	Communications		
		Frequency	
Deployable/	Mobility		
erectable			
antenna	Autonomy		
systems			
	Lifetime		
	Reliability		

APPENDIX L: MINING

The basic structure of a lunar mining operation which for our purposes will be assumed to include the operations shown in Figure Y and described below:

Overburden stripping:	Clearing the site of zero or low value ore and exposing the high value ore. The critical parameter is overburden ratio; the mass of overburden which must be excavated, moved, and dumped per unit mass of ore extracted. This parameter is a function of the mining method and mine design.
Ore excavation:	The physical process of freeing the ore from its place of origin, lifting it, and discharging it to the transportation system.
Transportation:	The physical process of moving the ore from the excavation site to the processing plant. It might include intermediate storage to accommodate different duty cycles in the mining and processing operations.
Size reduction:	The physical process of crushing the ore to increase its surface-to-volume ratio. This may be required to obtain acceptable recoveries in both beneficiation and extraction processes.
Beneficiation:	The physical/chemical process of increasing the concentration of the desired constituent per unit mass of ore retained in the system. This produces an ore concentrate and a tailings which reduces the mass of ore to be processed but also results in a net loss of desired constituents.

Simple models of this system can be constructed. For instance, the energy requirement (P_M) in equivalent kw can be related directly to the mass (M) of ore concentrate produced by the mining systems by

$$P = KM$$

The system constant K is a complex function of the many operating parameters which describe the individual sub-element operations. One possible general relationship is

$$K = \alpha_{OS} K_{RO} + \alpha_x (1-f_x) + \alpha_T [(1-f_x) + f_T] L_T$$

$$+ \alpha_{SR} (1-f_x) K_{SA} + \alpha_B (1-f_X) (1-f_{SR})$$

where

α_{OS} = energy requirement per unit overburden mass

K_{OS} = overburden ratio

α_x = energy requirement per unit mass of ore

f_x = fraction ore lost during extraction

α_T = energy requirement for ore transport

f_T = fraction of ore lost during transport per unit of transport distance

L_T = transport distance

α_{SR} = energy requirement for size reduction

K_{SA} = increase in specific surface area during size reduction

Y = empirical exponent

α_B = energy requirement during beneficiation

f_{SR} = fraction of ore lost during size reduction

The numerical value of each constant is dependent upon

- the type of technology to be used in each sub-element
- the type of equipment used to implement the technology used in each sub-element.

The values are best determined by developing conceptual level engineering descriptions of at least three possible moon mining systems where two different technologies and two different scales of production are used:

Similar relations can be established for:

- equipment cost
- equipment weight
- operating/maintenance labor
- maintenance materials
- O & M cost

These relationships are expected to be non-linear rather than linear as in the power relationship. They are also highly dependent upon system decisions which have yet to be made such as those regarding single purpose vs. multipurpose vehicles and operating methodologies. Two such examples are:

- The mine excavator could be used initially as a habitat construction vehicle and at later stages as a ground transport vehicle, waste burial vehicle, etc. in addition to its mining role. Allocation of the cost of this vehicle FOB the lunar base and vehicle O & M cost to various parts of lunar base operation must be decided.

- Lunar soil moving operations at the mine could be completed most optimally in a little as one or two days per week of beneficiation/extraction operations freeing the mining vehicle(s) for other duties during the remaining time. Again, this affects vehicle size, cost, and the allocation of those costs.

It is clear that screening studies must be done to identify most probable scenarios and eliminate technologies which have little potential for cost effective lunar operations. Given these results, a few mining scenarios can be selected for model development. These models can be used for optimization of the overall lunar base model and suboptimization of mining element design and operations within the larger context of the overall lunar base model.

The input variables (requirements) and output variables (attributes) for such models are listed for each sub-element in Table Z.

