NASA Contractor Report CR-187167

Infrastructure for Deployment of Power Systems (Task Order No. 7)

Kenneth M. Sprouse
Rockwell International
Rocketdyne Division
Canoga Park, California

June 1991

Prepared for
Lewis Research Center
Under Contract NAS3 25808

NASA

National Aeronautics and
Space Administration

FOREWORD

This final report documents the work performed by Rockwell International's Rocketdyne Division on NASA Contract No. NAS3-25808 (Task Order No. 7) entitled "Infrastructure for Deployment of Power Systems." This work was performed for the Lewis Research Center (LeRC) of the United States National Aeronautics and Space Administration. The NASA LeRC Task Order Contract Technical Manager was Mr. William A. Poley and the Specific Task Manager was Mr. Robert Cataldo. The Rocketdyne program manager was Mr. Vernon R. Larson and the Rocketdyne project engineer was Mr. James M. Shoji. The principal investigator throughout this task order was Mr. Richard B. Harty and Mr. Kenneth M. Sprouse served as his lead engineer.

CONTENTS

FIGURES

TABLES

1.0 SUMMARY

The emplacement of an integrated surface power system and its related infrastructure on the lunar surface is an extremely important effort for the successful establishment of a permanent manned presence on the moon. These power systems and infrastructure must survive hostile launch environments from the earth's surface as well as being reasonably sited, operated, and maintained in another relatively hostile setting. This report investigates numerous emplacement options and conceptual ideas for power system hardware. It provides (among other things): very preliminary values for equipment mass and size; task breakdown descriptions for hardware emplacement; the required heat, forces, torques, and alignment tolerances for equipment assembly (where capable of reasonable estimation). This information should be of some preliminary value to NASA's Space Exploration Initiative (SEI) Humans, Automation, Robotics, and Telerobotics (HART) design team.

Since the concepts presented in this report are very preliminary, this document spends some time detailing the important issues which must be resolved before undertaking the design of complete integrated power plants and their related infrastructure systems. For example, the shock, vibration, acoustics, and quasi-static accelerations expected to be exerted on the power plants and infrastructure hardware during their flight from launch to the lunar surface must be developed. Likewise, further detail regarding lunar regolith soil mechanics needs to be determined in addition to the nominal internal friction angles and cohesion coefficients now reported. This further detail in soil mechanics is necessary because the current Space Exploration Initiative (SEI) options rely heavily on keeping power system and infrastructure masses to as low as reasonably achievable. This translates into lunar construction/grading equipment having low horsepower and low torque -- greatly reducing the margins of error in infrastructure design.

The dynamic issues associated with setting-up and maintaining lunar power systems with robotic equipment are also discussed in this document. This report advocates the development of detailed feedback and control mathematical models and their use in conjunction with subscale experimental hardware testing in lunar simulation facilities. These experimental and analytical

efforts must be performed concurrently with detailed power plant and infrastructure system design. It is further recommended that the use of robots and telerobots be integrated reasonably and methodically into all power plant and infrastructure system designs. All early designs should include the capability of astronaut "hands-on" back-up until extensive operating experience with remote mobile robotic methods has been obtained.

2.0 INTRODUCTION

The latest NASA Reference architecture description for establishing a permanent lunar outpost -- Option 5a with In-Situ Resource Utilization (ISRU), Ref. 1 -- shows lunar construction (emplacement) equipment arriving on the moon by July 2002 with the first lunar stationary power system being flown to the moon's surface in July 2003. Construction and start-up of this initial 100-kWe stationary power system is expected to be performed entirely by tele-robotic means (from the earth's surface) so that the system is producing electrical power at 100 percent capacity by the time the first astronauts arrive in July 2004. These short construction lead times -- together with the use of novel tele-robotic construction methods -- require a significant amount of intensive development work to be completed within the next few years in order to successfully meet these proposed launch schedules.

This report documents a preliminary effort in characterizing the types of stationary lunar power systems which may be considered for emplacement on the lunar surface from the proposed initial 100-kW unit in 2003 to later units ranging in power from 25-kW to 825-kW. Associated with these power systems are their related infrastructure hardware including (among other things): electrical cable, wiring, switchgear, and converters; deployable radiator panels; deployable photovoltaic (PV) panels; heat transfer fluid piping and connection joints; power system instrumentation and control equipment; and interface hardware between lunar surface construction/maintenance equipment and power system.

This report presents estimates of the mass and volumes associated with these power systems and their related infrastructure hardware; provides task breakdown descriptions for emplacing this equipment; gives estimated heat, forces, torques, and alignment tolerances for equipment assembly; and provides other important equipment/machinery requirements where applicable. Packaging options for this equipment will be discussed along with necessary site preparation requirements. Design and analysis issues associated with the final emplacement of this power system hardware will also be described.

3.0 BACKGROUND

For the past few years NASA has been conducting preliminary studies on the feasibility of establishing permanent manned bases on the moon and Mars. These efforts were initiated with the "case studies" and then transitioned into the "Human Exploration Initiative (HEI)" and more recently the "Space Exploration Initiative (SEI)." For each of the manned bases currently being planned, stationary electrical power generating systems will be required. The responsibility for the design, development, and emplacement of these electrical power systems resides within NASA's Planet Surface Systems (PSS) group headquartered at the Johnson Space Center (JSC), Houston, TX. This group recently completed a 90-day study which identified two stationary power systems for use on the lunar surface and provided conceptual construction equipment designs for their emplacement (Ref. 2). Further details of these preliminary concepts are provided below.

3.1 EARTH/MOON TRANSPORTATION EQUIPMENT

For delivering lunar electrical power systems and their related infrastructure from the earth to the moon's surface, NASA's Marshall Space Flight Center (MSFC) -- in Huntsville, AL -- has identified a number of delivery systems for transporting this equipment from the Kennedy Space Center (KSC) in Florida to low earth orbit (LEO) at Space Station Freedom (SSF), see Ref. 3. These baseline launch vehicles are shown in Figure 1.

Figure 1 illustrates three generic launch vehicles for use in launching payloads into low earth orbit: the Shuttle, the Shuttle-C, and the Advanced Launch System (ALS). The Shuttle has a payload mass capability of 22 tonnes with a payload volume envelope of 4.6-m diameter by 18.2-m length; this launch vehicle is available today. The Shuttle-C is expected to be available in two versions once it is developed for use in the late 1990's: the first has a payload mass capability of 71 tonnes with a payload volume envelope of 4.6-m diameter by 25-m length; the second provides a reduced payload mass capability (61 tonnes) but gives a much larger payload volume envelope (7.6-m diameter by 27-m length). The ALS is expected to be available for use sometime by the year 2010 and it will also come in two versions: the first has a payload mass

