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RESOURCE MODELING FOR DESIGN OPTIMIZATION: LUNAR BASE MOBILE MINER

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Technical Report

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1.0 Introduction

To accommodate mission planning tasks and tradeoff analyses, Astronautics has developed the Resource Estimation and Tradeoff Analysis Model, or RESTAM. RESTAM is a generic modeling tool which can be applied to determine resource requirements/logistics of any operation. Using parametric descriptions of technologies and operations, RESTAM determines direct resources required and the indirect resources required to support the direct resources. A major attraction of RESTAM is the flexibility of the program to allow for new technologies and different operational strategies to be integrated into a previously produced database. Through the use of RESTAM, the task of optimizing space operations and space system architectures is greatly enhanced. This paper describes the fundamentals of RESTAM and demonstrates its effectiveness as a tool for optimizing space systems design.

2.0 RESTAM Description

RESTAM is a systems engineering tool used to assist design decisions based on total resource requirements of systems and operations. RESTAM enables the creation of user-defined functional hierarchy which allows the user to analyze alternative models of systems, operations, and technologies using existing / modified data. RESTAM allows the user to define and manipulate:

- functional activities and operations
- system and technology alternatives
- infrastructure and support systems and technologies

Figure 1 shows the RESTAM modeling approach. RESTAM implements this approach on a PC/AT using Turbo Pascal. Other characteristics of RESTAM include:

- user defined functions and functional hierarchy with no limitation of number of levels
- user defined functional relationships
- user defined technology alternatives and technology parameter values
- support resources estimated through recursive iteration from direct resources

- standard / baseline data files may be called for mission functions, technologies, support infrastructure concepts, and environmental / physical parameters

This section describes the objectives of RESTAM and the fundamentals of its operation.

2.1 Objectives of RESTAM

The overall objective of RESTAM is to evaluate logistics support tradeoffs and sensitivities allowing insight to most cost effective systems concepts, operations, and technologies. RESTAM not only determines resources directly required by the system, but includes indirect resources required to support the direct resources. Since RESTAM is only a tool to determine resource requirements of a system, it can be applied to any system or operation. Thus, RESTAM provides mission planners with the means to evaluate space systems or operations to determine optimal system configurations to minimize costs.

RESTAM achieves its objective by relating functions to resources. RESTAM databases contain functions, the functional hierarchy, and resource estimation equations. The functional relationships and values of variables and parameters used are defined when creating a model from a database.

2.2 Database Development

Databases in RESTAM contain all the information needed to organize a task or to model a system or operation. The databases do not reflect the relationships of one function in a system to another, but do contain parametric relationships between all variables and parameters that would require definition to evaluate a system. Once a database is completed, many models may be run from it to evaluate system alternatives. The database may also be updated with additional functions and new technologies.

2.2.1 Functions

Functions represent required activities that must occur to sustain mission systems and operations and will be broken down by operational level. Each of the functions in each of the levels will require a different type and priority logistics support which must be quantified by a consistent set of parameters representing the efficiency and effectiveness of the function. The lowest ordered functions are referred to as primitives. Essentially, the list of primitives is a toolbox. When using the database to model an operation or system, the user must select the appropriate primitives, or tools, from the list to perform the job or accept the default tools. Defaults are defined within the database and may be edited.

2.2.2 Data/Algorithms

Each function within the database may have certain variables/parameters that define the efficiency and effectiveness of the function. The major distinction between variables and parameters is that parameters represent specific hardware selections while variables define certain characteristics of the functional relationships and task objectives. The parametric definitions of a specific function are entered into the database but the values of the parameters/variables are defined when setting up a model from a database. The data/algorithms may be edited within the database to accommodate new technologies or operational alternatives.

The data/algorithms, or system parametric definitions, are the bridge between functions and resources. Therefore, the accuracy of a model is dependent on the precision of the parametric definitions entered in the database. Since a database is created only once and used to generate many models (representing system alternatives or tradeoffs), much care must be taken in determining the parametric definitions.

2.3 Operations Modeling

The first step in the modeling of an operation is to determine the necessary functions to perform the operation and the hierarchy of the functions. Once the functions and functional hierarchy have been determined, parametric definitions of systems to perform the functions are needed to determine resource requirements. This section describes how the parametric definitions are used to determine direct and indirect resources required and how these results are outputted.

2.3.1 Calculation of Direct Resources

The parametric definitions and resource estimation equations used to calculate direct resources are entered into the database. The values of the parameters and variables used in these equations are determined by the selections the RESTAM user makes while creating a model from a database. Direct resources are calculated after creating a model from a database.

The RESTAM model developer has total control over parameter/variable values. Default values based on alternative selections are defined when setting up the database the model is run from. The user may accept or change these values. The various values used for parameters/variables in the creation of a model are stored in the database the model is being run from. Future model runs from the database would include the option to select alternatives or parameter/variable values defined in other model runs. Also, the user may refer to the model run that used a specific parameter/variable value to determine how that alternative affects overall resource requirements. Thus, the RESTAM database's options or alternatives grow from creating models from it.

2.3.2 Calculation of Indirect/Support Resources

Once direct resources have been calculated, the RESTAM user has the option to calculate support, or indirect, resource requirements for any or all of the direct resources. The major direct resources that require iteration for determination of support resources are equipment mass, electrical power, thermal power, and man-hrs. After one iteration, a requirement for thermal heat to be rejected is calculated. Following iterations would include the support of rejecting heat. The iteration process continues until a user defined value for epsilon, the ratio of support resources of a specific iteration to the sum of support resources from all iterations performed, is reached for all resources in the iteration. A schematic of the iteration process for supporting equipment mass, electrical power, and thermal power from the direct resource calculation is shown in Figure 2.

This component of RESTAM is essential in the determination of overall logistics support. For many space systems and operations, support requirements are greater than the direct resource requirements and an overall evaluation of a system or operation could not be done based on direct resources alone. The RESTAM user has total control over the iteration process and can choose to support all, or just specific resources. This flexibility allows for tradeoff analyses to be conducted on the provision of support resources, in addition to the comparison of alternatives in the direct resource calculation.

2.3.3 Output of Results

The RESTAM output system consists of five different outputs: [1]direct resource calculations broken down by functions and primitives, [2]direct resource calculation totals, [3]indirect resource calculation totals, [4]total resource requirement including both direct and indirect resources, and [5]variable/parameter listings showing the descriptions and values of all variables/parameters used in the resource calculations. Results may be outputted to the computer screen or may be written to a file and printed out.

2.4 Tradeoff Analyses

RESTAM is designed to accommodate tradeoff analyses. Based on resource estimations for a space system or operation, various alternative configurations may be compared. The direct resources required determine the operational performance of the system or operation. Indirect resources define the supportability of the system or operation. Figure 3 shows a schematic of major design trades that can be conducted using RESTAM.

Analysis of space systems or operations should include requirements for the research and development of new hardware and processes. Although a database typically does not include research and development requirements for the functions within it, a separate database within RESTAM could be created to estimate these requirements. Determination of these requirements is not necessary for systems or operations utilizing only existent technologies and hardware systems.

3.0 Database Creation for Mobile Mining System for Solar Wind Gas Extraction

The mobile mining system for solar wind gas extraction was designed by the Wisconsin Center for Space Automation and Robotics (WCSAR) for the acquisition of lunar He-3, a valuable fusion fuel element with extremely limited terrestrial sources. The system represents a very simple model for RESTAM but demonstrates the uses of RESTAM very well.

It should be noted that a RESTAM database only needs to be created once for a specific application. The database may be revised or expanded to include new technologies or additional functions. From a database, many models can be created. This section will cover how to create a database for the mobile mining system and run models from it.

3.1 Compilation of Required Subsystems and Their Related Technology Parameters

The first step in creation of a RESTAM database is to identify all the required subsystems and the technologies and technology alternatives available to the subsystem. For the mobile miner, these subsystems and technology alternatives for these subsystems have been identified. This breakdown of subsystems and subsystem technology alternatives is shown in Figure 4.

The subsystems defined here constitute the requirements for a mobile mining system to obtain solar wind gases from the lunar surface. The next step in the creation of the RESTAM database is to organize these subsystems into a functional hierarchy which categorizes these subsystems into function groups.

3.2 Identification of Functional Hierarchy

Identification of the functional hierarchy begins with determining higher order functions and the associated lower order functions required. The functional hierarchy for the mobile miner is shown in Figure 5. For the case of the mobile miner, the highest order function is to "Obtain Solar Wind Gas". This higher order function is comprised of mobile miner operations, operations at the central facility, and the gas delivery system which delivers gas storage vessels from the mobile miner to the central facility. Each higher order function must be broken down to primitive functions. Primitives, or lowest-ordered functions, have well defined relationships with resources. The relationship of primitives to resources is represented by parametric descriptions that are based on selections of function and technology alternatives.

3.3 Definition of Parametric Descriptions

The parametric descriptions consist of constants, variables, and parameters. Constants are determined using a well defined baseline configuration of the system or operation. Different values for these constants are used to accommodate small and large scale configurations.

Variables represent:

- environmental and physical characteristics
- process characteristics
- function alternative selections
- resource availability / constraints

Variables are defined by function alternative selections and have specific values relating to each alternative selection. For example, determining resources required for the regolith beneficiation system will depend on the degree of beneficiation which is represented by variables. These variables represent the ratio of beneficiated regolith to unbeneficiated and the ratio of solar wind gas content in beneficiated regolith to unbeneficiated. The value of these variables is defined by the analysis of returned lunar samples. Therefore, following the selection of the degree of beneficiation in the creation of a model from a RESTAM database, values for the beneficiation variables are set at a default value. The user can accept the default value based on lunar sampling or may choose to change the value.

Parameters represent design characteristics of system and technology alternatives. Parameters determine resources, such as mass and power, for a given technology based on special characteristics of the system or operation being modeled. For example, for the selective condensation function the technology alternatives include a solar and a nuclear power source to run a condenser to remove quantities of heat to condense specific constituents of the solar wind. The size of this power source is directly related to the quantity of solar wind gas collected. Therefore, the selective condensation parameters relate power system mass and power to the amount of solar wind gas condensed.

Variable and parameter values for the preliminary configuration of the mobile miner have been determined based on a solar power source for heating the regolith and a nuclear power source for selective condensation. In the preliminary configuration, the solar power source for regolith heating necessitates operation of the miner during the lunar day only. Also, some down time must be accommodated for which yields an overall duty cycle of 45% (operation 90% of the lunar day). Sample variable and parameter values for this preliminary configuration are shown in Table 1.

RESTAM can also import values for variable and parameters from other databases. This allows the RESTAM user to use technologies and technology parameters from other researchers to update and expand the RESTAM database.

In the creation of the RESTAM database, these variables and parameters must be defined and the resource estimation equations must be determined. However, values for the variables and parameters are not defined in the database, but are defined in the creation of a RESTAM model from the database.

3.4 Creating a RESTAM Model from the Database

This section includes a sample model creation from the RESTAM solar wind gas extraction database. The creation of a model involves defining the functional relationships from the functional hierarchy and defining all needed variable and parameter values.

3.4.1 Alternative Selections

Figure 6 shows the RESTAM Main Menu. To build a model from a RESTAM database, the RESTAM user enters 'B'. The user is then prompted for the name of the database to run the model from. The Build Model Menu (see Figure 7) shows the level the user is on and the level the user is selecting from. The past path is also shown.