FIGURE C-1

Mining Operations Flow Diagram

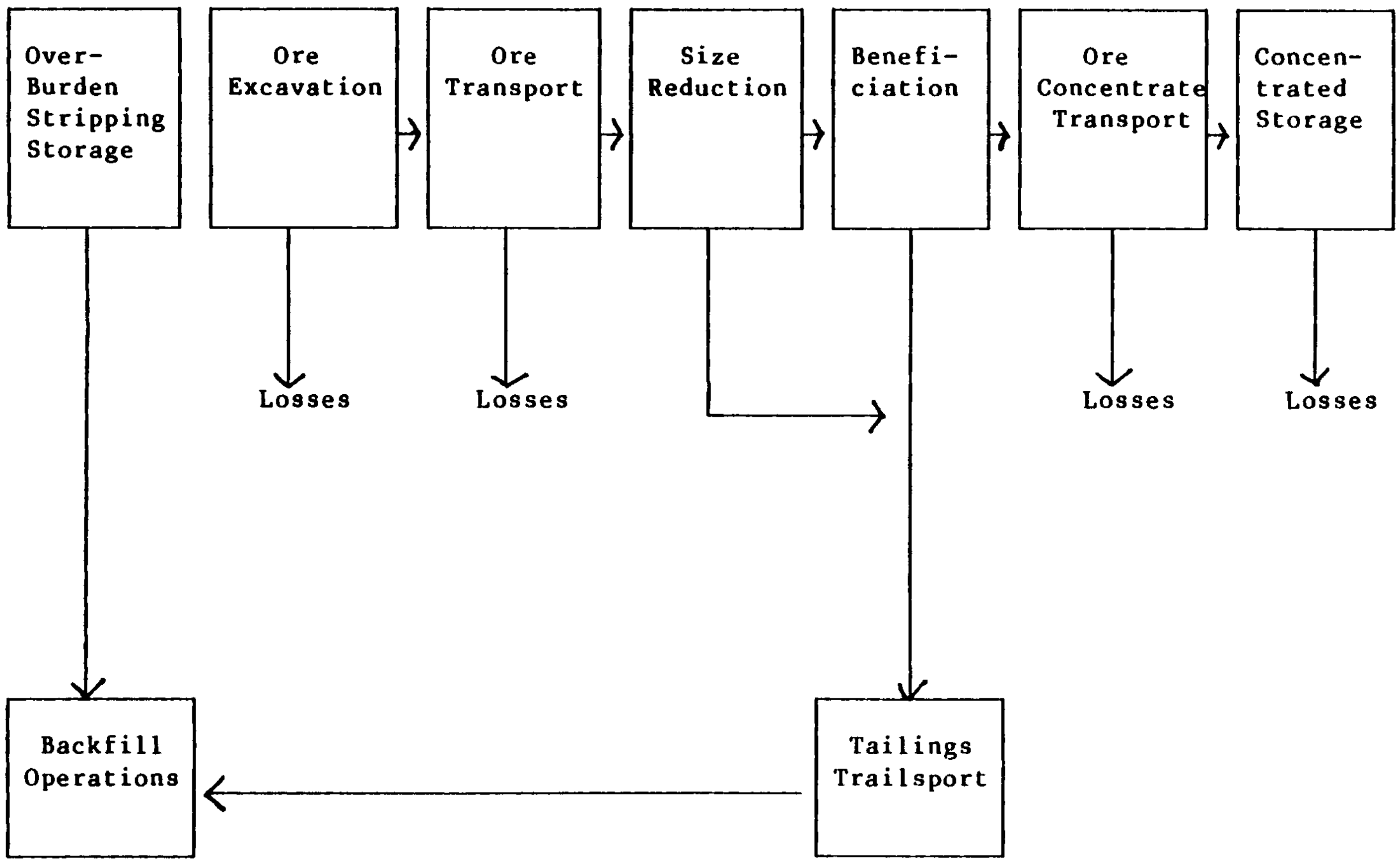


TABLE C-2

ELEMENT - MINING

SUB ELEMENT	REQUIREMENTS	ATTRIBUTES
1. Overburden stripping	1. Overburden ratio Stream factor	All - Power requirements Earth produced equipment/shelter weight Maint. Mat'l weight/year Operating and maintenance labor Capital cost FOB lunar base O & M cost
2. Ore excavation	2. Mass rate to benefication Stream factor	
3. Transport	3. Distance Stream factor	
4. Size reduction	4. Run of mine particle size dist. Manufacturing plant part. size dist. Stream factor	
5. Benefication	5. Run of mine composition Manu. plant feed composition Mass rate to manu. plant Stream factor	
6. Waste/overburden backfill	6. Beneficiation reject mass rate Manufact. plant waste mass rate Stream factor	

APPENDIX M: MANUFACTURING ON THE MOON

The subelements of a generalized manufacturing facility on the lunar surface are shown in table M-1. Examples are discussed below.