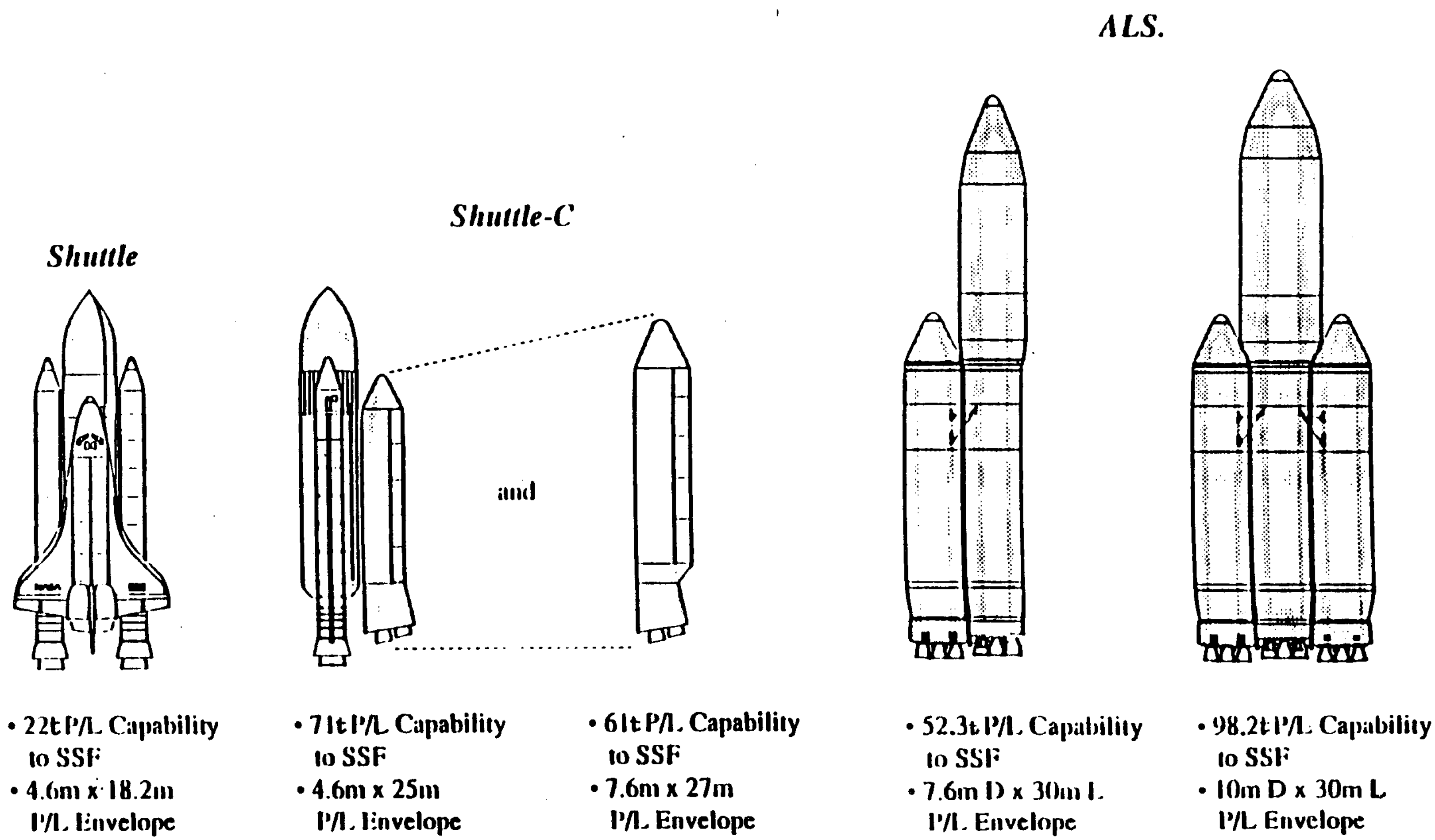


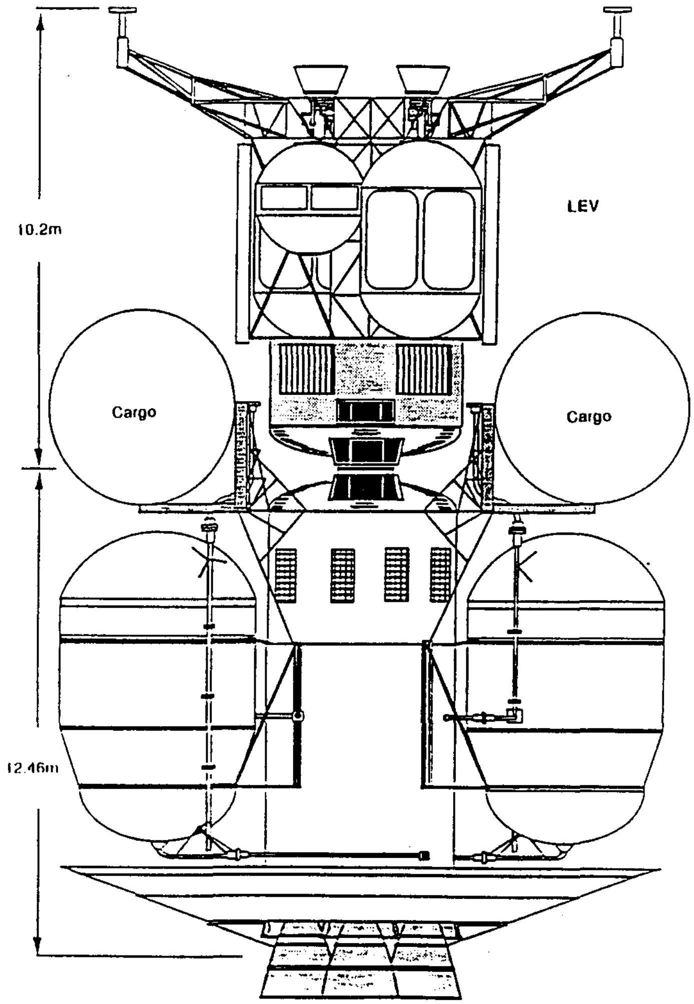
Figure 1. Baseline Launch Vehicles

capability of 52.3 tonnes with a payload volume envelope of 7.6-m diameter by 30-m length; the second has a payload mass capability of 98.2 tonnes with a payload volume envelope of 10-m diameter by 30-m length.

Exactly which launch vehicles will be used to transport which lunar power systems and related infrastructure has not yet been determined. NASA MSFC has yet to lay out any ground rules for sharing these payload cargo bays with other lunar equipment (such as habitat modules, air locks, excursion vehicles, etc.). Whether each system and its related hardware will be simply given an independent cylindrical section of the cargo bay or be custom packaged in an integral fashion among the other systems is not yet known.

Once a launch vehicle has been used to transfer a cargo payload to SSF, this cargo will be transferred from the launch vehicle to another transportation space vehicle for subsequent delivery to the lunar surface. MSFC has identified two candidate transportation systems for landing payloads on the lunar surface: a combined Lunar Transfer Vehicle (LTV) and Lunar Excursion Vehicle (LEV) as shown in Figure 2; and a Single P/A (Propulsion/Avionics) Vehicle. The Single P/A Vehicle is quite similar to the combined LTV/LEV Vehicle except that it has only one set of rocket engines on one end of the vehicle.

The payload landing capacity for each of these vehicles is being sized for approximately 33 tonnes. The payload volume envelopes for each of these lunar transportation systems is effectively the same envelope noted above for the JSC launch vehicles except that the lengths of each of the two cargo cannisters are to be effectively one-half those shown for the JSC launch vehicles. Essentially, it should be assumed that the cargo bay of each JSC launch vehicle will contain two payload cannisters having a diameter approximately equal to the diameter of the JSC launch vehicle's cargo bay and a length of one-half the launch vehicle's cargo bay. Hence, the only cargo operation to be performed at SSF is to remove the two payload cannisters from the launch vehicle's cargo bay and attach them to the lunar landing transportation system. No assembly of payload components (e.g., power plant hardware and related infrastructure) is to take place while the payload is in orbit around the earth at SSF.



DRAWING COURTESY OF MARTIN MARIETTA

Figure 2. Baseline Lunar Transfer Vehicle - Lunar Excursion Vehicle (LTV/LEV)

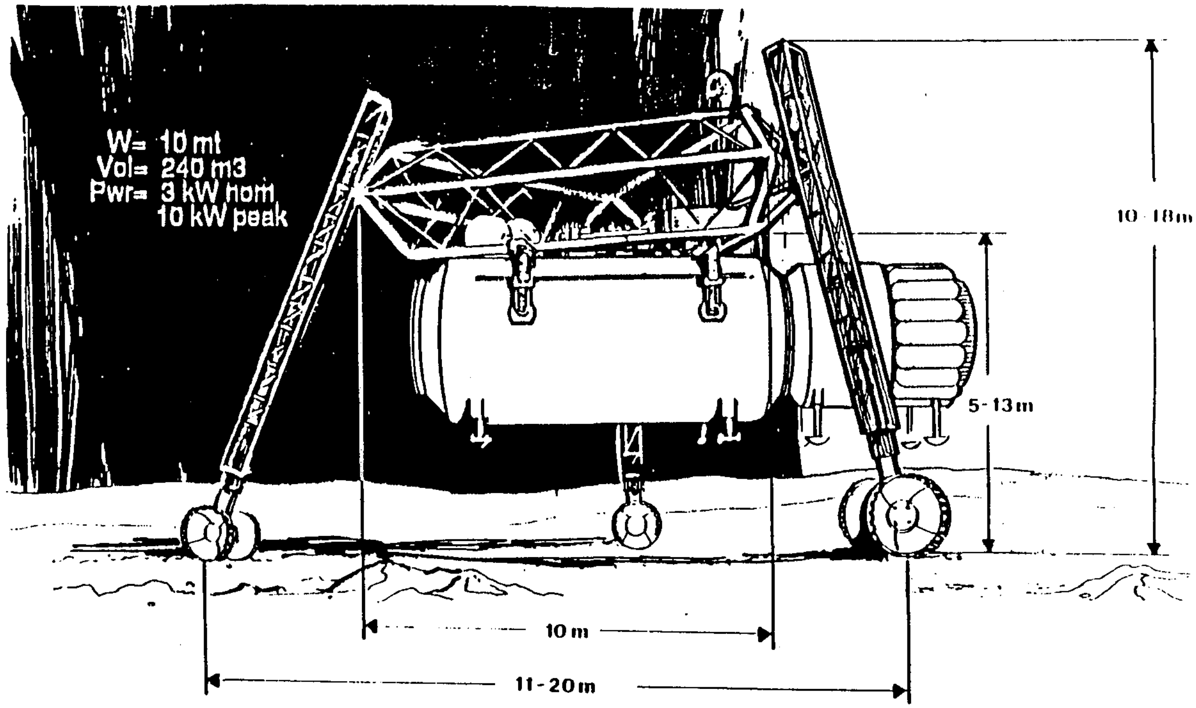
3.2 LUNAR SURFACE CONSTRUCTION EQUIPMENT

Conceptual designs for some of the construction equipment available on the lunar surface for assembling the various electrical power systems is shown in Figures 3 through 5. These designs were reported by Sluka (Ref. 4) during the NASA 90-day study. The work-horse construction device is the Lunar Excursion Vehicle Payload Unloader (LEVPU) shown in Figure 3. It serves as a mobile bridge and crane that also comes with removable attachments for performing other tasks such as digging and drilling. The critical dimensions and power capacity for this device are shown in Figure 3 and it is designed to lift the heaviest equipment being delivered to the lunar surface.

Perhaps the next most important lunar construction vehicle is the unpressurized tele-rover (with robotic capabilities) shown in Figure 4. This device can be used for (among other things): hauling small, relatively light equipment from one location to another; performing relatively intricate robotic assembly tasks such as connecting wires and piping, or unfolding radiator and photovoltaic panels; and surveying various construction sites and obtaining soil samples. The critical dimensions, weight, and power capacity of this device are also shown in Figure 4.

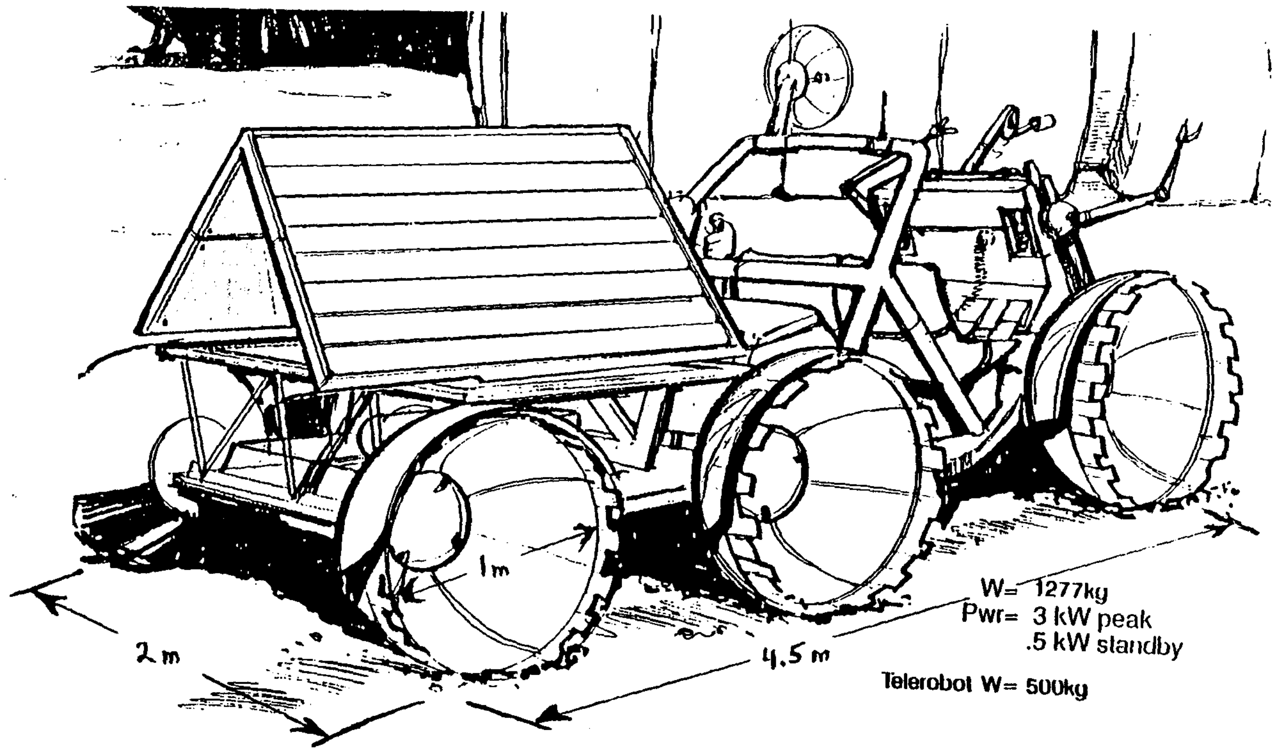
Figure 5 shows an excavator/loader device which also may be used on the lunar surface for digging and trenching. Although this device is not shown to be delivered to the lunar surface under the "Option 5a" manifest, it could serve as a possible backup to the Payload/Unloader for the excavation tasks identified.