From the Build Model Menu, the RESTAM user chooses to 'Select Activities / Primitives'. After making this choice, the user proceeds to make choices of technology alternatives while entering or accepting default values for the associated variables and parameters. Figure 8 shows the selection of primitive functions directly required to ~Operate Mobile Miner' (see past path). Figure 9 shows the definition of variable and parameter values associated with the primitive 'Beneficiate Regolith'. Upon the selection of option #3, <50 micrometers, default values for the associated variables and parameters appear and may be accepted or changed. These default values may be altered from th RESTAM database.

The selection process continues until all functions are defined by primitives and all required variable and parameter values are entered. RESTAM shows that the model is complete and returns the user to the Main Menu. After all selection have been made, direct resources may be calculated by choosing 'C', "Calculate Resources".

3.4.2 Sample Direct Resource Calculation

Before the direct resource calculation, the RESTAM user is prompted to choose to let RESTAM perform the calculation or to confirm all variable and parameter values involved. This feature allows a user to run a simple tradeoff without having to go through the Build Model Menu (assuming all function alternatives are the same and only parameter values are changed).

If a user decides to confirm all variable and parameter values, RESTAM shows the user the resource estimation equation, values and descriptions of all variables and parameters used, and the past path to the primitive function requiring the resource. The user can then accept or change the values of the variables and parameters used. A sample resource calculation is shown in Figure 10.

3.4.3 Sample Indirect Resource Calculation

After RESTAM completes the calculation of direct resources, the user is returned to the Main Menu. To determine indirect, or support, resource requirement, the user chooses "Iterate" (see Figure 11). The "Iterate" option will iterate support resource requirement until epsilon, the ratio of additional support resources from one iteration to total support resources from all iterations, reaches a user defined value for all resources iterated.

The direct resources that will be iterated are: [1]total equipment mass, [2]electric power, [3]thermal power, and [4]thermal heat rejected. Support mass required depends on electrical and thermal power requirements and on the lifetime of the equipment comprising the direct mass total. Support electric power is driven by pump requirements to transport thermal power required and to remove excess thermal heat. There is no requirement for thermal heat rejected from the direct resource calculation. The requirement for rejection of thermal heat is derived in the support resource calculation from the electric power requirement. Thermal energy is not required for direct resource support and is not iterated.

For the mobile miner, the ratio of additional support resources from one iteration to total support resources from all iterations, or epsilon, was set at 0.01. The results of the first six iteration is shown in Figure 12. RESTAM determines the value of epsilon for each iteration and stops the iteration process when all the epsilon for all resources iterated reaches the user defined value of 0.01. Epsilon values from each iteration are shown in Figure 13. From Figure 13, epsilon values for all resources iterated reaches the user defined value after 4 iterations. When the iteration process is complete, indirect resources are totaled and may be added to the direct resource required to determine the overall resource requirement for the mobile miner.

3.4.4 Sample RESTAM Output

RESTAM may output to the screen or to a file to get hardcopy output. The RESTAM output reporting system consists of five major parts:

- functional hierarchy with direct resource requirements
- direct resource calculation totals
- indirect resource calculation totals
- overall resource requirement with direct and indirect resources
- variable and parameter listing

The RESTAM output reporting system for the functional hierarchy with direct resource requirements for all primitives is shown in Figure 14. The RESTAM output reporting system for direct resource calculation totals is shown in Figure 15. Figure 16 shows the RESTAM output reporting system for the total resource listing including both direct and indirect resource totals.

4.0 Application of RESTAM to Mobile Miner Design

This section will cover how RESTAM is used to optimize the design of the mobile miner which includes tradeoff analyses of system alternatives and the expansion of the RESTAM database through model creation.

4.1 Analysis of System Alternatives

System alternatives may be generated with RESTAM by two methods: [1]altering function selections which would alter variable values in the model and [2]selection of alternative technologies which would alter parameter values in the model. Each overall system configuration is represented by a model run. Tradeoffs are identified by comparing several models run from one database. The following sections will show system comparisons using both of the previously mentioned methods.

4.1.1 Variable Tradeoff Analyses

To determine the best function alternative for a system, models runs are created by altering the selections for one subsystem while keeping the other subsystems constant. To demonstrate this for the mobile miner, alternatives for regolith beneficiation were investigated. The options for the primitive function "Beneficiate Regolith" included [1]no beneficiation, [2]less than 100 microns only, [3]less than 50 microns only, and [4]less than 25 microns. The variables associated with this function are 'P', kg beneficiated regolith per kg unbeneficiated regolith, and 'Q', kg solar wind gas in beneficiated regolith per kg solar wind gas in unbeneficiated regolith. The results of the tradeoff analysis on the regolith beneficiation system are shown for all the miner subsystems in Figure 17 and for the total mobile miner system in Figure 18.

From the above figures, the RESTAM user can follow the effects of beneficiation alternatives on all the miner subsystems and for the total miner system. An optimal level of beneficiation can be identified in Figure 19 to be less than 50 microns. It is important to note that this is an optimal level only for reducing system mass and does not include support resources. Support resources for this system should also include research and development efforts because the technology for a beneficiation system of this type is not yet established.

4.1.2 Technology Parameter Tradeoff Analyses

RESTAM can also analyze tradeoffs of technology alternatives. Tradeoffs of technology alternatives can show [1]the sensitivity of a subsystem to a technology and [2]the least resource intensive technology for the system.

To study the sensitivity of a technology to a subsystem, the RESTAM user may alter parameter values that relate a subsystem to resources. In the case of the regolith beneficiation system, parameter values were chosen at a percent amount above a baseline value. This was necessary because of the limited information on various types of lunar regolith beneficiation hardware systems. To conduct this analysis, four models must be run from the mobile miner database, each with a different parameter value for the beneficiation system. The results of this sensitivity analysis is shown in Figure 19. This figure shows that a beneficiation system requiring 30% more mass than the baseline system only increases the total system mass by less than 1%. Thus the total system mass is not significantly affected by reasonable increases in the beneficiation system mass.

The solar wind gas extraction system will be used to demonstrate how RESTAM can be used to identify the least resource intensive technology alternative. The two technology options for supplying required power are solar and nuclear sources. Not only do these technology alternatives affect parameters in the model but affect the variable 'E', the duty cycle of operation. The use of a solar power source necessitates operation 90% of the lunar day only yielding a duty cycle of 45%. A nuclear power source would enable operation during 90% of the lunar day and night yielding a duty cycle of 90%. The duty cycle affects many of the miner subsystems as it is used in the determination of the rate at which the lunar regolith must be handled. Figures 20 and 21 show the effects of these technology alternatives on susbystem and total mass. Figures 22 and 23 show the effects of these technology alternatives on susbystem and total power.

From these figures, the nuclear power option appears more favorable than use of solar power from a resource minimization point of view. These figures do not include indirect resources required. Considerations of maintainability, safety, and other qualitative measures may have significant impact on the selection of a nuclear power source for the extraction of solar wind gases from the regolith.

4.2 Expansion of Database with System Alternatives Generation

As models are run from a database, the RESTAM database's function and technology alternatives expand and broader tradeoff studies may be conducted. New functions and primitive functions can be added to meet the demand for increased capability in the mobile miner. For example, if Lunar Base users wanted to know the feasibility of using solar wind sourced hydrogen for oxygen production via hydrogen reduction of ilmenite on the mobile miner, functions such as "Remove Ilmenite From Regolith", "Separate Hydrogen From Collected Solar Wind Gas", and "Pump Gas Through Regolith" could be added to the database. Some functions currently in the RESTAM database may be used twice, with one set of variables and parameters for the solar wind gas extraction and another set for the hydrogen reduction of ilmenite. This ability eliminates the need to set up separate databases for similar systems or operations and enables evolutionary growth of the RESTAM database to meet future demands of the system being modeled.

5.0 Future Enhancing Features of RESTAM

Future versions of RESTAM will include many features that will enhance the ability to use RESTAM and RESTAM's ability to perform tradeoff analyses. These enhancements include: ability to see results of past models while creating a new model; and enhanced user interface implementing pop-up windows and roll down menus; output directly to graphs; and the integration of artificial intelligence or expert systems.

Giving the RESTAM user the ability to see results of past models while creating a new model will allow the user to see the effects of certain variables or parameters before defining new values. For example, if a user is trying to determine the optimum alternative for the regolith beneficiation system, past models could be accessed and variable and parameter values for the model with the mininmal resource requirement for beneficiation could be found. This enhancement would increase RESTAM's efficiency in analyzing tradeoffs.

An enhanced user interface using a mouse or other pointing device, pop-up windows, and roll down menus would greatly reduce learning time for using RESTAM. There would be enhanced access to RESTAM operations which would also reduce the time it takes to create a model. A concept for this enhanced user interface is shown in Figure 24.

Enhancements to the output reporting system of RESTAM are also expected. RESTAM output could be enhanced by direct generation of graphical output showing direct and indirect resources and resources consumed by each subsystem. Sample graphical output from the RESTAM enhanced output reporting system is shown in Figure 25.

It is expected that future versoins of RESTAM employ AI, or expert systems, technology. AI would enable RESTAM to identify when it is performing a function that has been previously modeled and would prompt the user to accept the results of the previous run or to go through the selections again. AI could also be used to identify system configurations which minimize resource requirements for a particular subsystem. AI could also enable RESTAM to determine optimum function selections and variable and parameter values to minimize overall resource requirements for the system.

6.0 Summary and Conclusions

RESTAM is a valuable systems engineering tool for modeling of space systems and operations. RESTAM efficiently analyzes tradeoffs of functional activities and technology alternatives. RESTAM determines resources directly required by a system or operation and then iterates these direct resources through support resource calculations to determine indirect, or support, resource requirements. This is valuable in that many times indirect resource requirements dominate over direct resource requirements. RESTAM is not specific to any application. The RESTAM user creates databases of applications and creates models from these databases. RESTAM's ability to aid optimization studies of design concepts has been demonstrated with the Lunar Base mobile miner for the extraction of solar wind gases. RESTAM's capabilities grow as it is used and future possiblities are vast. With the predicted growth of the space infrastructure in the beginning of the 21st Century, RESTAM would provide space systems design engineers with a valuable tool giving them insight to the most cost effective designs.