Mat'ls inventory: This is the receiving, storage, and dispensing facility for all raw materials, maintenance materials, and other quantities consumed by the manufacturing operation.

Feed Preparation: This includes any physical/chemical modification of feed materials which are essential to prepare them for the primary manufacturing operations (PM). Such activities could include disassembly of space transport modules, removal of paint from same, etc.

Thermal Processing: This is any primary manufacturing operation (PMO) which involves heating, cooling, or phase change as its primary function such as hydrogen boiloff from regolith.

Chemical Conversion: This is any PMO which is based upon conversion of one or more chemical constituents to different chemical forms such as Ilmenite to water to oxygen.

Purification: Any PMO intended to improve the quality of either a raw material or a product such as urea recovery from human urine.

Fabrication: Any PMO which produces finished physical forms such as sheet metal, cinder blocks, etc.

Assembly: Any PMO which creates a product from components such as satellite assembly.

Packaging: Any operation which prepares a product for export from the manufacturing facility such as painting, encapsulation, etc.

Product Inventory: Storage to accumulate production for bath shipment or usage.

Waste Heat
Rejection: This is the lunar analog of the terrestial cooling tower essential to any manufacturing facility which uses thermal energy or produces waste thermal energy via mechanical work.

Waste Solids
Disposal: This reclaims all usable solid materials for recycle and exports all non-usables for disposal.

The LO_2 and LH_2 manufacturing facilities can be described in terms of these subelement components. Other examples of potential manufacturing facilities are:

- production of metal powders and shapes from lunar minerals for propellant use, structural shapes, etc.

- manufacture and reclaiming of water.

- forming of aggregate blocks from lunar regolith for structural construction.

- hydroponic production of foodstuffs.

- reclaiming of usable gases constituents from habitat atmospheres

- processing of human wastes for usable chemicals such as ammonia, urea, methane, nitrogen.

- maintenance of appropriate biochemical environments to preserve the human immunity system for eventual return to Earth.

A single generalized mathematical model relating input or independent variables (requirements) to output or dependent variables (attributes) would not be cost-effective. These input-output relationships are highly specific to the products made and the individual technologies selected to carry out the production.

It is recommended that product specific models be developed for each product considered worthy of production for lunar consumption and/or export to space. For those products where alternative technologies exist, screening studies should be carried out to identify the most probable technology and the limits of its lunar application. Models should then be developed for the selected technologies.

All models should be based on conceptual level engineering descriptions at levels of detail commensurate with the relevant moon resource data, transportation cost estimate, energy cost estimate, etc.

The structure of such a model can be visualized as shown in Table Y. Here an interactive model is proposed where the user first provides basic problem definition via inputs, establishes a design basis via question/answer (Q/A) interactions with the model, the model then constructs an engineering description of the manufacturing facility via use of computational routines, some sub-optimization of the engineering description can be authorized by the user, who then elects to output part or all of the engineering and east data.

The data base necessary to support such a model will include information such as that listed in Table 1.