Other construction devices identified during the 90-day study (such as a regolith hauler, pressurized manned rover, and the low frequency astronomical array construction machine) are reported in Ref. 4 and need not be repeated here. It is certain that as the SEI program matures, modifications to these devices will be made and even other construction vehicles will be identified. However, the sampling reported here should provide some background as to the possible approaches being considered by NASA at this time.



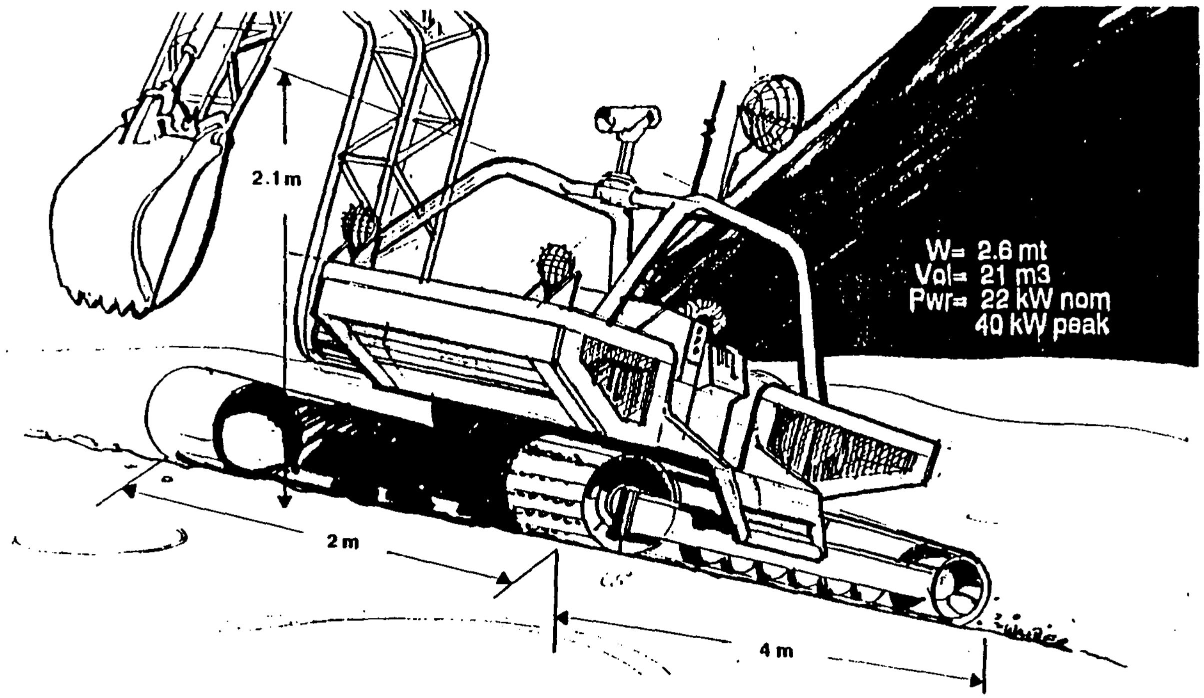
DRAWING COURTESY OF NASA

Figure 3. Baseline Payload Unloader (LEVPU)



DRAWING COURTESY OF NASA

Figure 4. Baseline Unpressurized Rover with Telerobot



DRAWING COURTESY OF NASA

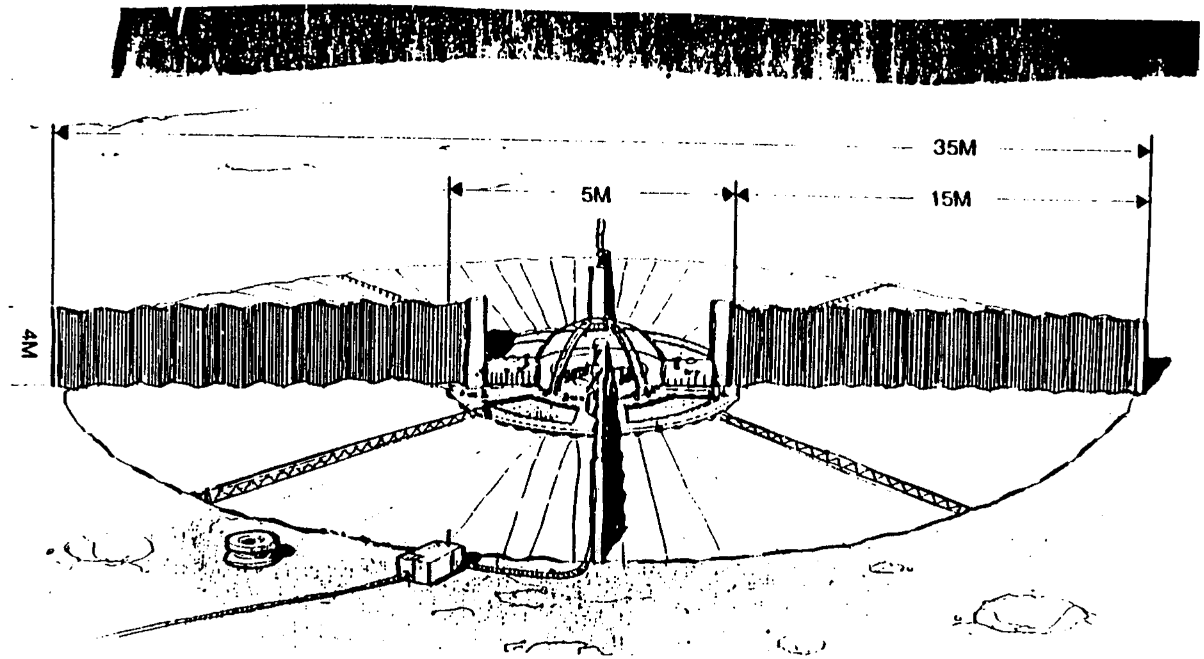
Figure 5. Baseline Excavator/Loader

3.3 POWER PLANTS AND THEIR EMPLACEMENT

Prior to and during the 90-day study, NASA identified three surface electrical power plants for emplacement on the lunar surface: a 100-kWe SP-100 class nuclear reactor (with thermo-electric converters or Stirling engines); an 800-kWe SP-100 class nuclear reactor (with Stirling engines); and a 25/12.5 (day/night) kW photovoltaic (PV) array with regenerative fuel cells (RFC) power package (see, Refs. 2 and 5). The installed 100-kWe nuclear reactor and 25/12.5 (day/night) kW PV/RFC systems are shown in Figures 6 and 7 respectively.

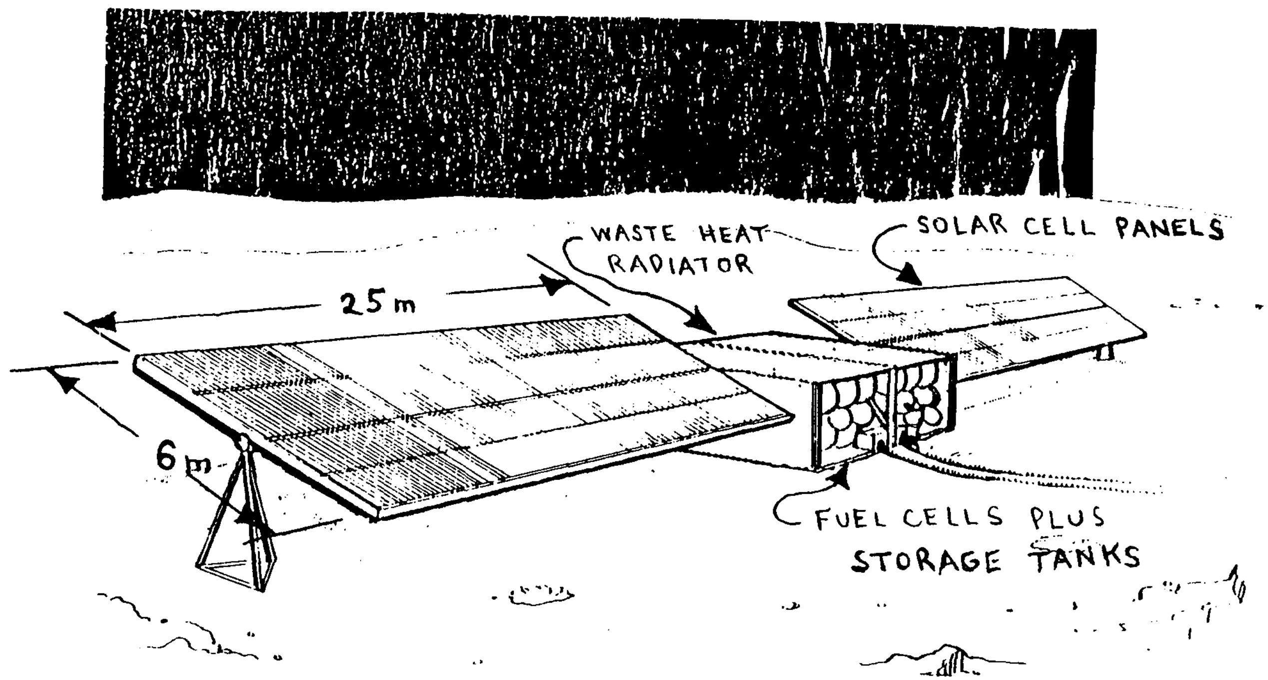
For the installed 100-kWe SP-100 nuclear reactor system, Sluka (Ref. 4) shows a five-step emplacement scenario storybroad. Emplacement of this nuclear reactor system involves first using the LEVPU (Figure 3) to drill and set explosive fracturing charges into the lunar regolith. Once these explosives are detonated, the LEVPU (with its digging attachments) then removes the rubble and clears the site for setting and detonating additional shape charges. These final shape charges and LEVPU clearing operations produce an excavated hole with the proper dimensions for placing the SP-100 nuclear reactor below grade (for radiation shielding and safety purposes). Subsequent to these excavation procedures, the LEVPU then carries the SP-100 reactor with its power conversion unit from the landing pad to the excavated site and places it into the finished hole. The heat rejection system and radiator panels are subsequently installed and the reactor brought on-line. The current philosophy behind this task breakdown description is that most if not all of the entire operation is to be conducted tele-robotically. Additional detail in the task breakdown descriptions for emplacing this reactor system -- including time estimates for each task -- are given in the draft final report by Bell and Boles (Ref. 6).