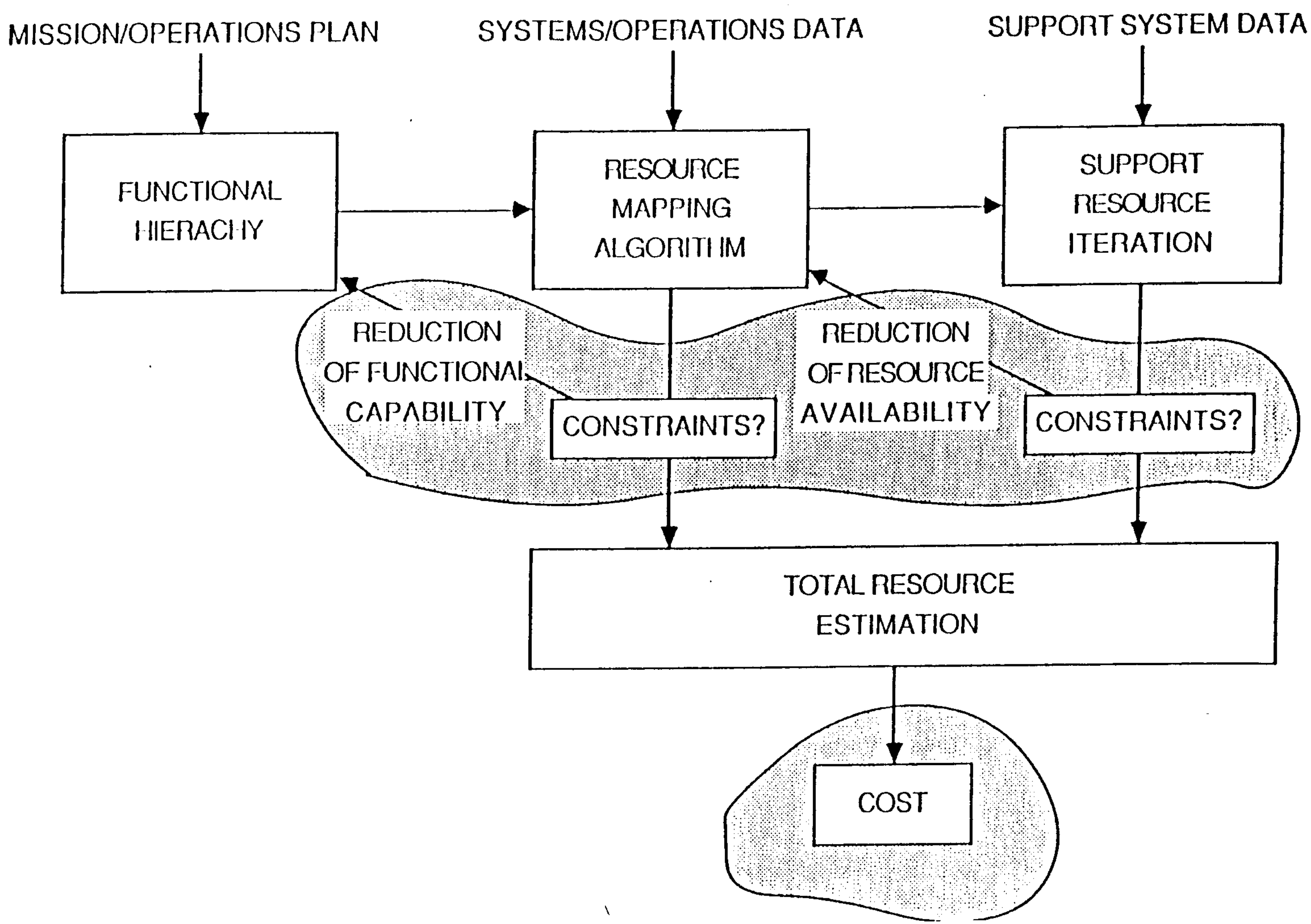


FIGURE 1. OVERALL MODELING APPROACH

DIRECT RESOURCES

M_d = MASS FROM DIRECT RESOURCE CALCULATION

PE = ELECTRIC POWER FROM DIRECT RESOURCE CALCULATION

PT = THERMAL POWER FROM DIRECT RESOURCE CALCULATION

T = THERMAL HEAT REJECTED

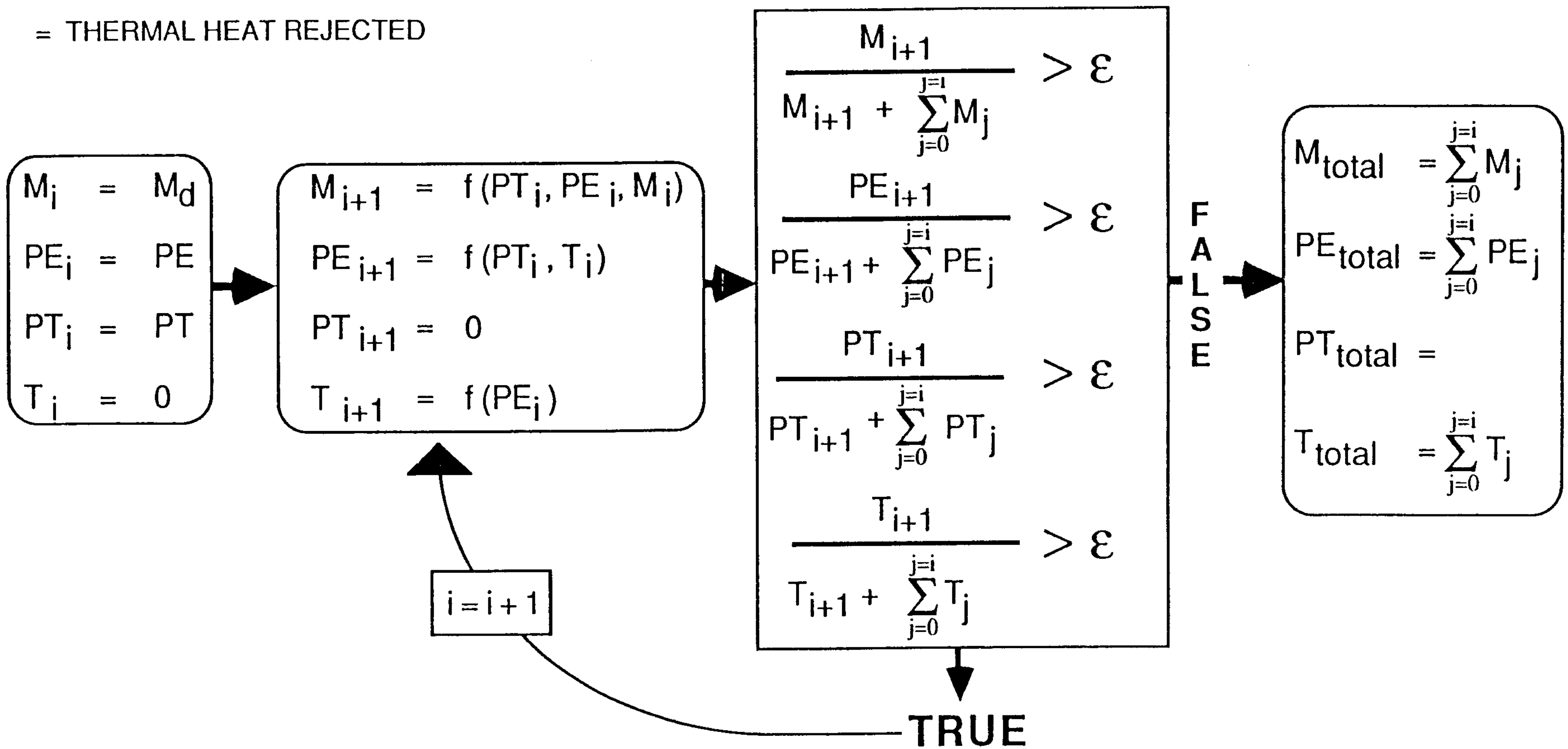


FIGURE 2. RESTAM INDIRECT RESOURCE ITERATION PROCESS

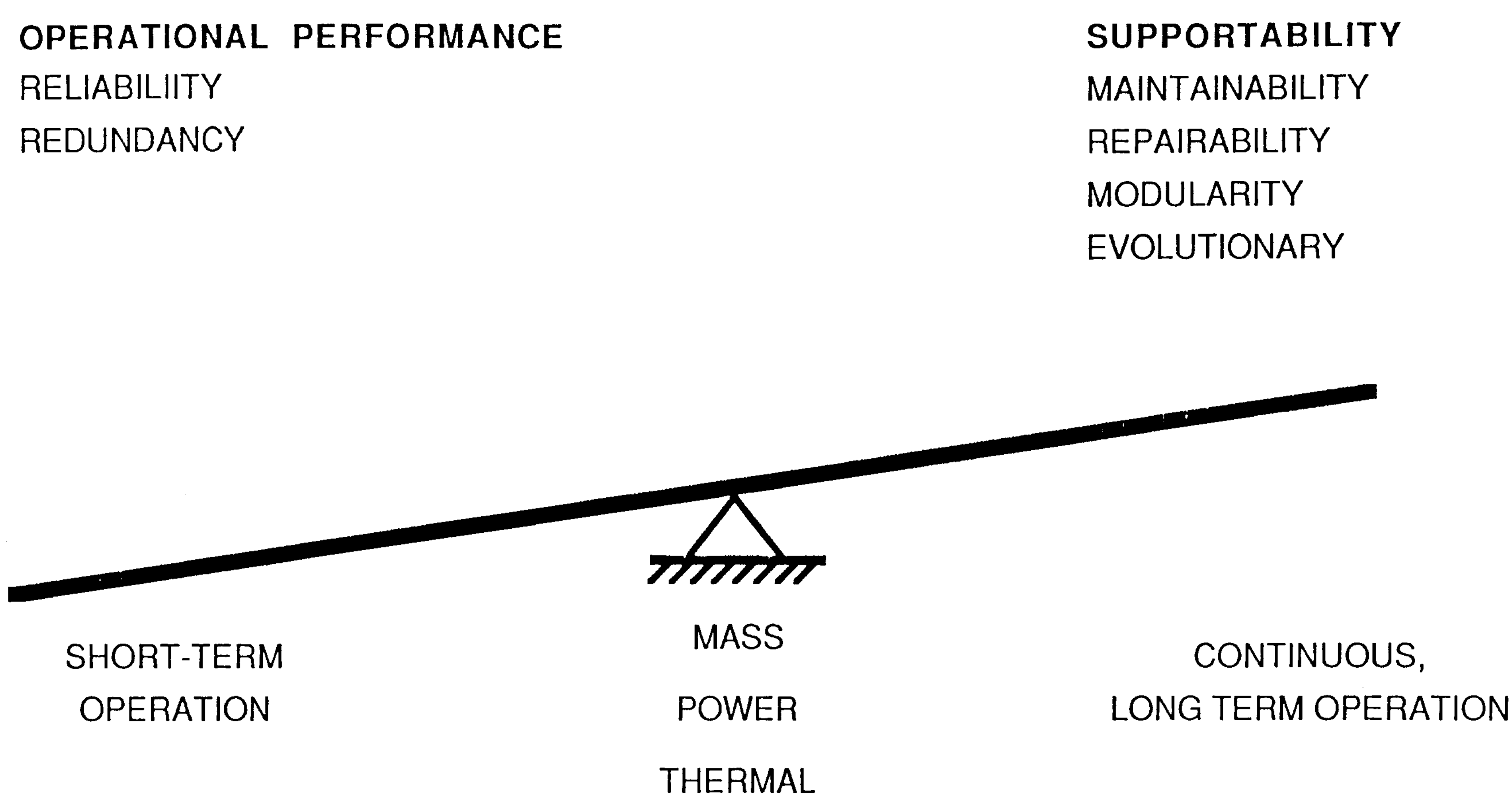


FIGURE 3. MAJOR DESIGN TRADES THAT CAN BE ACCOMMODATED BY RESTAM

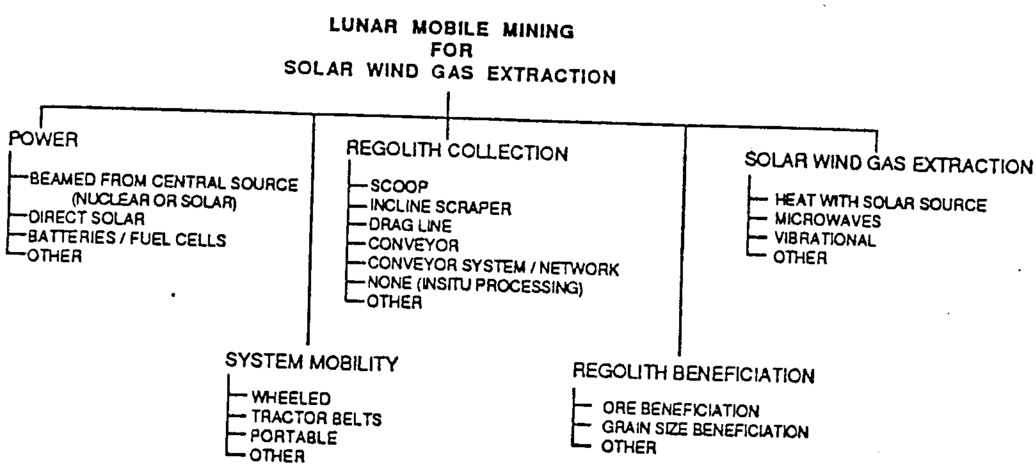


FIGURE 4. LUNAR BASE MOBILE MINING SYSTEM OPTIONS FOR SOLAR WIND GAS EXTRACTION

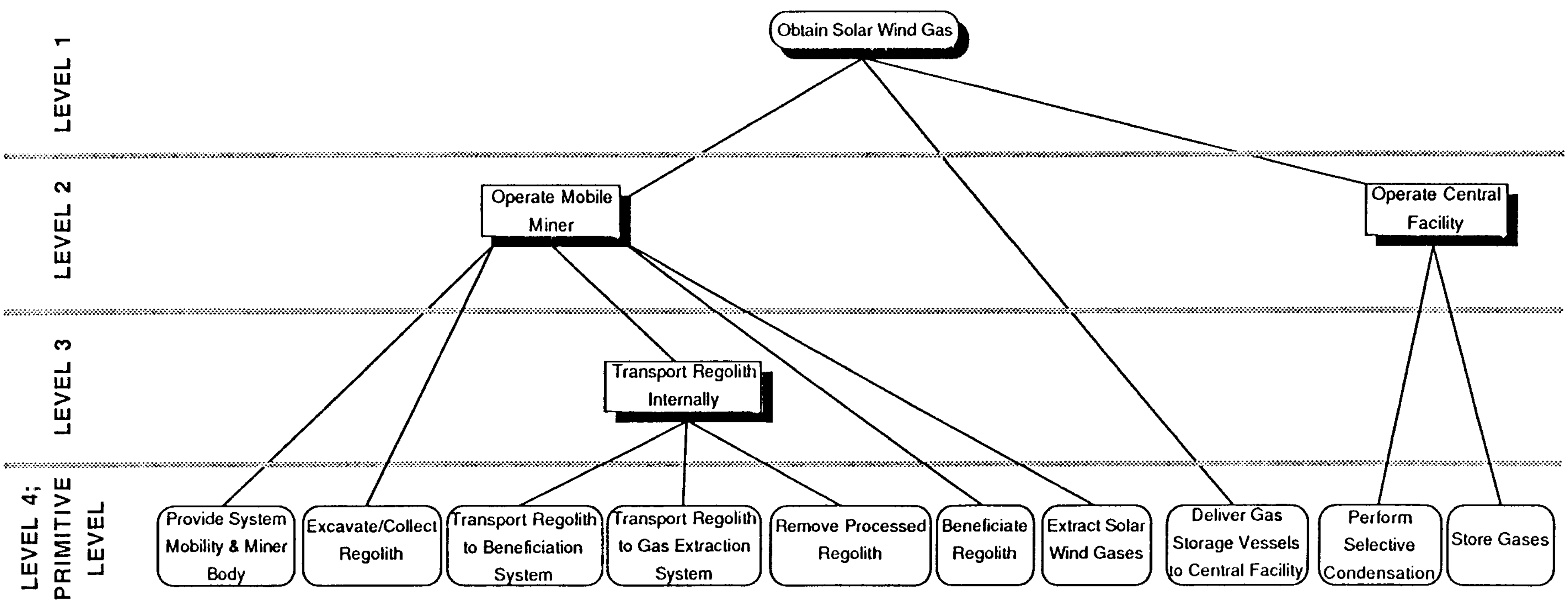


FIGURE 5. FUNCTIONAL HIERARCHY FOR LUNAR BASE MOBILE MINING SYSTEM FOR SOLAR WIND GAS EXTRACTION

TABLE 1. VARIABLE AND PARAMETER VALUES FOR PRELIMINARY CONFIGURATION OF THE LUNAR BASE MOBILE MINER FOR SOLAR WIND GAS EXTRACTION

	VARIABLES / VARIABLE DESCRIPTIONS	VARIABLE VALUES
A	Annual kg solar wind gas to obtain	1.0000E+3
B	Kg gas per kg unbeneficiated regolith	9.0000E-9
C	Mining depth, m	3.0000E+0
D	Width of excavated trench, m	1.1000E+1
E	Duty cycle	4.5000E-1
P	Kg beneficiated regolith per kg unbeneficiated regolith	4.5000E-1
Q	Kg gas in beneficiated regolith per kg gas in unbeneficiated regolith	8.0000E-1
V	Efficiency of gas collection (% gas in beneficiated regolith recovered)	9.0000E-1