TABLE M-1

ELEMENT - MANUFACTURING (GENERALIZED)

SUB-ELEMENT	REQUIREMENTS	ATTRIBUTES
1. Materials inventory	1. Consumption rates Conservation efficiencies Maintenance materials	1,9 Enclosed volume and its capital cost
2. Feed preparation	2. Size reduction Phase change Disassembly Cleaning	2-8, 10, 11 Equipment weight, Equipment cost Operating labor Consumables mass rates By-product mass rates Energy requirements
3. Thermal processing	3. Production rate	
4. Chemical conversion	4. Production rate Product mix	
5. Purification	5. Product specifications Production rate	
6. Fabrication	6. Product specifications Production rate	
7. Assembly	7. Product specifications Production rate	
8. Packaging	8. Transport requirements Physical form	
9. Product inventory	9. Production rate Production reserve	
10. Waste heat rejection	10. Production rates Thermal efficiencies	
11. Waste solids disposal	11. Production efficiencies/rates	

TABLE M-2

Inputs	Inputs	Q/A	Q/A	Q/A
Product Type	Production Specifications	Process Alternatives	Site Information	Process Parameters
	*Rate as f (time) *Chemical specs. *Physical specs. *Values	*By-products? *Moon derived feedstocks only? *Earth derived feedstocks? *Energy sources? 1. Solar 2. Nuclear	*Non-specific? *Location? *Topography? *Resource data? 1. Composition 2. Vertical extent/variation 3. Lateral extent/variation 4. Estimated mineable reserves *Waste disposal constraints? *Maximum load bearing stress Include Confidence Intervals	*Benefaction? 1. Efficiency 2. Recovery * Chemical conversion 1. Primary product yield 2. By-product yields *Recycle efficiencies 1. Consumable chev. 2. Thermal energy *Electrical effi-ciencies *On-stream factors *Turnaround frequencies Include Confidence Intervals

TABLE M-2 (Cont.)

Computational Routines	Potential Sub-optimization	Outputs
*Constituent Balances	*Minimum earth equipment wt	*Production data
*Mass Balance	*Minimum bubble size	1. Products (Gross &
*Energy Balance	*Maximum value of produced products	2. By-products Export)
1. Thermal	*Minimum earth derived feedstocks	*Consumable quantities
2. Electrical	*Preventive maintenance vs. unscheduled shutdown vs. redundant systems	1. Chemical
*Major equipment sizing/wts		2. Thermal
*Minor equipment sizing/wts		3. Electrical
*Bubble size/wt		4. Maintenance materials
*Site preparation		*Waste product quantities
*FOB lunar site equipment cost		1. Solid
*Lunar site erection		2. Gaseous
1. Schedule		3. Thermal energy
2. Labor		*Process description
*Operating costs		1. Block flow diagram
1. Labor		2. Block description
2. Maintenance		3. Layout
		*Facility description
		1. Major systems
		2. Support
		*Labor requirements
		1. Construction
		2. On-site operations
		3. Off-site maintenance
		*Total Facility
		1. Size
		2. Weight
		3. Lunar surface area
		*Costs
		1. Earth manuf.
		2. FOB site
		3. Total capital
		4. Operations
		5. Maintenance
		6. Product as 8 (bP)
		7. Life cycle
		*Ad infinitum

TABLE M-3

1. Resource

   A. Extent and variability data
   B. Average content per unit bulk volume
   C. Topographical problems
   D. Constructability of site
   E. ETC.

2. Chemical Processing for each technology

   A. Beneficiation efficiencies
   B. Conversion efficiencies
   C. Energy requirements
   D. Recycle (consumable mat'ls recov.) eff.
   E. Heat rejection requirements
   F. Waste production/disposal
   G. On stream factors vs. cost
   H. Labor vs. automation cost/reliability

3. Manufactured Products (each has one or more technologies)

   A. LO_2
   B. LH_2
   C. Metal powders
   D. Metal shapes
   E. H_2O
   F. Construction materials
   G. Food
   H. ETC.

4. Reclaimed Products

   A. CH_4
   B. Urea
   C. Human organisms
   D. H_2O
   E. CO_2
   F. N_2
   G. NH_3
   H. ETC.

CHEMICAL PROCESSING

Processing of lunar materials into a different chemical or physical form is very complex and poorly understood. A "laundry list" of process variables has been generated. most of these variables do not interact with the overall lunar base design. Many of them describe interactions among the various unit operations blocks. Optimizing plant design is probably as difficult as modeling the rest of the lunar base program. Some adequate means of optimizing oxygen and other product plants without having to model them fully is probably needed.

There are a lot of possible chemistries to choose from. Two randomly selected ones have been described in limited detail.