Due to the relative simplicity of installing the identified 25/12.5 (day/night) kWe PV/RFC power system, the NASA 90-day study did not develop an emplacement scenario for this option other than showing the LEVPU deploying PV panels on a lunar surface support structure.



DRAWING COURTESY OF NASA

Figure 6. Baseline Nuclear Reactor System with Detached Radiator Panels



DRAWING COURTESY OF NASA

Figure 7. Baseline Photovoltaic Array with Regenerative Fuel Cells (PV/RFC)

4.0 POWER PLANT EMPLACEMENT (DESIGN, ANALYSIS, AND ISSUES)

Certainly prior to successfully emplacing and operating lunar surface electrical power systems, a substantial number of detailed analyses and experiments must be performed. During the performance of this NASA task order, numerous questions regarding earth/lunar transportation vehicles, PSS Operations, robotic construction methods, and lunar regolith data (among others) were identified which have significant bearing on the types of lunar power systems and infrastructure to be designed and developed. Most of these questions were left unanswered during this NASA task order study, but they will be documented in the following subsections for future reference. Without reasonable resolution, these issues could lead to mission failure or significant overdesign of lunar power system hardware and construction equipment (i.e., size and weight). A quick summary of the design issues to be discussed below is shown in Table 1.

4.1 EARTH/MOON TRANSPORTATION

As shown in Figures 1 and 2 and discussed in Section 3.1, payload volume and weight capabilities of the various launch and transport vehicles are reasonably identified. However, additional specifications on: payload center-of-gravity; shock, vibration, and acoustical spectrums in the cargo bays; and average g-loads at launch and during flight were not obtained for many of these vehicles. In order to adequately design these power systems and related hardware to ensure their operational reliability after flight, data for each of these vehicles -- similar to the specifications developed earlier for the Titan IV vehicle (see Ref. 7) -- need to be defined and any uncertainties quantified.

For example, structural engineers need to determine the "equivalent static design loads (or body forces)" from reported shock, acoustical, vibration, and average g-load data to apply to the design of the various structures and equipment which are to be contained inside a given vehicle's cargo bay (see, e.g., Veljovich and Larson -- Ref. 8; and Owen and Schmidt -- Ref. 9). Hence, power system weights, volumes, and viable design concepts

Table 1. Summary of Infrastructure Issues

Information Needed	Why?	Status/ Availabil.	How to Obtain
1. E-M Transportation			
- Payload Center-of-gravity	Hardware Design	Not Avail.	Vehicle Designer
- Shock Spectrum	Hardware Design	Not Avail.	Vehicle Designer
- Vibration Spectrum	Hardware Design	Not Avail.	Vehicle Designer
- Acoustical Spectrum	Hardware Design	Not Avail.	Vehicle Designer
- Flight G-loads	Hardware Design	Not Avail.	Vehicle Designer
2. PSS Operations & HART			
- EVA Suit Capabilities	Set-up & Maint.	In Work	HART Team
- Autonomous & Tele-Robots	Set-up & Maint.	In Work	Hart Team & Test
3. Lunar Regolith			
- Friction Angles	Trenching/Exca.	Ltd. Data	Sample Testing
- Cohesion Coefficients	Trenching/Exca.	Ltd. Data	Sample Testing
- Stress Tensor Alignment	Trenching/Exca.	Not Avail.	Sample Testing
- Elastic Non-slip Coefs.	Trenching/Exca.	Not Avail.	Sample Testing
- Viscous Flow Parameters	Trenching/Exca.	Not Avail.	Sample Testing
4. Infrastructure Equipment			
- Dedicated Tools versus General Tool Use	Set-up & Maint.	In Work	Trade Studies
- Detailed Power System Designs & Specs.	Set-up & Maint.	In Work	Power Designer
5. Integrated Design/Analysis			
- Dynamic Math Models	Set-up & Maint.	Not Started	Analytical Dev.
- Sub-scale Exp. Hardware	Set-up & Maint.	Not Avail.	R & D Program

must be based on this information in order to be adequately determined. Ground rules -- regarding these launch/flight structural loads and who is to be given the lead in developing them -- need to be established. This information is one of the first pieces of data needed for beginning preliminary PSS hardware and system design.

4.2 PSS OPERATIONS AND HART

Probably the most critical and least understood area -- of the overall SEI program to date -- deals with the operational capabilities of the lunar crew and the degree of complexity to which they can perform construction, start-up, operations, and maintenance tasks on stationary electrical power systems. These concerns are compounded by the fact that not only is the lunar surface a remote/hostile environment but the PSS team is proposing the substantial involvement of mobile robots and tele-robots for the performance of most tasks. This use of mobile robotic methods requires a substantial advancement in the current state-of-the-art.

At this time, most robots are employed in the manufacturing industry. Most are designed as stationary (non-mobile) devices and are pre-programmed to perform simple unintegrated repetitive tasks. For lunar surface applications, this next generation of robots and tele-robots will most likely have to be: mobile; highly versatile in the movements they perform and the accuracy/precision with which they perform these movements; capable of performing a myriad of non-repetitive tasks; equipped with reasonable optical/touch sensory perception; capable of coordinating their movements with those of other machines and humans; and probably equipped with some form of on-board artificial intelligence (AI) for adapting to constantly changing environments.

Raj Reddy of Carnegie Mellon University's Robotics Institute has indicated that none of these issues are insurmountable (Ref. 10); however, it is his opinion that a greater interdisciplinary understanding of robotic questions must be developed by the scientists and engineers involved in the design process before overall program successes will be achieved. The interdisciplinary issues which must be mastered for these next generation robots involve: kinematics (the study of motion without regard to its causes -- i.e., the forces imposed on a particular body); mechanics and dynamics (the study of motion and its causes); telecommunications and electronics; computer science and computer programming; artificial intelligence; materials science; management science; and optics (just to name a few).

Within the NASA community, JSC has recently formed the "Humans, Automation, Robotics, and Telerobotics (HART)" design team for the rapid assembly of this interdisciplinary body of knowledge (see, e.g., Ref. 11). This team has been also been given the task of producing highly sophisticated and reliable "next generation" robotic equipment within a very aggressive time frame -- i.e., before the year 2002 (the date for the first scheduled lunar flight under Option 5a). The consequences of not adequately developing this hardware will probably require a change in the Option 5a scenario to one that employs more astronaut involvement or "built-in" automatic self-deployment of the power system equipment itself.

Currently, the HART team and PSS Operations have produced (among other things): a draft report defining many of the construction tasks required to be performed on the lunar surface along with "first-cut" (non-substantive) estimates as to the times required to perform these tasks (Ref. 6); and a kinematic simulation of a "lunar transit telescope" robotic set-up (Ref. 12). Conversations with the HART power systems lead engineer has indicated that kinematic modeling of the nuclear SP-100 and PV/RFC stationary power plant emplacements is unlikely to begin until 1992.

4.3 LUNAR REGOLITH

For the stationary electrical power systems being considered, lunar soil (or regolith) is expected to play a very important role in providing long term stable support for this equipment and in shielding astronauts and electronic equipment from nuclear reactor radiation. Hence, it is expected that appreciable amounts of lunar regolith will have to be moved in order to level emplacement sites, provide underground (or below grade) excavations, and/or provide above ground berms or other cover.

Some "soil mechanics" data for this material has been compiled by Binder (Ref. 13) in a preliminary lunar data base. This limited data includes the regolith's internal friction angle, and the coefficient of cohesion at a nominal regolith bulk density. Other important soil mechanic parameters for this material are not known.

For example, the regolith's internal friction angle and cohesion coefficient (as functions of the bulk density) are not given, nor is the regolith's true solids (non-void) density. Furthermore, the regolith's effective "modulus of elasticity" and Poisson's ratio in the elastic stress-strain region (i.e., its non-slip region) are not reported. In the regolith's Mohr-Coulomb failure region (i.e., its sliding friction low void fraction slip region), no data is provided on the alignment of the soil's stress tensor with its associated strain-rate tensor -- i.e., whether principles of isotropy can be employed (see, e.g., Refs. 14 through 24), or whether more elaborate slip-plane alignment principles must be considered (see, e.g., Refs. 25 through 31). Finally, in the regolith's viscous flow region (i.e., its high void fraction slip region), there is no data on the soil's effective eddy viscosity coefficient -- i.e., the proportionality constant between the magnitude of the soil's stress tensor and its strain-rate tensor (see, e.g., Refs. 32 through 36). Without this additional data, understanding the mechanics of regolith handling in terms of system scaling and construction design methods will be extremely difficult.