	PARAMETERS / PARAMETER DESCRIPTIONS	PARAMETER VALUES
f	System mobility mass parameter, kg/km/day	5.2473E+3
g	System mobility power parameter, kW/km/day	7.0170E+1
h	Excavate/Collect regolith mass parameter, kg/kg reg./hr	3.8827E-3
i	Excavate/Collect regolith power parameter, kW/kg reg./hr	2.3245E-5
j	Internal regolith transport mass parameter #1, kg/kg reg./hr	9.6421E-5
k	Internal regolith transport power parameter #1, kW/kg reg./hr	1.8680E-6
l	Internal regolith transport mass parameter #2, kg/kg reg./hr	8.4632E-4
m	Internal regolith transport power parameter #2, kW/kg reg./hr	2.4731E-6
n	Internal regolith transport mass parameter #3, kg/kg reg./hr	3.3132E-4
o	Internal regolith transport power parameter #3, kW/kg reg./hr	1.3429E-6
p	Beneficiation mass parameter, kg/(kg unben. reg. - kg ben. reg.)/hr	9.1480E-4
q	Beneficiation power parameter, kW/(kg unben. reg. - kg ben. reg.)/hr	7.0370E-6
r	Gas extraction mass parameter, kg/kg ben. reg./hr	1.3737E-2
s	Gas extraction power parameter, kW/kg ben. reg./hr	2.8261E-4
t	Gas Transport Vehicle mass parameter, kg/km/day	2.5288E+3
u	Gas Transport Vehicle power parameter, kW/km/day	3.4000E+1
v	Selective condensation mass parameter, kg/kg gas	7.2400E-3
w	Selective condensation power parameter, kW/kg gas	2.1985E-4