ELEMENT:

Oxygen production factory using carbon reduction of molten ilmenite combined with solid state electrolysis of carbon dioxide.

SUBELEMENTS:

Miner
Beneficiator
Reduction reactor
Off gas disproportionator
Electrolysis cell
Radiator
Liquefier
Storage

SUBELEMENT	REQUIREMENTS	ATTRIBUTES
Miner	Mine model Avg. production capacity Transport distance	Duty cycle Mass Size Setup effort Operating effort PM effort UM effort Pit geometry Power consumption Surge storage Spares inventory Spares consumption Failure profile
Beneficiator	Feed compositions Avg. Prod. capacity Output composition Transport distance Feed storage requirements	Duty cycle Mass Size Setup effort Operating effort PM effort UM effort Power consumption Surge storage Spares inventory Failure profile Spares consumption Product composition Product/feed ratio Trailings/feed ratio

SUBELEMENT	REQUIREMENTS	ATTRIBUTES
Reduction reactor	Feed composition Feed temperature Avg. production capacity Output compsition constraints Feed storage Output pressure	Duty cycle Mass Size Setup effort Operating effort PM effort UM effort Power consumption Spares inventory Spares consumption Product composition Failure profile Product properties Product temperatures
Off gas disproportionator	Feed rate Feed composition Feed temperature Feed stream factor Input pressure	Size Mass Duty cycle Power consumption Spares inventory Spares consumption Output pressure Setup effort Operating effort PM effort UM effort Product composition Heat rejection requirement Output temperatures
Solid state electrolyzer	Feed rate Feed composition Feed temperature Feed stream factor Input pressure	Size Mass Duty cycle Power consumption Spares inventory Spares consumption Heat rejection Output pressure Output composition Output temperature Setup effort Operating effort PM effort UM effort
Reduction Reactor		Output composition Heat consumption Spares consumption Spares inventory Failure profile Pressure drop

SUBELEMENT	REQUIREMENTS	ATTRIBUTES
Electrolysis Reactor	Feed composition Feed temperature Avg. production cap. Input steam factor	Output composition Power consumption Efficiency Output temperature Duty cycle Mass Size Setup effort Operating effort PM effort UM effort Spares inventory Spares consumption Pressure drop Failure profile
Radiator	Power rejected Rej. temperature Gas flow rate	Duty cycle Mass Size Setup effort Operating effort PM effort UM effort Setup effort Operating effort Pressure drop Failure profile
Pump	Flow rate Feed composition Pressure head Input temperature	Duty cycle Mass Size Setup effort Operating effort Power consumption PM effort UM effort Spares inventory Spares requirements Failure profile

SUBELEMENT	REQUIREMENTS	ATTRIBUTES
Liquefier	Flow rate Input pressure Input temperature Output temperature Output pressure Input steam factor	Duty cycle Mass Size Setup effort Operating effort Power consumption PM effort UM effort Spares inventory Spares requirements Failure profile Heat rejection (power vs. temp)
Storage	Temperature Pressure Input flow rate Output flow rate Size of taps Time of taps	Size Mass Setup effort Operating effort PM effort UM effort Spares inventory Spares requirements Failure profile "spillage" or "boiloff" Power requirements Heat rejection requirements

ELEMENT:

Oxygen production factory using hydrogen reduction of subsolidus ilmenite and high temperature electrolysis.

SUBELEMENTS:

Miner
Beneficiator
Reduction reactor
Electrolysis reactor
Radiator
Pump
Liquefier
Storage

SUBELEMENT	REQUIREMENTS	ATTRIBUTES
Miner	Mine model Avg. production capacity Transport distance	Duty cycle Mass Size Setup effort Operating effort PM effort UM effort Pit geometry Power consumption Surge storage Spares inventory Spares consumption
Beneficiator	Feed compositions Avg. Prod. capacity Output composition Transport distance	Duty cycle Mass Size Setup effort Operating effort PM effort UM effort Power consumption Surge storage Spares inventory Failure profile Spares consumption Product composition Product/feed ratio Tailings/feed ratio