Currently, the HART team is supporting studies in sub-scale pyrotechnic excavation methods. Small samples of lunar regolith simulant have been prepared, packed, and blasted with small pyrotechnic charges; and video data have been obtained. However, determining how this observed data will scale in 1/6 gravity and vacuum environments will be difficult without the fundamental data described in the above paragraphs. Also, this fundamental data can be used to determine the expected angle of an excavated hole to the vertical direction from blasting and/or digging operations. This angle is important in the design and packaging of nuclear reactor stationary power systems. Designs which package components in a true cylindrical envelope will require backfilling of the excavation if angles substantially greater than 10 degrees are found. Designs which package components in a conical envelope will require more effort in digging an excavation if this soil's angle turns out to be substantially different than the cone's design angle. So far HART estimates of this angle have ranged from 10 degrees to 35 degrees (a significant level of uncertainty).

4.4 INFRASTRUCTURE EQUIPMENT

At the interfaces between the basic stationary power system and its emplacement construction, operating, and service equipment; specific components must be designed to allow for the smooth inter-relations among these devices. These components may be individual tools which are attached to the power system, construction equipment, service equipment, etc. as needed and then subsequently removed; or these components may be integrally designed as a permanent part of the power system and its construction and service equipment.

In order to adequately design these tools and interface equipment, reasonable detail concerning the proposed stationary power generating system and its construction, operating, and service hardware must be known. At present, only preliminary sketches and artist conceptions of these systems and construction hardware have been produced. Hence -- at this stage -- only additional sketches and preliminary concepts can be reasonably produced for various infrastructure devices and options. These preliminary infrastructure concepts can be presented to the groups developing the power systems and construction/operating hardware for feedback and comments.

Eventually, however, the mechanics/dynamics of this infrastructure hardware must also be pursued. Stress, heat transfer, vibration, and other important considerations must be quantitatively evaluated. Due to the infancy of the current state of power system and construction hardware designs, only preliminary sketches for various infrastructure concepts will be provided in this report.

4.5 INTEGRATED DESIGN AND ANALYSIS

In addition to developing quantitative data and analyses (on an individual basis) for each of the power systems, construction equipment, operation equipment, and service equipment to be selected; integrated testing and analysis of this hardware -- as a complete working system -- must also be performed prior to flight in order to determine the overall system stability of the servo-control mechanisms involved and whether any excessive stresses or hardware failures will be observed. Successful completion of full-up hardware system testing and analyses (with all signal and dynamic feedback loops included) will be contingent upon adequately understanding the inter-relationships among the various components as well as the intra-relationships within each component.

Figure 8 shows an example of a dynamic feedback and control analysis block diagram for an integrated robot/load system. In this diagram, the load portion of the drawing could represent any number of components (e.g., a radiator panel, the lunar regolith soil, the power conversion unit, etc.). The position of the robot's arm is denoted by the symbol "x," the force being exerted on the arm and the load by the robot is denoted by the symbol "F_R," and the force being exerted back on the arm and the robot by the load is denoted by the symbol "F_L." Based upon the addition of these forces, the transfer function, G(x, t), provides the new position of the arm. Upon sensing the new position (via video camera, laser optics, skin pressure sensors (touch), etc.), the robot's transfer function H(x, t) determines what new force to be applied to the arm and load. On the other hand, the force exerted by the load back onto the robot's arm is determined by the load function L(x, x′, x", t). This load function can be quite simple in nature (as would be the case for moving a hanging weight, i.e., mg) or one that is very complex and difficult to calculate (as would be the case in determining the lunar regolith's resistance to a robotic shovel). This load function may be dependent upon not only the robotic arm's position but also of its speed, and acceleration. Depending upon the time constants involved in the complete integrated system, this load function could drive the robot unstable resulting in damage to it or the power system hardware it's handling.

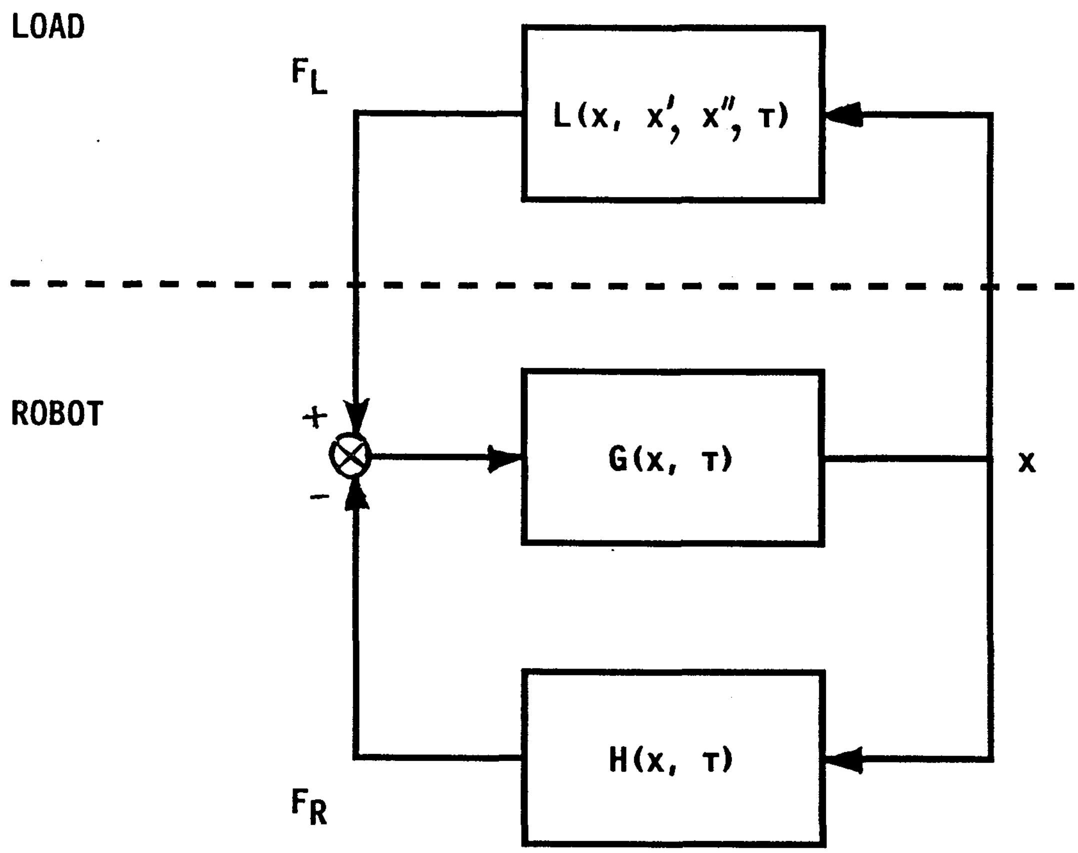


Figure 8. Robot/Load Dynamic Feedback and Control Block Diagram

Hence, complete testing and quantitative analysis of all steps in power system construction, operation, and servicing need to be adequately investigated to ensure program success. Such success begins by first adequately understanding the intra-relationships within the lunar environment and each of the individual hardware components, and finally concludes by quantitatively investigating the inter-relationships among the lunar environment and individual hardware components.

5.0 EMPLACEMENT OPTIONS AND PRELIMINARY REQUIREMENTS

Section 4.0 showed that there are many areas of operational uncertainty that must eventually be resolved prior to finalizing any power system and infrastructure design. Some preliminary conceptual work on these power systems and infrastructures needs to be integrated into an operations scheme so that some assessments -- as to the construction methods to be employed -- can be made. To provide such an assessment, this section provides over 20 conceptual power system emplacement options and concepts for consideration. Order-of-magnitude estimates for many of the option characteristics (such as size of hole, forces required, heat required, electrical power required) are provided where practical. In most instances these characteristics are estimates only and are not substantiated by either reliable references or detailed analyses.

5.1 DOCUMENTS

The following documents are general boilerplate specifications that may be eventually applied to the power emplacement options described in Sections 5.2 et seq. Hence, the requirements stated in these documents should be considered in conjunction with those requirements also reported in Sections 5.2 et seq. However, any conflicts between the requirements of the following applicable documents and the explicit requirements stated in Sections 5.2 et seq. should be resolved in favor of the explicit option requirement. The documents listed in Section 5.1 should be considered very preliminary at this time. No critical review of their contents -- as they relate to the proposed Space Exploration Initiative's (SEI's) lunar missions -- has been conducted.

5.1.1 Government Documents

STANDARDS

Federal Standards

FED-STD-102B	Presentation, Packaging, and Packing Levels
FED-STD-209B(1)	Clean Room and Work Station Requirements, Controlled Environment

Department of Defense (DOD)

DOD-STD-2167	(June 1985)	Defense System Software Development
DOD-E-8983C		Electronic Equipment, Aerospace, Extended Space Environment, General Specification for
OSNP-2, Rev. 0		Quality Assurance Program Requirements for Space and Terrestrial Nuclear Power Systems

Department of Transportation

DOT-Title 49	(CFR)	Department of Transportation Hazardous Materials Regulations

Military Standards

MIL-STD-12D		Abbreviations for Use on Drawings, Specifications, Standards, and Technical Documents
MIL-STD-129J		Marking for Shipment and Storage
MIL-STD-143B		Standards and Specifications, Order of Precedence for the Selection of
MIL-STD-419C		Cleaning and Protecting Piping, Tubing and Fittings for Hydraulic Power Transmission Equipment
MIL-STD-454J	(Notice 2)	Standard General Requirements for Electronic Equipment
MIL-STD-461B		Electromagnetic Emission and Susceptibility Requirements for Control of Electromagnetic Interference
MIL-STD-462	(Notice 5)	Electromagnetic Interference Characteristics, Measurement of
MIL-STD-767C		Cleaning Requirements for Special Purpose Equipment, Including Piping Systems
MIL-STD-794E		Parts and Equipment, Procedures for Packaging and Packing of
MIL-STD-810D		Environmental Test Methods and Engineering Guidelines
MIL-STD-889B	(Notice 1)	Dissimilar Metals