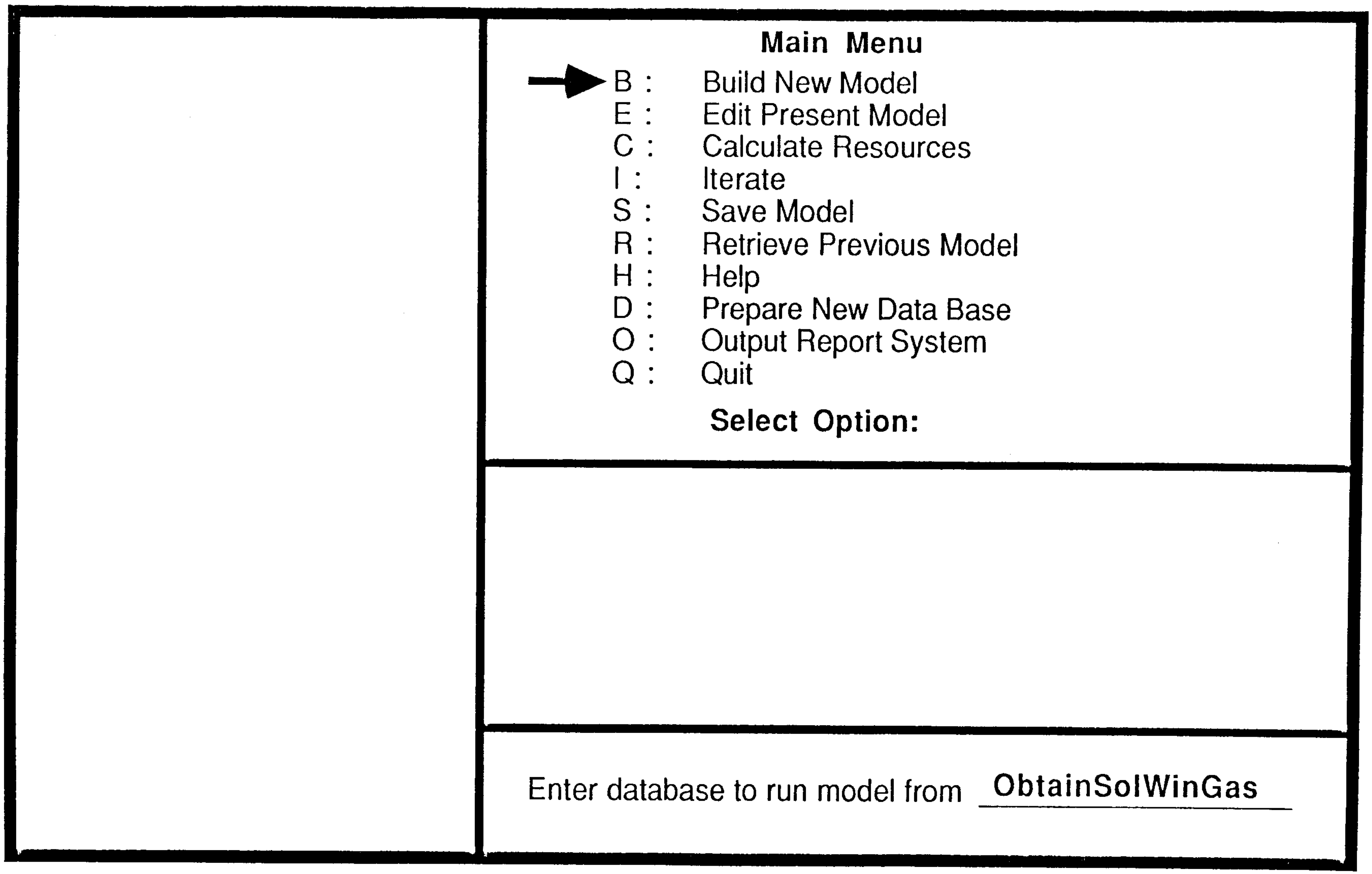


FIGURE 6. RESTAM MAIN MENU

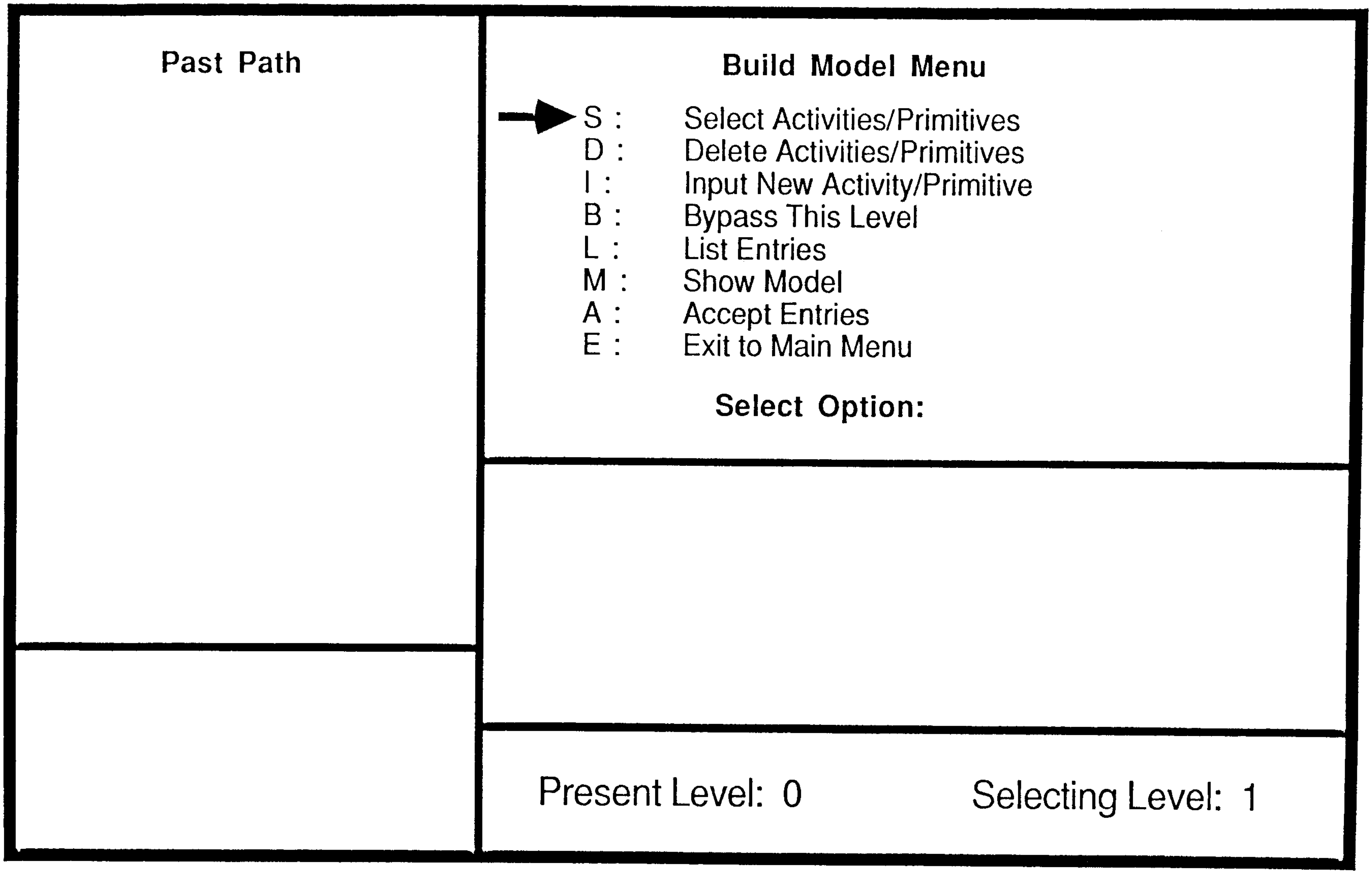


FIGURE 7. RESTAM BUILD MODEL MENU

Past Path

L1: Obtain Solar Wind Gas

L2: Operate Mobile Miner.

L3:: Primitive Link

Select numbers, separate by commas:

PRIMITIVE LIST

1. Provide System Mobility
2: Excavate/Collect Regolith
3: Internally Transport Regolith to Subsystem
4: Remove Processed Regolith
→5: Beneficiate Regolith
6: Extract Solar Wind Gas
7: Transport Gas Storage Vessels to Central Facility
8. Perform Selective Condensation
9. Store Gas

Present Level: 3 Selecting Level: 4

FIGURE 8. PRIMITIVE SELECTION IN RESTAM BUILD MODEL

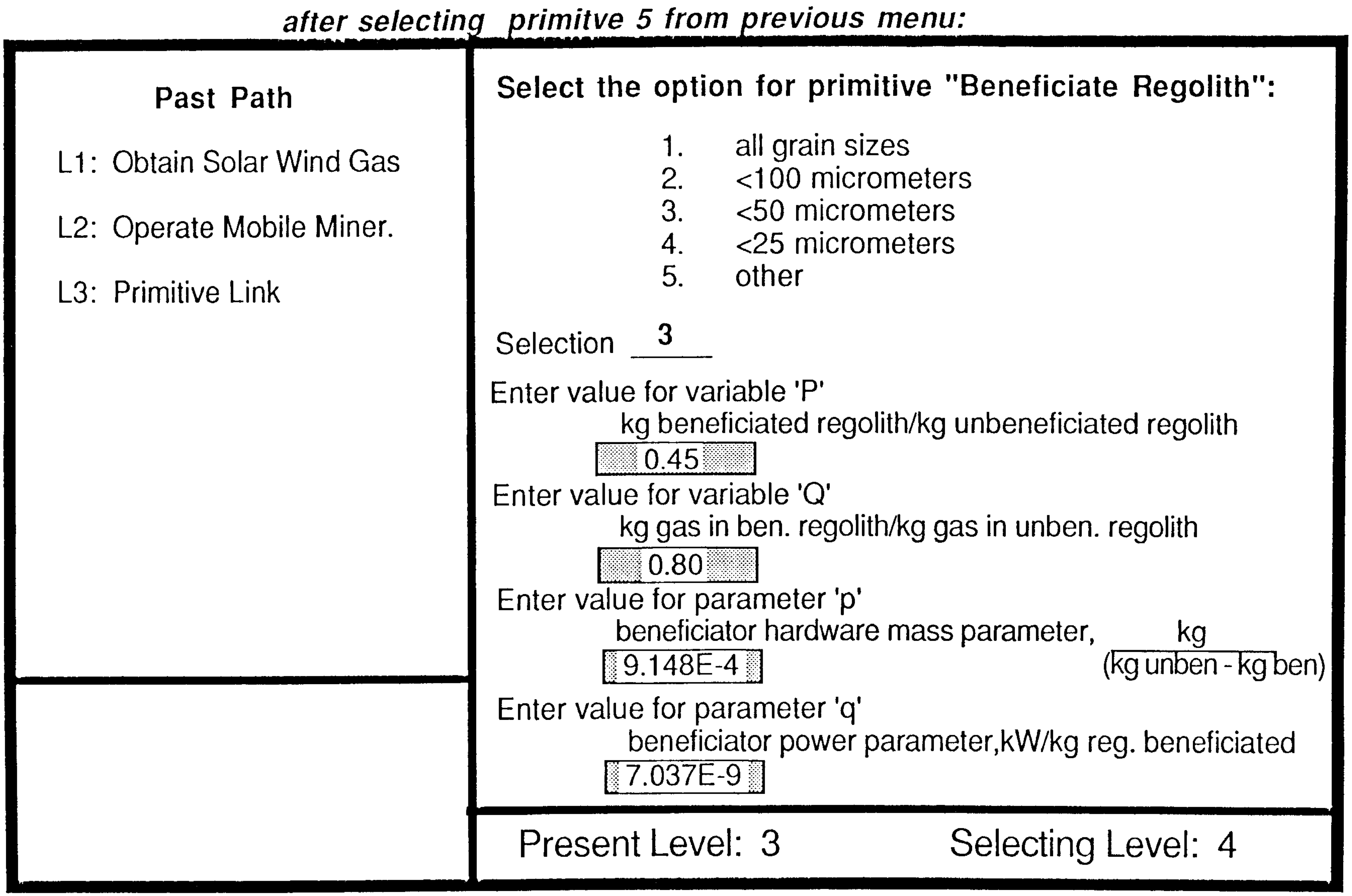


FIGURE 9. VARIABLE AND PARAMETER DEFINITION

Past Path

L1: Obtain Solar Wind Gas

L2: Operate Mobile Miner.

L3: Primitive Link

L4: Beneficiate Regolith

Calculating Resource "Beneficiator", kg:

2.578 E-7 * [A*p*(1-P)] / Q*B

A	kg gas obtained annually - defined at L1 CURRENT VALUE = 1000
p	beneficiator hardware mass parameter - defined at L4 CURRENT VALUE = 9.148E-4
P	kg ben. regolith/ kg unben. regolith - defined at L4 CURRENT VALUE = 0.45
Q	kg gas in ben. reg./kg gas in unben. reg. - defined at L4 CURRENT VALUE = 0.80
B :	kg solar wind gas/kg unben. regolith - defined at L1 CURRENT VALUE = 9 E-9