SUBELEMENT	REQUIREMENTS	ATTRIBUTES
Reduction reactor	Feed composition Avg. production capacity	Duty cycle Mass

		Size Setup effort Operating effort PM effort UM effort Output composition Heat consumption Spares consumption Spares inventory Failure profile Pressure drop
Electrolysis Reactor	Feed composition Feed temperature Avg. production cap. Input stream factor	Size Mass Duty cycle Power consumption Spares inventory Spares consumption Output composition Setup effort Operating effort PM effort UM effort Efficiency Output temperature Failure profile Pressure drop
Radiator	Power rejected Rej. temperature Gas flow rate	Size Mass Duty cycle Setup effort Operating Effort PM effort UM effort Pressure drop Failure profile
Pump	Flow rate Feed composition Pressure head Input temperature	Duty cycle Mass Size Setup effort Operating effort Power consumption PM effort UM effort Spares inventory Spares requirements Failure profile
Liquefier	Flow rate Input pressure	Duty cycle Mass

	Input temperature Output temperature Output pressure Input stream factor	Size Setup effort Operating effort Power consumption PM effort UM effort Spares inventory Spares requirements Failure profile Heat rejection (power vs. temp)
Storage	Temperature Pressure Input flow rate Output flow rate Size of taps Time of taps	Size Mass Setup effort Operating effort PM effort UM effort Spares inventory Spares requirements Failure profile "spillage" or "boiloff"

APPENDIX N: ELEMENT--GEOCHEMICAL LABORATORY

Description: Capability for analysis of collected rock and soil samples. Level of analysis sufficient to identify interesting scientific samples for detailed analysis on Earth. Analysis of samples for possible resource exploitation.

SUBELEMENT	REQUIREMENTS	ATTRIBUTES
Access	Allow passage of persons, samples, stores, equipment. Desirable to bring sealed specimens and examine them in controlled atmospheric environment (N_2 atmos.; vacuum)	
Life-support	Support 2 to 4 persons working. (Round-the-clock utilization?) (Sporadic utilization?) (Utilization only during lunar night?)	Connected to base.
Mass Storage	Supplies, replacements, some chemicals.	
Module	Space station module.	
Equipment	Scanning electron microscope with x-ray dispersive spectrometer. X-ray diffractometer. X-ray fluorescence spectrometer. Petrographic microscope. Thin section manufacture. Computer. Small workshop. Small chem. lab.	Mass Power Volume

Power	
Environment Control	Maintain shirt-sleeve environment (space station); clean benches.
Computational Facility	Data collection, manipulation, storage. Instrument control.
Communication	Voice to rest of base. Access to central data storage for communication with Earth.

SUBELEMENT	REQUIREMENTS	ATTRIBUTES
Inputs	People	O_2
	Lunar samples	N_2 (chemically inert gas)
	Water	Chemicals
	Power	Bytes
	Vacuum	
Outputs	People	Packaged samples
	Wastes (Biological, Geological)	Data
Safety Requirements		
Mass, Volume	Equivalent to Space Station Module	

GEOLOGICAL INVESTIGATIONS (TRAVERSES)