MIL-STD-975F Appendix B	NASA Standard, Electric/Electrical/ Electromechanical (EEE) Parts List
MIL-STD-1264A	Product Cleanliness Levels and Contaminated Control Program
MIL-STD-1247B	Marking, Function and Hazard Designations of Hose, Pipe, and Tube Lines for Aircraft, Missiles, and Space Systems
MIL-STD-1472C (Notice 2)	Human Engineering Design Criteria for Military Systems, Equipment and Facilities
MIL-STD-1522A	Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems
MIL-STD-1540B	Test Requirements for Space Vehicles
MIL-STD-1541 (USAF) Tailored (15 October 1973)	Electromagnetic Compatibility Requirements for Space Systems
MIL-STD-1553B	Aircraft Internal Time Division Command/Response Multiplex Data Base
MIL-STD-1568A	Materials and Processes for Corrosion Prevention and Control Aerospace Weapons Systems
MIL-STD-1574A	System Safety Program for Space and Missile Systems
MIL-STD-1815A	ADA Programming Language
MIL-STD-45662 (Notice 3)	Calibration System Requirements

SPECIFICATIONS

Military Specifications

MIL-P-116H	Methods of Preservation
MIL-C-5015G (4) Supp 1	Connector, Electrical, Circular Threaded, An Type, General Specification for
MIL-E-6051 D(1)	Electromagnetic Compatibility Requirements, Systems

MIL-B-50878 (2)	Bonding, Electrical, and Lightning Protection for Aerospace Systems
MIL-P-55110D	Printed Wiring Boards
MIL-S-7742B(1) (Notice 2)	Screw Threads, Standard Optimum Selected Series, General Specification for
MIL-S-8879A(1) (Notice 2)	Screw Threads, Controlled Radius Root with Increased Minor Diameter, General Specification for
MIL-P-9024G (USAF)	Package, Handling, and Transportation in System Equipment Acquisition
MIL-Q-9558A	Quality Program Requirements
MIL-C-38999H (2) Suppl 1	Connector, Electrical, circular, Miniature, High Density, Quick Disconnect (Bayonet), Threaded, and Breech Coupling, Environment Resistant, Removable Crimp and Hermetic Solder Contacts, General Specifications for

HANDBOOKS

DOD H4-1	Federal Supply Catalog
MIL-HDBK-5D	Aerospace Vehicle Structures, Metallic Materials & Elements for
MIL-HDBK-17A-1	Plastic for Aerospace Vehicles, Part 1, Reinforced Plastics
MIL-HDBK-17A-2	Plastic for Aerospace Vehicles, Part 2, Transparent Glazing Materials
MIL-HDBK-23A	Structural Sandwich Composites

NASA PUBLICATIONS

NASA/Headquarters

NSS/GO 1740.9	NASA Safety Standard for Lifting Devices and Equipment

NASA/Johnson Space Center

NASA TM-82473 (1982 Revision)	Terrestrial Environment Criteria for Use in Aerospace Vehicle Development
NASA TM-78119 (Nov. 1977)	Space and Planetary Environmental Criteria Guidelines for Use in Space Vehicle Development

NASA/JSC SP-R-0022A	General Specification -- Vacuum Stability Requirements of Polymetric Materials for Spacecraft Application

Marshall Space Flight Center

NHB 8060.1B	Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environment That Supports Combustion
MSFC-SPEC-522B	Design Criteria for Control of Stress Corrosion Cracking

5.1.2 Non-Government Documents

STANDARDS

American Society of Testing Materials (ASTM)

ASTM-E-595-84	Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment

American National Standards Institute (ANSI)

ANSI-B-46.1	Surface Texture

OTHER DOCUMENTS

Institute of Printed Circuits

IPC-CM-770	Guidelines for Printed Circuit Board Mounting

Martin-Marietta Corp.

Titan IV Standard	Titan IV Users Handbook
Titan IV Standard	Titan IV RTG Safety Data Book

5.2 SMALL 100-kWe NUCLEAR REACTOR (EXCAVATION AND REGOLITH BERM SHIELDING)

A relatively small 100-kWe nuclear reactor power system has been identified as one possible means of supplying the required user electrical power for the lunar base. One concept being considered uses a buried reactor which is partially placed into an excavation and encircled with a lunar soil berm. This option was developed by General Electric (GE) Aerospace in an earlier NASA/Rocketdyne task order. The option developed by GE uses thermoelectric power conversion. However, this option is also capable of being used in conjunction with a dynamic (Brayton/Stirling) power conversion system as well.

5.2.1 Scope

The basic power system to be incorporated into the 100-kWe nuclear reactor -- with excavation and regolith berm shielding -- emplacement concept is the SP-100 Reference Flight System (Ref. 37). This reactor system is shown in Figures 9 and 10. The basic reactor system is a 5.91 m long by 4.44 m diameter cylinder in the space shuttle cargo bay stowed position. Its heat rejection radiator panels are folded back onto itself while it is in the stowed position and are later self deployed to a badminton "birdie" configuration in its subsequent operating position. The nuclear reactor core resides at the "nose" of the birdie.

The excavation and berm shielding option is shown in Figure 11. This concept employs the use of a small excavation in order to have the reactor core below the lunar grade. Placing the reactor core below grade effectively provides infinite lunar regolith shielding for the direct beam component of the radiation. The scattered component of radiation from the SP-100 power conversion assemblies are attenuated by a small above grade regolith berm. General Electric has estimated that this concept gives an operating dose of approximately 5 rem/year at a distance from the reactor of 1000 m and a dose rate of 10 rem/hour at the edge of the shielding (see Ref. 38).

5.2.2 Requirements

5.2.2.1 Emplacement Characteristics. The SP-100 reactor system in its stowed configuration weighs approximately 4,840 kg. It has a basic conical shape with a diameter of 4.5 m at its upper end; the point of the cone is approximately 6.5 m from the upper end. The heat rejection radiator panels are in a daisy wheel configuration and approximately 6.8 m long. They fold