Enter 'a' to accept above values or 'c' to change **c**

Enter variables/parameters to change separated by commas **A,p**

FIGURE 10. RESTAM RESOURCE CALCULATION

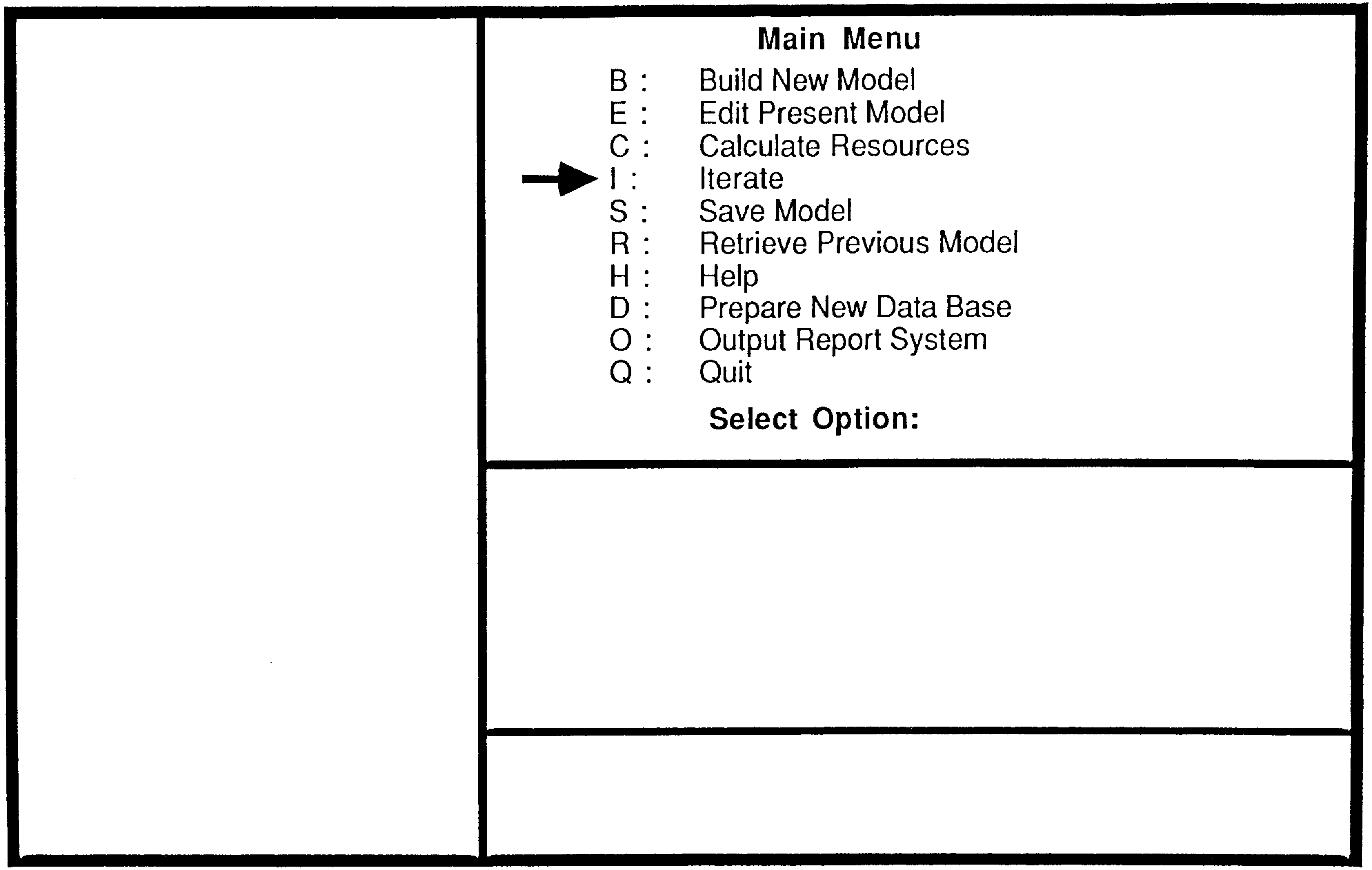


FIGURE 11. SELECTION OF "ITERATE" OPTION FROM RESTAM MAIN MENU

DIRECT RESOURCES	ITERATION NUMBER 1	2	3	4	5	6	INDIRECT RESOURCE TOTALS *
M_d = 8.10E+5 kg	2.11E+5	1.06E+4	1.75E+3	87.96	13.19	0.662	2.23E+5
PE = 8,014 kW	2.424	57.66	1.74E-2	4.15E-1	1.25E-4	2.99E-3	60.52
PT = 4,848 kW	0	0	0	0	0	0	0
T = 0	1.15E+5	34.88	829.7	0.251	5.97	1.81E-3	1.16E+5

<u>SUPPORT RESOURCE CALCULATION COMPLETE AFTER 4 ITERATIONS</u>

* INDIRECT RESOURCE TOTALS INCLUDE RESULTS OF FIRST 4 ITERATIONS ONLY

FIGURE 12. RESULTS OF FIRST SIX ITERATIONS FOR LUNAR BASE MOBILE MINER FOR SOLAR WIND GAS EXTRACTION INDIRECT RESOURCE CALCULATION

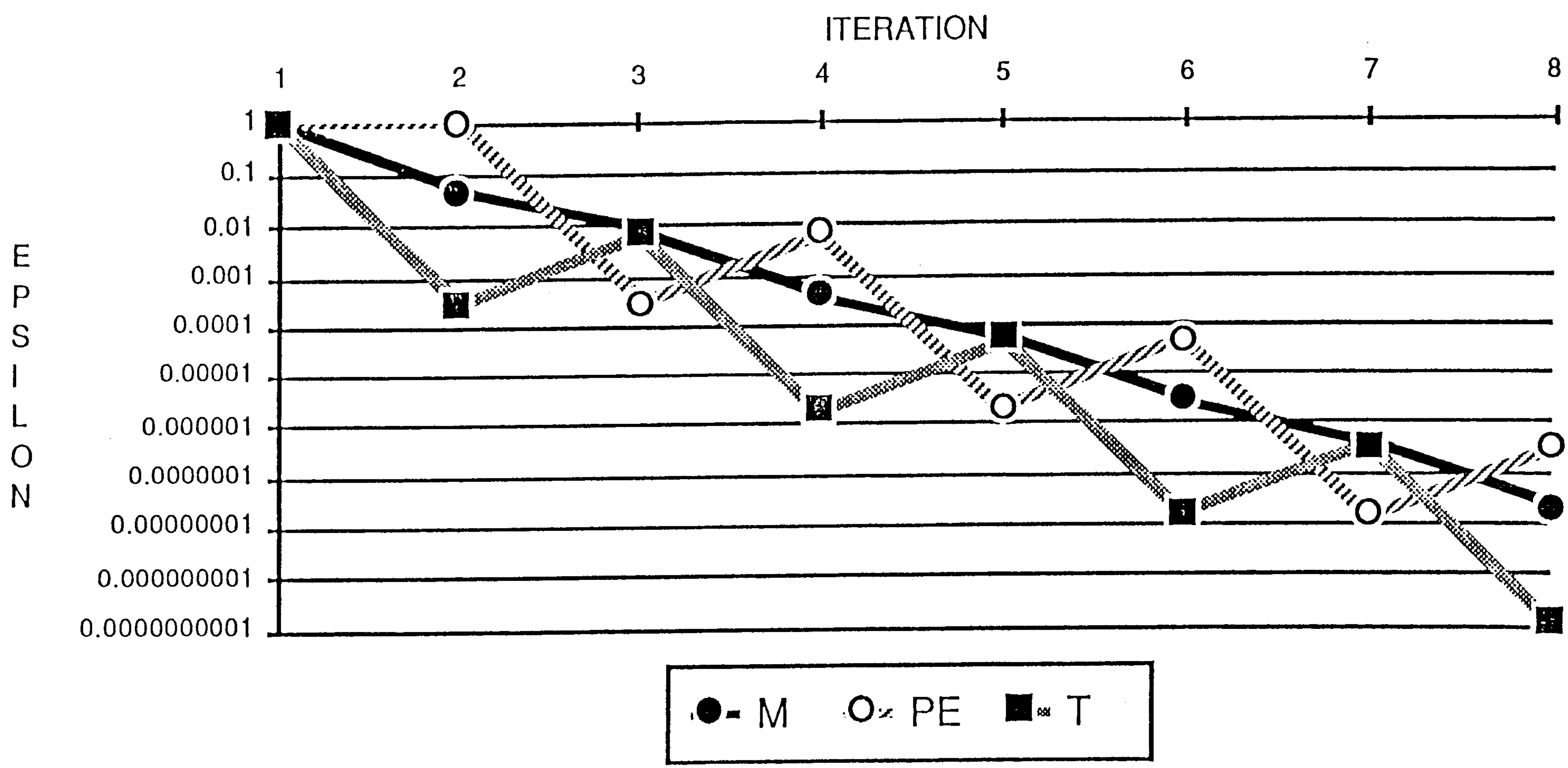


FIGURE 13. EPSILON VALUES FROM INDIRECT RESOURCE CALCULATION

LEVELS

```
1   2   3   4   Resources
Obtain Solar Wind Gas / He3
    Operate Mobile Miner
        Primitive Link
            Provide System Mobility -> Wheels.
                Power                   Value      1110 kW
                Mobility System Mass    Value:    83000  kg
        Primitive Link
            Excavate/Collect Regolith -> Bucket Wheel
                Power                          Value:      910 kW
                Excavator/Collector Mass       Value:   152000  kg
        Primitive Link
            Beneficiate Regolith -> <50 microns
                Power               Value:      150 kW
                Beneficiator Mass   Value:    20000  kg

"More output follows. Hit any key to continue."
```

FIGURE 14. RESTAM OUTPUT REPORTING SYSTEM FUNCTIONAL HIERARCHY WITH DIRECT RESOURCE REQUIREMENTS

DIRECT RESOURCE CALCULATION TOTALS

Power			
Thermal	Value	4,848	kW
Electric	Value	8,014	kW
Mobility Sys	Value	83,000	kg
Excavator	Value	200,000	kg
Internal Reg. Trans.	Value	49,000	kg
Beneficiator	Value	20,000	kg
Heater	Value	242,000	kg
Selective Cond.	Value	180,000	kg
Gas Vessel Trans.	Value	18,000	kg
Gas Storage	Value	67,000	kg

Mass Total = 8.11E+5 kg

"Hit any key to see variable / parameter values for this model run"

FIGURE 15. RESTAM OUTPUT REPORTING SYSTEM DIRECT RESOURCE CALCULATION TOTALS

TOTALS and VARIABLE/PARAMETER VALUES

Resource Totals

Power	Value	5.679E+9	kw
Beneficiator	Value	4.115E+6	kg
Excavator	Value	1.041E+7	kg
Transport Sys	Value	2.741E+6	kg
Heater	Value	1.644E+9	kg
Storage Vessel	Value	7.404E+7	kg

Power Total = 5.679E+9 kw

Mass Total = 1.735E+9 kg

Variable / Parameter Values

Variable / Parameter	Name	Level Defined	Value
a	beneficiator mass parameter	L5	6.667E-5
b	beneficiator power parameter	L5	6.667E-8
f	excavator mass parameter	L5	1.687E-4
h	excavator power parameter	L5	2.623E-7
l	transport sys mass parameter	L5	4.44E-5
n	transport sys power parameter	L5	4.44E-7
A	kg solar wind gas obtained	L1	500
H	kg S.W.G. per kg unbenificiated reg	L4	9E-9
B	grain size mass fraction	L4	0.90
G	grain size separation parameter	L5	1
I	S.W.G. mass fraction in sized reg	L1	0.8
L	temperature of gas separation (K)	L5	3.2

"Hit any key to return to Main Menu"