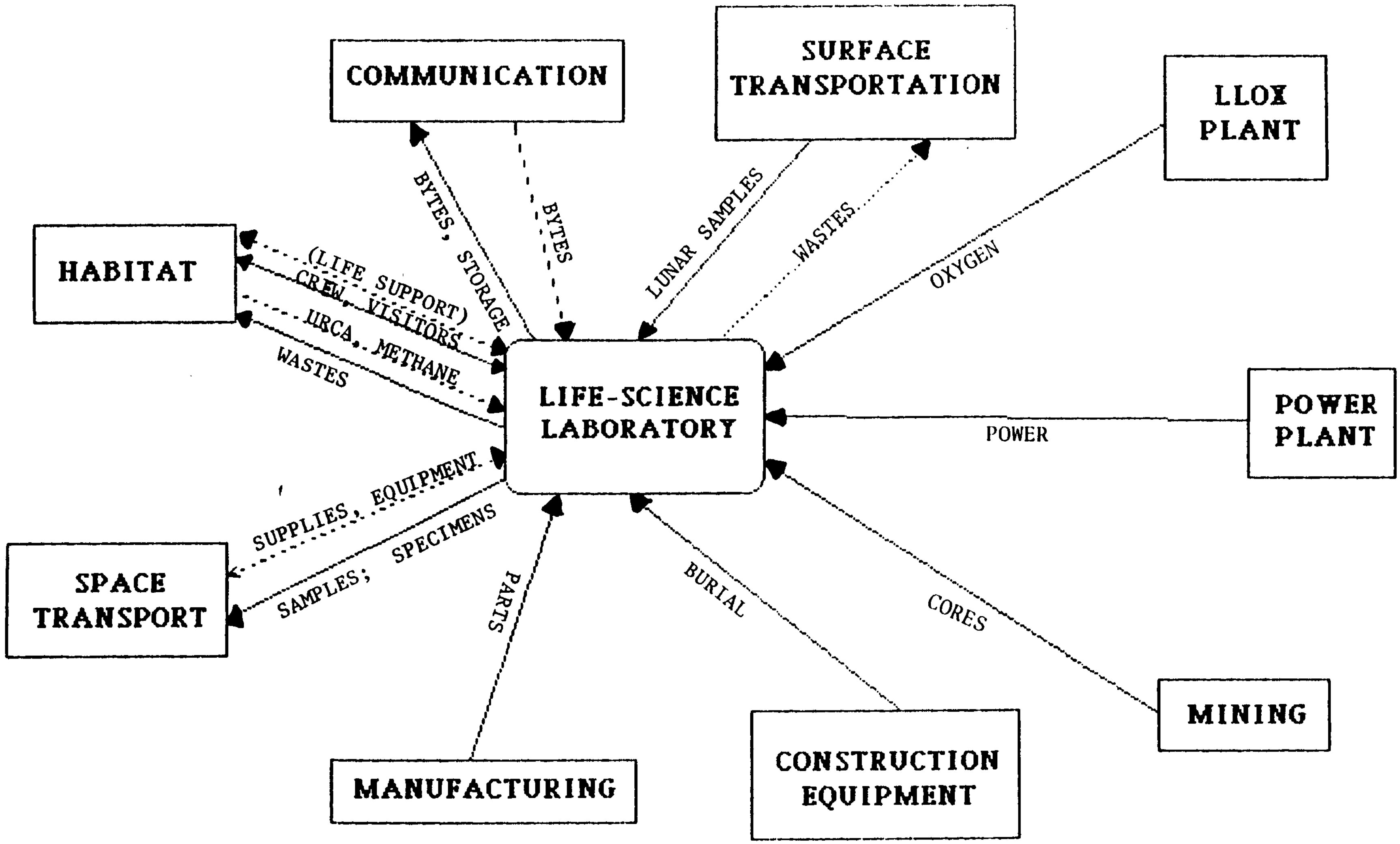
[TRAVERSE VEHICLE WITH LIFE SUPPORT]

Description:	Two or more geologists travel to a remote site for geologic investigation. Time spent at the site will be at least two days. Distance to the site should be at least 50 km from the base. Scenarios could include traverses up to thousands of kilometers lasting for months.	
Sub-elements:	Requirements	Attributes
Access	Airlock or depressurization for EVA. Possible collection of samples with remote arm.	
Life-support	4 or more days of air, water, food, waste storage for 2 or more people. Shirt-sleeve environment nominally.	
Mass Storage	Supplies, collected samples, deployable equipment, waste storage.	
Vehicle	Range, speed, slope climbing capability, rough terrain capability.	

GEOLOGICAL TRAVERSE VEHICLE

Sub-element:	Requirements	Attributes
Equipment	Scanning electron microscope with x-ray dispersive spectrometer. Petrographic microscope. Deployable geophysics experiments. Traverse geophysics, gravity, magnetism. Limited drilling & coring capability. Geological land tools.	
Environment Control	Shirtsleeve working environ.; dust control from EVA's	
Computational Facility	Data collection, instrument control, monitoring vehicle subsystems	
Communications	Voice back to control base (Relay satellite). Warning for imminent solar flare event.	
Mass, Volume	Less than space station module.	
Power	Portable, rechargeable.	
Safety	Require emergency procedure in case of solar flare. Probably consists of excavation under vehicle.	