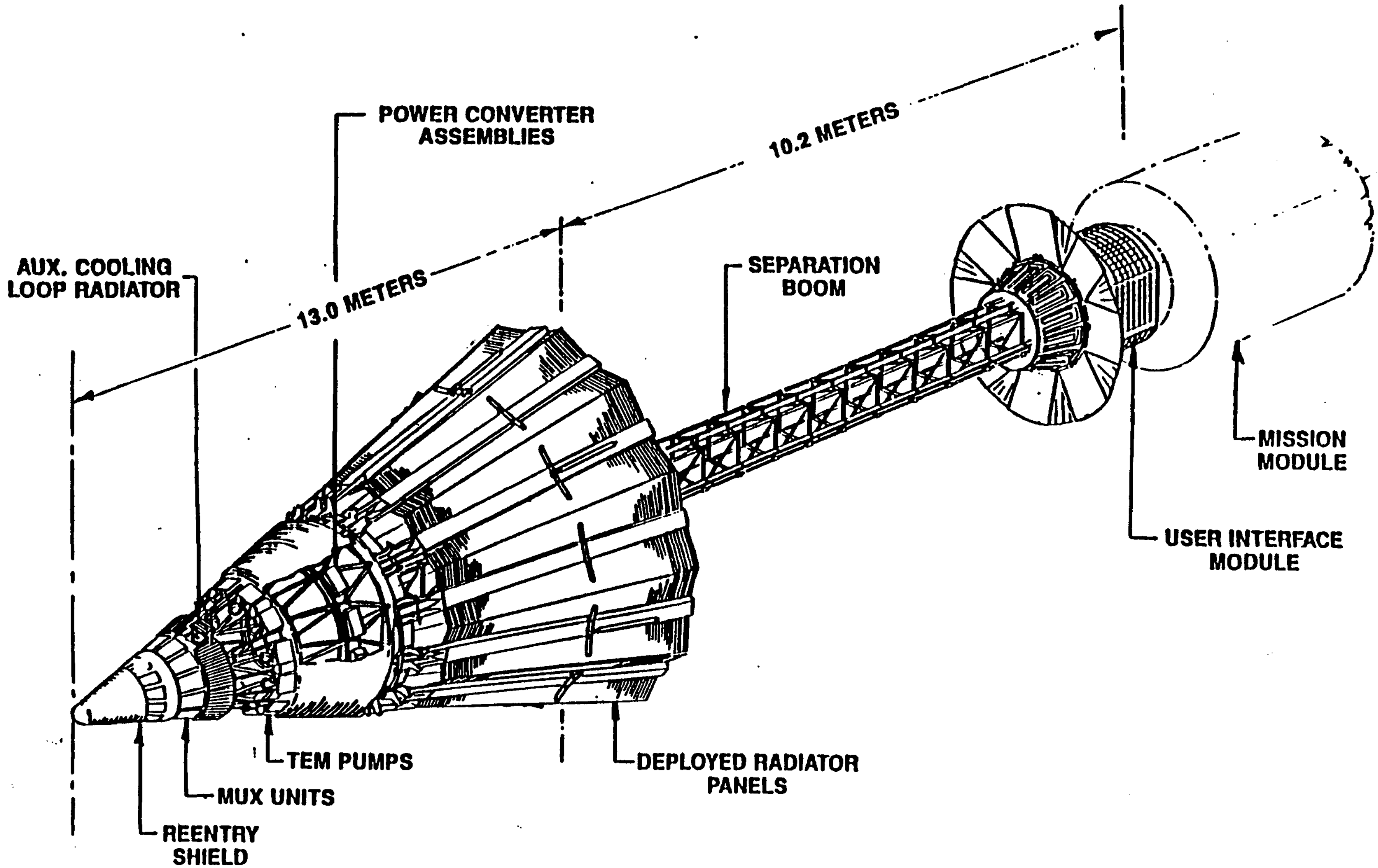


Figure 9. SP-100 Reference Flight System - Deployed Configuration

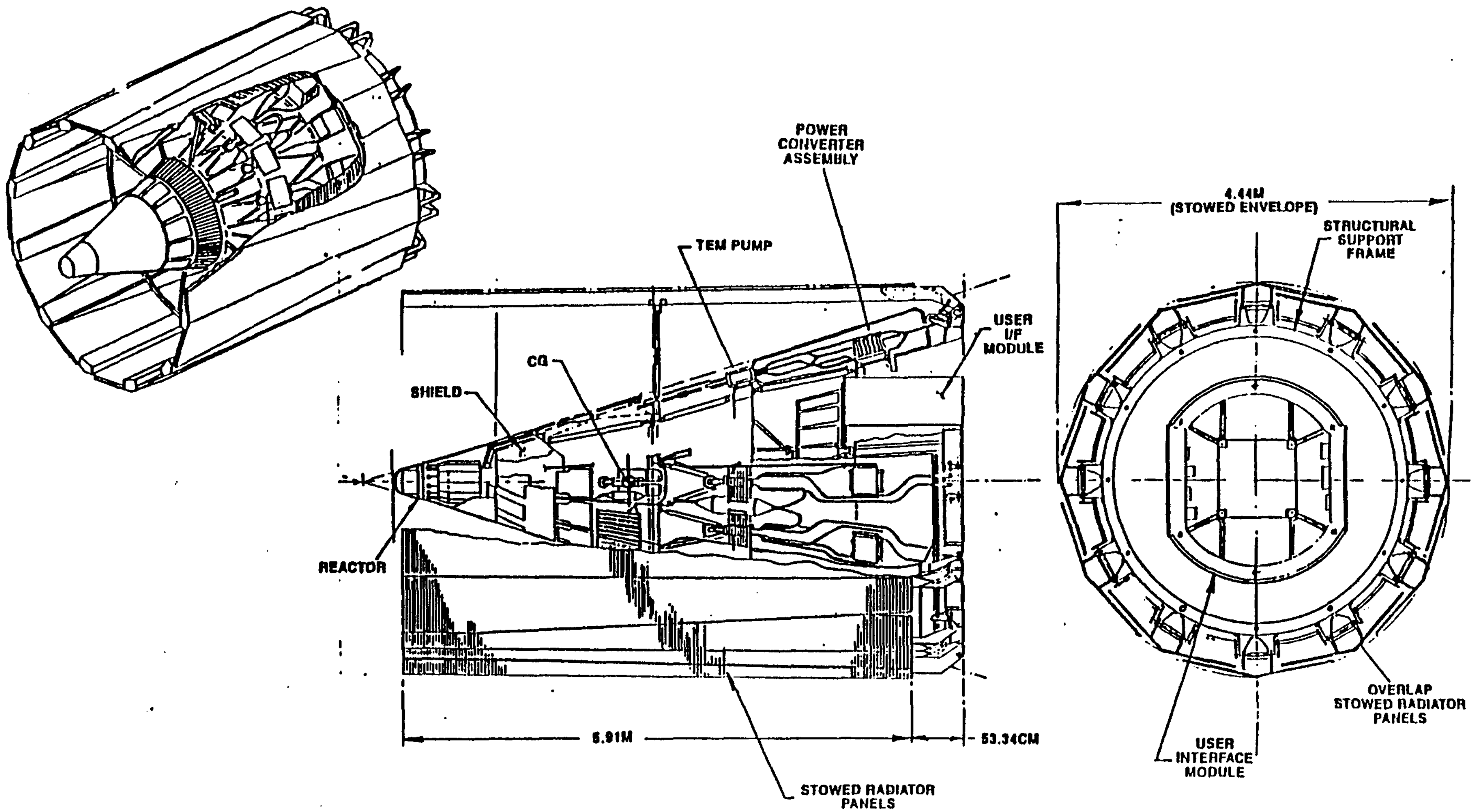
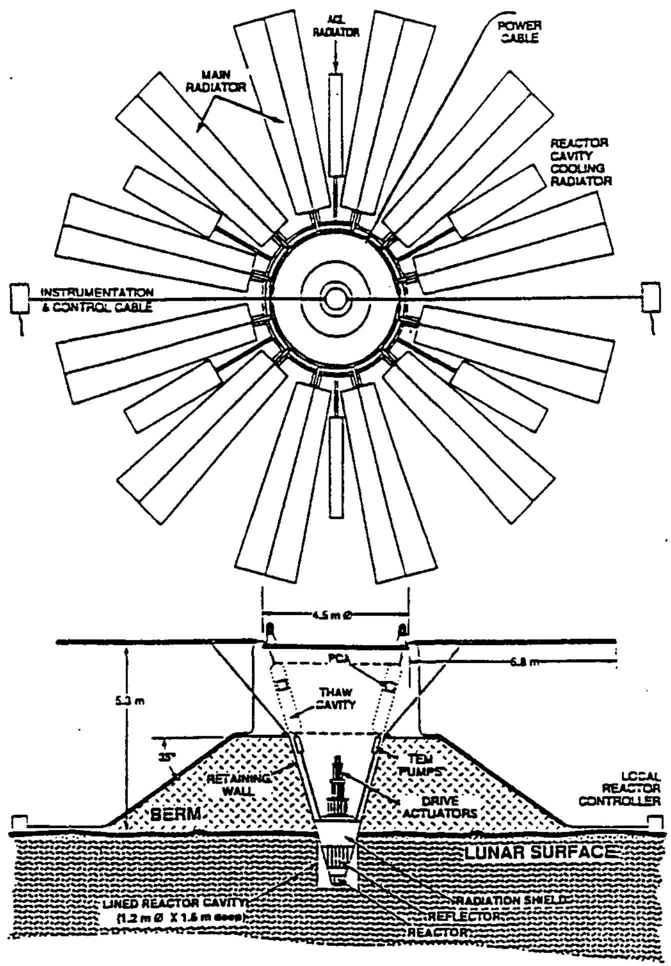


Figure 10. SP-100 Reference Flight System - Stowed Configuration



DRAWING COURTESY OF GENERAL ELECTRIC

Figure 11. Small SP-100 Lunar System - Excavation/Berm Shielding Baseline

down onto the reactor while in the stowed position and are self deployable (via hinges) to the horizontal orientation for operation.

Added to this system -- for the excavation and regolith berm placement option -- are the following required ancillary equipment: bulkhead, retaining wall, and cooling module. This additional equipment -- which is not contained with the SP-100 reactor and is installed separately -- weighs approximately 1350 kg.

For siting this reactor, PSS Operations must provide a cylindrical hole in the lunar regolith of approximately 1.2 m in diameter by 1.6 m deep. Also a regolith shield must be constructed which is approximately 3 m high and 18 m in diameter at its base with an estimated slope on its side of 35 degrees to the horizontal (base on the lunar regolith's angle of repose).

5.2.2.2 __Task Breakdown Description__. The following tasks must be accomplished in the emplacement of this power system option.

1) Excavate a small cylindrical hole in the lunar regolith that is 1.2 m in diameter by 1.6 m deep.

2) Place the following auxiliary equipment -- bulkhead and cooling module -- in hole and backfill as required.

3) Place and align the conical regolith retaining wall in a position over the excavated hole and stabilize its position in the vertical direction to within a tolerance of 3 degrees tilt to the vertical centerline.

4) Construct a 3 m high regolith berm around retaining wall to an outer diameter at its base of approximately 18 m. Pack regolith as required.

5) Lift stowed SP-100 reactor from the lunar lander, place reactor on a lunar surface transportation vehicle, and transport system to power plant emplacement site.

6) Orient reactor in the vertical position and unfold the reactor's radiator panels to the horizontal position. Ensure panels are locked in place.

7) With bridge and crane assembly, pick reactor up 3.5 m and place entire assembly over the excavation and berm centerline.

8) Lower assembly into excavation bulkhead and attach radiator supports to retaining wall.

9) Deploy control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position.

10) Initiate automatic reactor thaw and start-up.

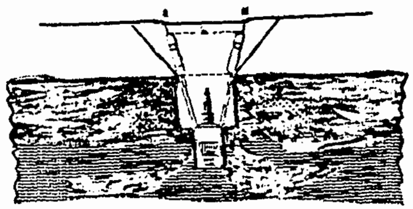
5.3 SMALL 100-kWe NUCLEAR REACTOR (EXCAVATION ONLY SHIELDING)

This emplacement option is similar to the concept as described above in section 5.2. However, in order to minimize the amount of regolith being handled during construction while maximizing the radiation attenuation from regolith material, this option places the entire reactor, its power conversion units, and control assemblies into the lunar excavation. This option assumes that most uncertainties and contingencies associated with lunar mining methods have been resolved.

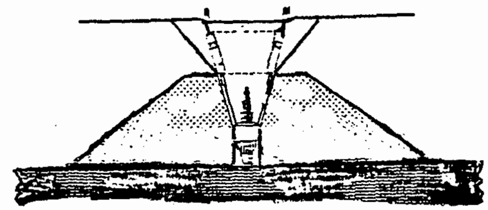
5.3.1 Scope

The basic power system to be incorporated into the 100-kWe nuclear reactor -- with excavation only shielding -- emplacement concept is the General Electric SP-100 Reference Flight System (Ref. 37). This reactor system is shown in Figures 9 and 10. The basic reactor system is a 5.91 m long by 4.44 m diameter cylinder in the space shuttle cargo bay stowed position. Its heat rejection radiator panels are folded back onto itself while it is in the stowed position and are later self deployed to a badminton "birdie" configuration in its subsequent operating position. The nuclear reactor core resides at the nose of the birdie.

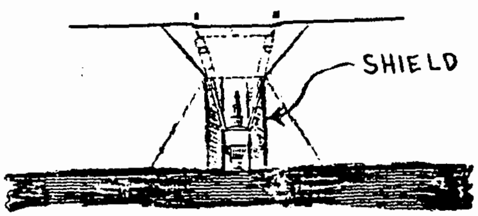
The excavation only shielding option is shown in Figure 12a. This concept employs the use of a large excavation in order to place the reactor core, its control assemblies, and its power conversion modules below the lunar grade. Placing all of these components below grade effectively provides infinite lunar regolith shielding for the beam component of the radiation and effectively attenuates the radiation's scattered component from the control assemblies and power conversion units. Operating doses well below 5 rem/year



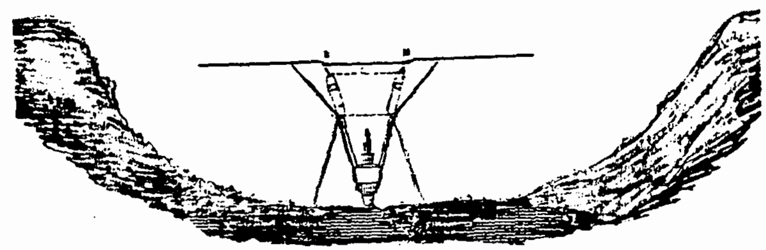
a. Excavation Only Shielding



b. Regolith Berm Only Shielding



c. Four Pie Shielding



d. Crater Shielding

Figure 12. Small SP-100 Lunar System - Options

at a distance from the reactor of 1000 m should be feasible. In fact this option could probably enable the SP-100 reactor to be placed much closer to the lunar habitat due to the significantly reduced scattered component of radiation from above grade hardware.