FIGURE 16. RESTAM OUTPUT REPORTING SYSTEM TOTAL RESOURCE LISTING

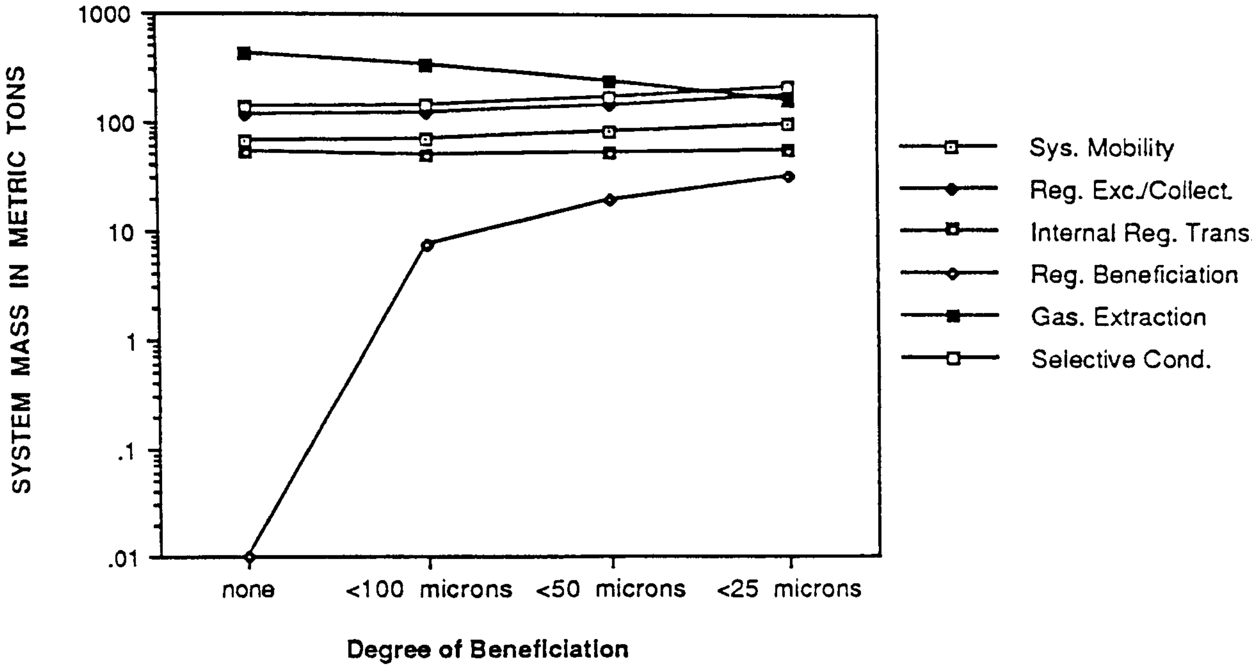


FIGURE 17. SUBSYSTEM MASS FOR BENEFICIATION SYSTEM ALTERNATIVES

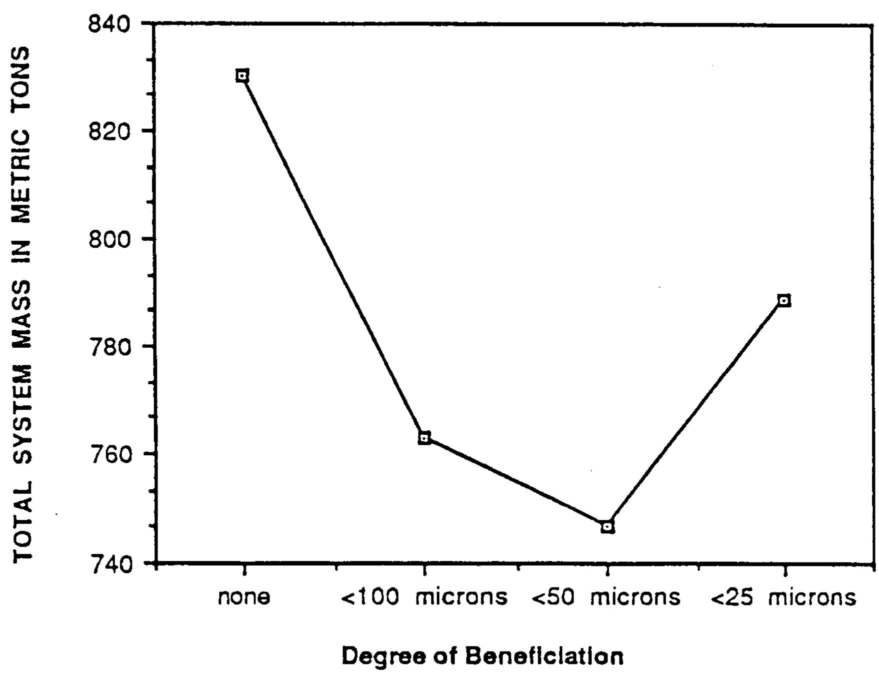


FIGURE 18. TOTAL SYSTEM MASS FOR BENEFICIATION SYSTEM ALTERNATIVES

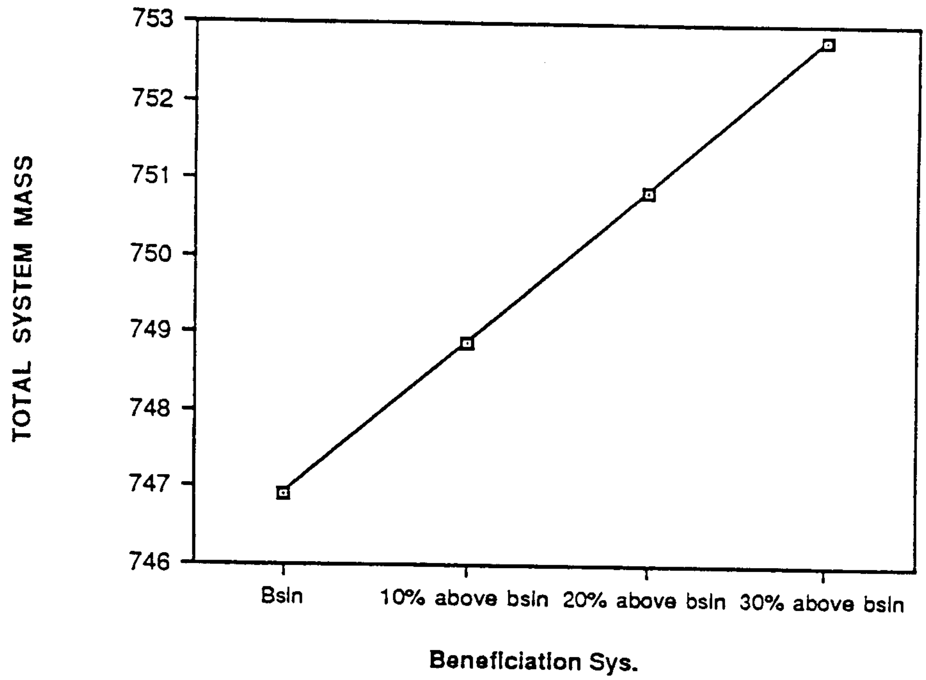


FIGURE 19. TOTAL SYSTEM MASS SENSITIVITY TO BENEFICIATION SYSTEM HARDWARE SELECTION

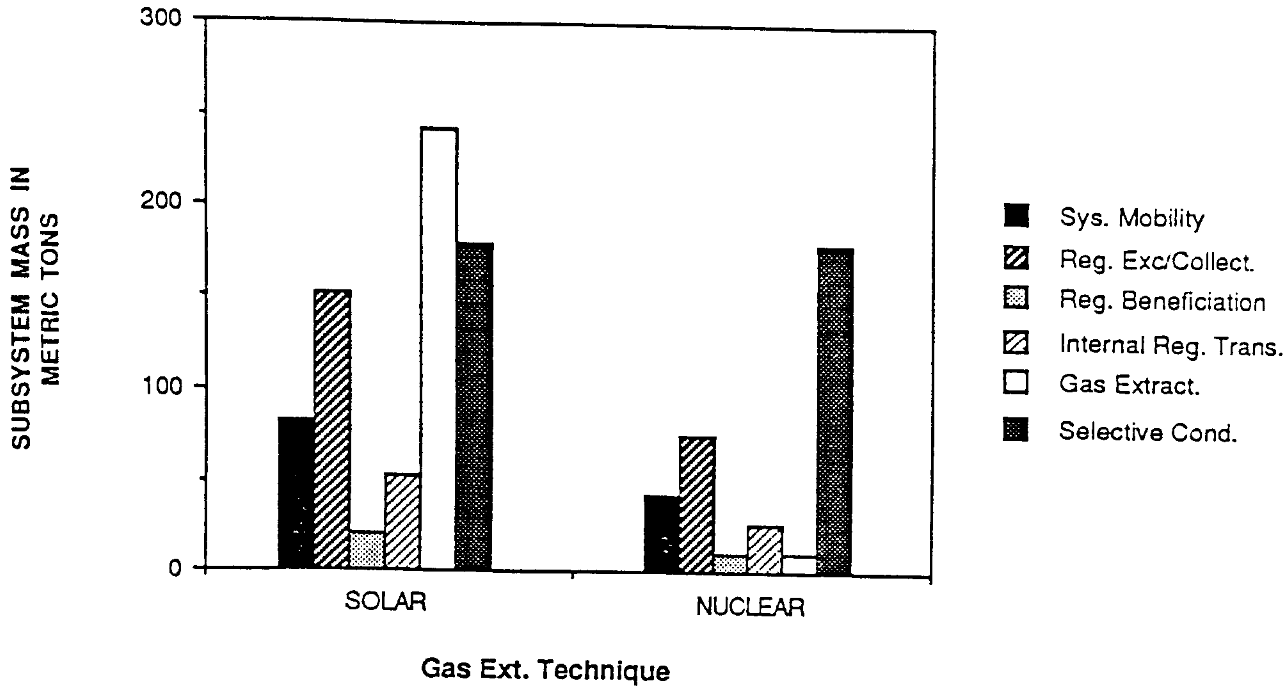


FIGURE 20. EFFECT ON SUBSYSTEM MASSES OF GAS EXTRACTION TECHNOLOGY

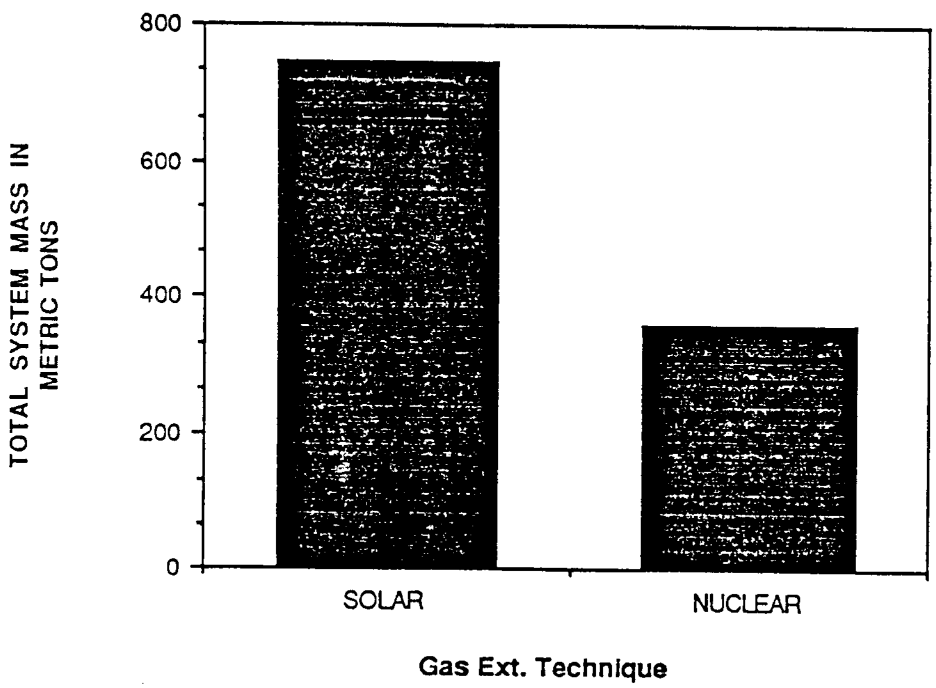