LIFE SCIENCE LABORATORY/LUNAR ELEMENTS INTERACTIONS



ELEMENT - BIOLOGICAL LABORATORY

A. Assumptions

1. Lunar science module(s) derived from space station science module(s)

2. Experiments are life-science oriented (bio-medical, space biology, celss, exobiology experiments)

B. Systems Analysis [Functions]

Egress/ Exit	Life Support	Supply Storage	Communication	Computers
Spe-cialized Eqpt.	Environ. Control	Clean Room	Control Temperature of Rooms	

C. Inputs

1. People
2. Lunar materials
3. O_2
4. Water
5. Power
6. Bytes
7. Biological specimens
8. Chemicals
9. Stores, supplies

D. Outputs

1. Bytes
2. People
3. Wastes
   - -solids [chemicals--toxic, non-toxic, lunar materials, specimens]
   - -liquids [urine, solvents, toxic and non-toxic solutions]
   - -gases
4. Records
5. Heat
6. Materials for terrestrial analysis

ELEMENT LABROATORY (BIOLOGICAL)

SUB-ELEMENT	REQUIREMENTS	ATTRIBUTES (vol.,mass, power, etc.)
Entrance/exit	Allow passage of persons,sample specimens, stores, etc. Direct EVA? (soil a problem)	EVA; non-leakage, dust removal
Life support	Connected to base system or separate? For 4 persons; separate for animals, plants? Life-boat concept requires separate system.	4 KW (see habit. element)
Mass Storage	Store toxic & non-toxic chemicals, solvents, gases, etc.	15% of volume $20M^3$, safety provisions for fires, explosions.
Module	Space-station module	4.27M diam. x 9.8M L = $140M^3$
Equipment	Carry out experiments for celss, Space biology, biomedical, exobiology in safety	60% of volume = $80M^3$ Protection from fires, spills, explosives etc. 10-20 kw
Environ. Control	Maintain shirt-sleeve environment (space-station)	1 kw
Computer	Data collection, manipulations, storage, experiment control	Sensors, bulk storage device
Communication	Receive and transmit information outside of laboratory	Appropriate rate
Clea Room	Maintain biological barrier & dust-free area	Air-flow, filters; UV lamp
Temperature Controlled Rooms	For incubation and growth studies for microbes, plants, animals, cells, etc.	Temp, humidity, gas concentration, air flow filters, illumination

ELEMENT = FARM

SUB-ELEMENT	REQUIREMENTS	ATTRIBUTES
Pressure chamber	Contain all sub-elements required for food production	Area = $25M^2$/person Volume = $25M^2 \times 1.5M$ = $37.5M^3$/person Additional volume = $10M^3$/person Total volume = $47.5M^3$/person
Water	Water for plant growth for 1 person	2000 kg/person
Water storage	Store water for plant growth	1 tank = 73.5kg tank capacity, 22.9kg/tank dry weight 27 tanks/person
Plant support structure	Suuport plant mass & nutrients	7.2 kg/M^2 180 kg/person
Light & support structure	Artificial illumination for plant growth	34 kg/M^2 850 kg/person 400 w/M^2, 10 KW/person
Control console and gas analysis	Monitor & control Plant environmental parameters	16 kg (fixed wt) 250 W
Humidification/ Dehumidification equipment	Maintain optimal relative humidity (= 75%)	68 kg/person 650 W/person
Thermal control	Maintain temperature during growth period, ventilation, heat transport and rejection	1.5 KW/person

Food processing equipment	Produce edible food from plant harvest	134 kg/person
Food waste	Waste produced in growing food plants	17.4 kg/person/day
Waste processing equipment	Process food, human, trash wastes	60 kg/person

APPENDIX O

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FOR

NASA/LSPI WORKSHOP ON LUNAR BASE METHODOLOGY DEVELOPMENT
August 26-30, 1985
La Jolla, California

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