FIGURE 21. EFFECT ON TOTAL SYSTEM MASS OF GAS EXTRACTION TECHNOLOGY

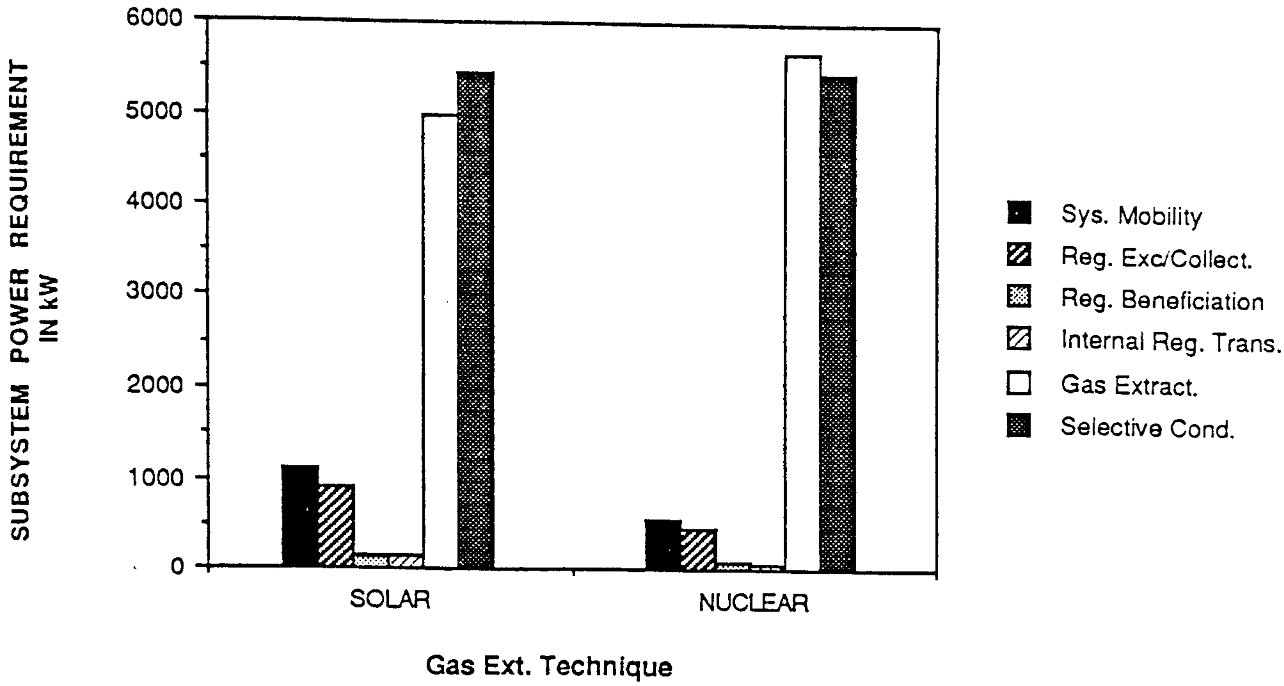


FIGURE 22. EFFECT ON SUBSYSTEM POWER OF GAS EXTRACTION TECHNOLOGY

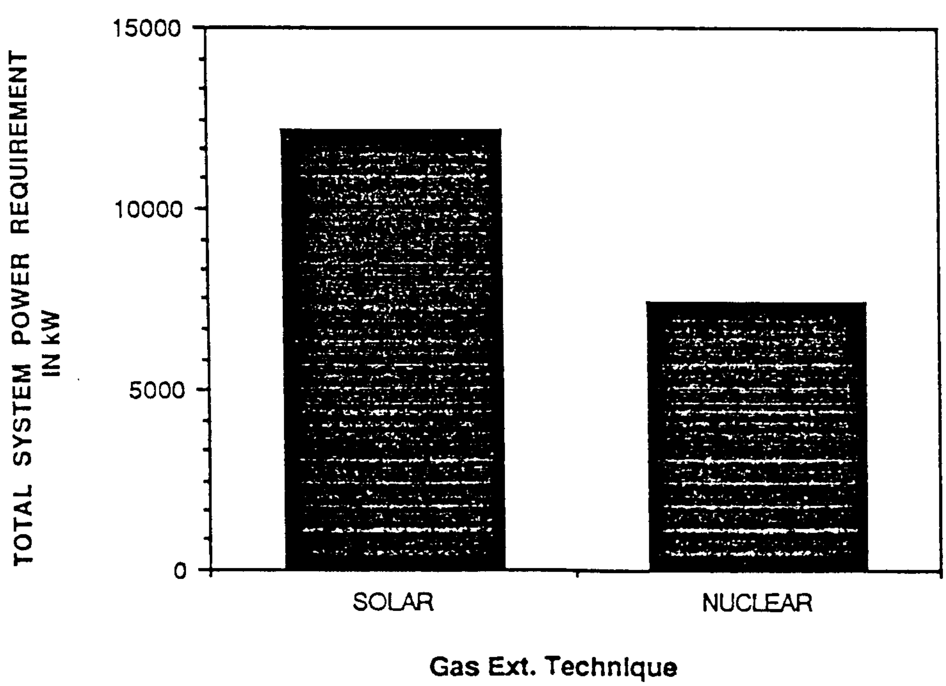


FIGURE 23. EFFECT ON TOTAL SYSTEM POWER OF GAS EXTRACTION TECHNOLOGY

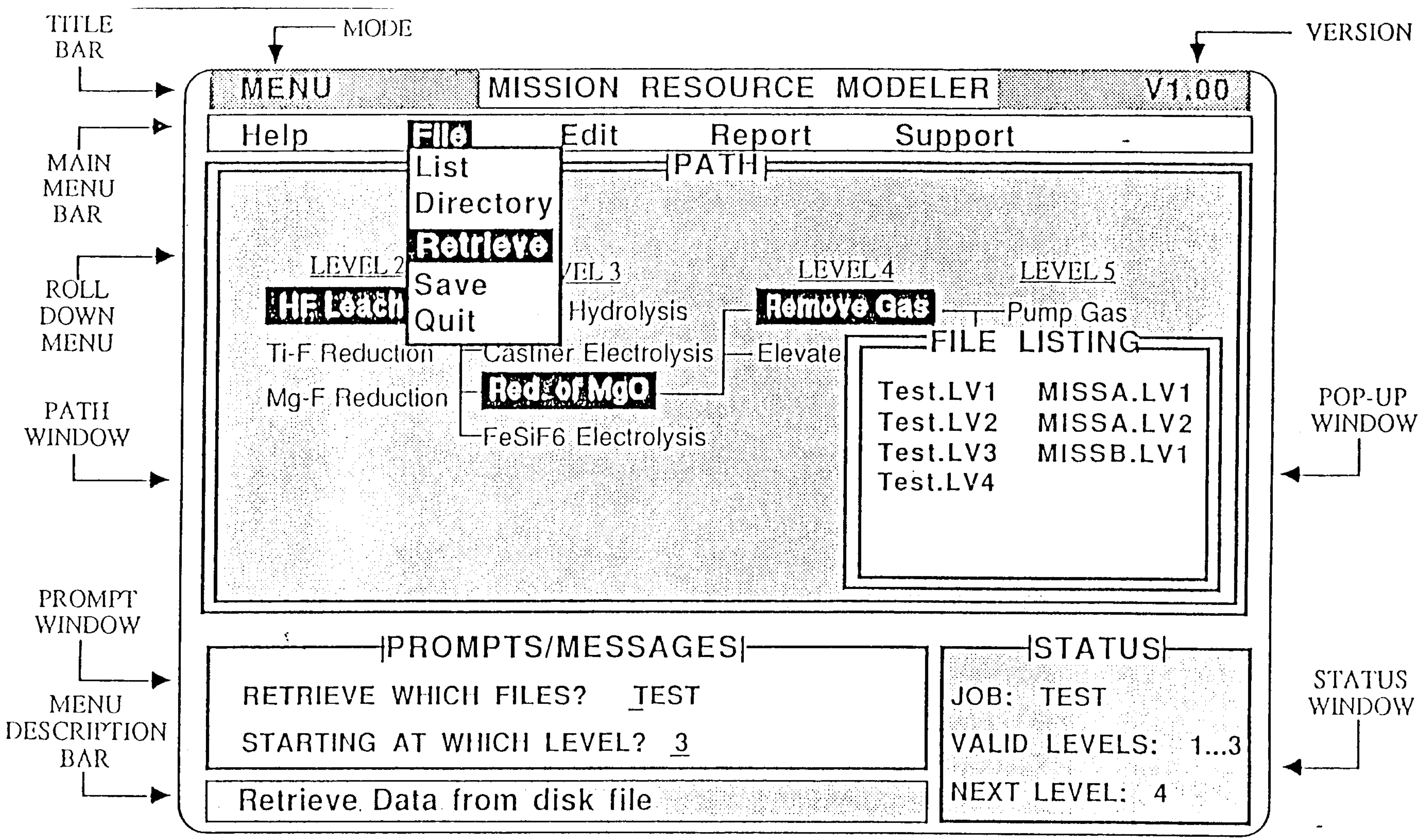
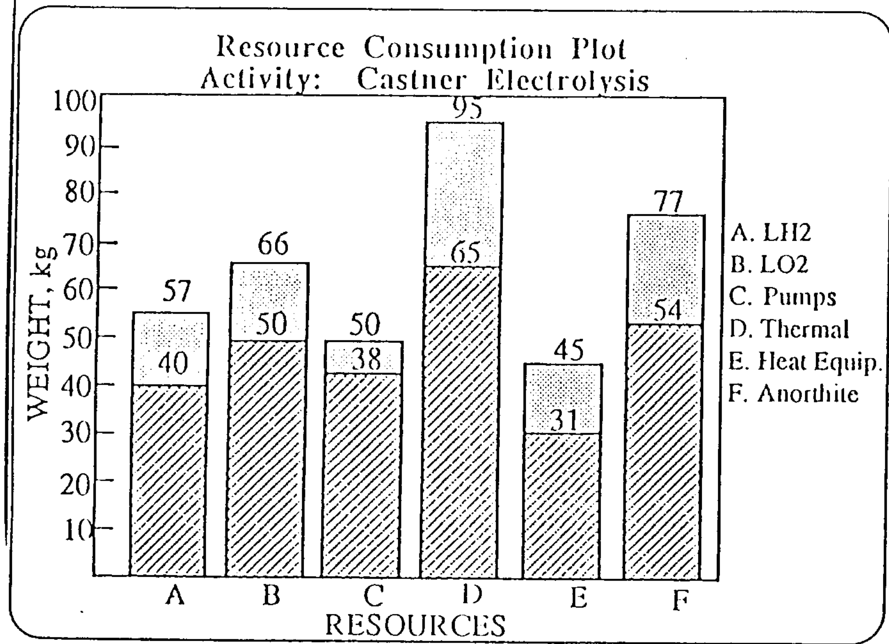
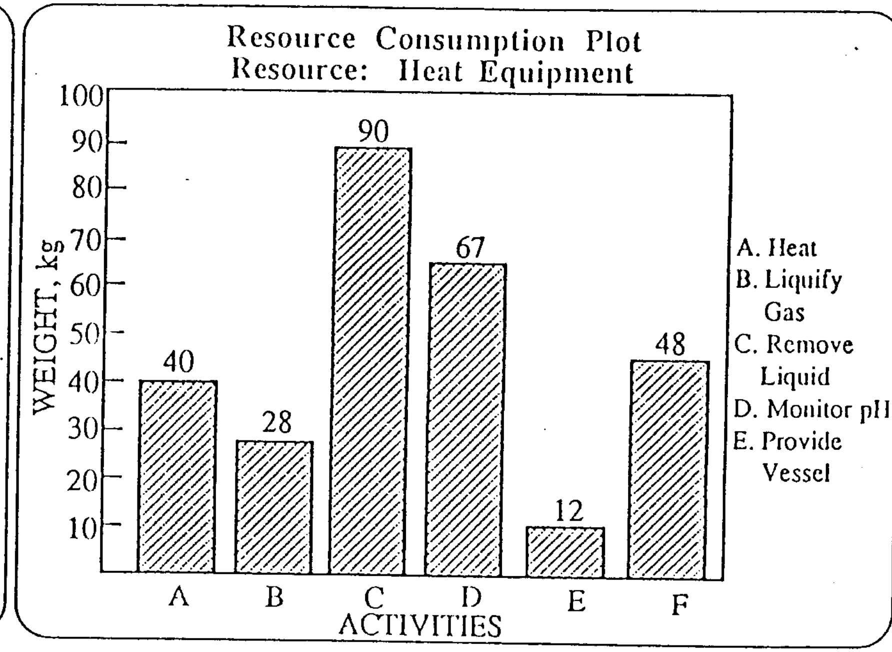


FIGURE 24. RESTAM ENHANCED USER INTERFACE



Resources Consumed For a Given Activity



Activities Accessing a Given Resource

FIGURE 25. RESTAM ENHANCED OUTPUT REPORTING SYSTEM