5.3.2 Requirements

5.3.2.1 Emplacement Characteristics. The SP-100 reactor system in its stowed configuration weighs approximately 4,840 kg. It has a basic conical shape with a diameter of 4.5 m at its upper end; the point of the cone is approximately 6.5 m from the upper end. The heat rejection radiator panels are in a daisy wheel configuration and approximately 6.8 m long. They fold down onto the reactor while in the stowed position and are self deployable (via hinges) to the horizontal orientation for operation.

Added to this system -- for the excavation only placement option -- are the following required ancillary equipment: bulkhead and cooling module. This additional equipment -- which is not contained with the SP-100 reactor and is installed separately -- weighs approximately 1450 kg.

For siting this reactor, PSS Operations must provide a contoured cylindrical hole in the lunar regolith which is approximately 4.6 m deep. The lower 1.6 meters of this hole must have a diameter of approximately 1.2 m, while the upper portion has a diameter of approximately 2.5 m.

5.3.2.2 Task Breakdown Description. The following tasks must be accomplished in the emplacement of this power system option.

1) Excavate a large cylindrical hole in the lunar regolith that is 4.6 m deep. The diameter of the lower 1.6 meters is 1.2 m while the diameter of the upper 3.0 meters is 2.5 m.

2) Place the auxiliary equipment -- bulkhead and cooling module -- in hole and backfill as required.

3) Lift stowed SP-100 reactor from the lunar lander, place reactor on a lunar surface transportation vehicle, and transport system to power plant emplacement site.

4) Orient reactor in the vertical position and unfold the reactor's radiator panels to the horizontal position. Ensure panels are locked in place.

5) With bridge and crane assembly, pick reactor up 0.5 m and place entire assembly over the excavation centerline.

6) Lower assembly into excavation bulkhead and attach radiator supports to top of bulkhead at grade level.

7) Deploy control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position.

8) Initiate automatic reactor thaw and start-up.

5.4 SMALL 100-kWe NUCLEAR REACTOR (REGOLITH BERM ONLY SHIELDING)

This emplacement option is another option which follows that described above in section 5.2. However, in order to eliminate the uncertainties in successfully producing a lunar regolith excavation, this option places the entire reactor, its power conversion units, and control assemblies above grade and enclosed within a regolith berm. This option assumes that most uncertainties and contingencies associated with producing a massive regolith berm structure have been resolved.

5.4.1 Scope

The basic power system to be incorporated into the 100-kWe nuclear reactor -- with regolith berm only shielding -- emplacement concept is the SP-100 Reference Flight System (Ref. 37) as shown earlier in Figures 9 and 10. As stated above, the basic reactor system is a 5.91 m long by 4.44 m diameter cylinder in the space shuttle cargo bay stowed position. Its heat rejection radiator panels are folded back onto itself while it is in the stowed position and are later self deployed to a badminton "birdie" configuration in its subsequent operating position.

The regolith berm only shielding option is shown in Figure 12b. This concept employs the use of a large above grade regolith berm in order to have the reactor core, its control assemblies, and its power conversion modules behind significant quantities of lunar soil. Enclosing all of these components within a regolith berm can effectively provide sufficient shielding for both the beam and scattered components of the nuclear radiation (except the scattered component from the thermal radiator) if the shield is massive enough. Operating doses below 5 rem/year at a distance from the reactor of 1000 m should be feasible with regolith berm diameters on the order of 30 m.

5.4.2 Requirements

5.4.2.1 Emplacement Characteristics. The SP-100 reactor system in its stowed configuration weighs approximately 4,840 kg. It has a basic conical shape with a diameter of 4.5 m at its upper end; the point of the cone is approximately 6.5 m from the upper end. The heat rejection radiator panels are in a daisy wheel configuration and approximately 6.8 m long. They fold down onto the reactor while in the stowed position and are self deployable (via hinges) to the horizontal orientation for operation.

Added to this reactor system -- for the regolith berm only placement option -- are the following required ancillary equipment: retaining wall and cooling module. The retaining wall is integral and attached to the SP-100 reactor; the cooling module is separate from the reactor as in the above three options. Both the retaining wall and cooling module weigh approximately 1300 kg.

For siting this reactor, PSS Operations must construct a cylindrical berm around the SP-100 reactor system subsequent to its siting on the lunar surface. This berm will be approximately 30 m in diameter at its base and 3 to 4 m high. The berm's sides will slope to the horizontal direction at an angle of 35 degrees.

5.4.2.2 Task Breakdown Description. The following tasks must be accomplished in the emplacement of this power system option.

1) Lift stowed SP-100 reactor with integral retaining wall from the lunar lander, place reactor on a lunar surface transportation vehicle, and transport system to power plant emplacement site.

2) Orient reactor in the vertical position and set reactor system on its lunar emplacement site; ensure SP-100 reactor is well supported and braced.

3) Install cooling module system around reactor.

4) Automatically deploy the SP-100 radiator panels. Ensure panels are locked in place.

5) Build up 4 m high regolith berm around reactor to an outer diameter at its base of approximately 30 m.

6) Inspect SP-100 reactor for any inadvertent damage from berm building operation and clean radiator panel surfaces if necessary.

7) Deploy control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position.

8) Initiate automatic reactor thaw and start-up.

5.5 SMALL 100-kWe NUCLEAR REACTOR (FOUR PI INTEGRAL SHIELDING)

This emplacement concept uses a modified SP-100 class reactor to provide integral four pi shielding. In order to eliminate the uncertainties in successfully producing a lunar regolith excavation and/or berm, this option places the entire reactor, its power conversion units, and control assemblies above grade. The reactor system is designed to carry its own shield from earth launch to the lunar reactor emplacement site.

5.5.1 Scope

The basic power system to be incorporated into the 100-kWe nuclear reactor -- with four pi integral shielding -- emplacement concept is the SP-100 Modified Reference Flight System (Ref. 37). This reactor system is again shown in Figures 9 and 10; it is 5.91 m long by 4.44 m in diameter. Its heat rejection radiator panels are folded back onto itself while it is in the stowed position and are later self deployed as described before.

The four pi integral shielding option is shown in Figure 12c. This reactor concept employs a lithium hydride & tungsten shield which is integral to the SP-100 reactor system. Calculations performed by Rockwell have shown that a 5,000 kg lithium hydride & tungsten radiation shield can reduce the radiation dose rate to approximately 5 rem/year to the lunar habitat when the reactor is sited 5 km away. Since the basic SP-100 reactor itself weighs approximately 5,000 kg, this concept effectively doubles the weight of the reactor system being carried to the lunar surface. Based upon the uncertainties associated with constructing lunar excavations and regolith berms (uncertainties which could ultimately be show-stoppers), this option should be seriously considered.

5.5.2 Requirements

5.5.2.1 Emplacement Characteristics. The SP-100 reactor system (with integral shield) weighs approximately 10,000 kg in its stowed configuration and has the same basic cylindrical shape and daisy wheel radiator panels as described in section 5.2.2.1.

For siting this reactor, PSS Operations only needs to transport the SP-100 reactor from the main LEV landing area to its emplacement location (about 5 km from the habitat). However, this concept also lends itself well to placing the reactor system on its own self contained lunar lander which subsequently lands directly in the emplacement site --thus eliminating all lunar surface transportation requirements. However, deployment of electrical equipment and 5-km of cables are required.

5.5.2.2 Task Breakdown Description. The following tasks must be accomplished in the emplacement of this power system option.

1) Lift stowed SP-100 reactor with integral retaining wall from the lunar lander, place reactor on a lunar surface transportation vehicle, and transport system to power plant emplacement site.

2) Orient reactor in the vertical position and set reactor system on its lunar emplacement site; ensure SP-100 reactor is well supported and braced.

3) Automatically deploy the SP-100 radiator panels. Ensure panels are locked in place.

4) Deploy control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position.

5) Initiate automatic reactor thaw and start-up.

Lunar Lander Alternate Emplacement Method.

1) Inspect lander and SP-100 system to ensure landing was completed with no damage to hardware.

2) Automatically deploy the SP-100 radiator panels. Ensure panels are locked in place.

3) Deploy control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position.

4) Initiate automatic reactor thaw and start-up.

5.6 SMALL 100-kWe NUCLEAR REACTOR (CRATER SHIELDING)

This option is of interest because of its simplicity of site preparation, emplacement, and natural shielding. In order to eliminate the uncertainties in successfully producing a lunar regolith excavation and/or berm, this option places the entire reactor, its power conversion units, and control assemblies inside a natural or man-made (produced from large pyro-technic devices) crater. The crater -- for this option -- is large enough so that the entire reactor sits within it. Hence, astronauts do not have to be concerned with any scattered radiation from the SP-100 deployable radiator panels. However, finding suitable craters (in reasonable proximity to the base) is an unknown as well as installing transmission cables within the crater itself.

5.6.1 Scope

The basic power system to be incorporated into the 100-kWe nuclear reactor -- with crater only shielding -- emplacement option is again the SP-100 Reference Flight System (Ref. 37) as seen in Figures 9 and 10.

The crater shielding option is shown in Figure 12d. This reactor concept places the entire SP-100 system inside a crater so that the radiator panels are below the horizon. This emplacement concept should produce the lowest radiation dose rates to the habitat of any of the small SP-100 emplacement options. Radiation doses should be well below 5 rem/year at distances of 500-m or less from the habitat.

5.6.2 Requirements

5.6.2.1 Emplacement Characteristics. The SP-100 reactor system in its stowed configuration weighs approximately 4,840 kg. It has a basic conical shape with a diameter of 4.5 m at its upper end; the point of the cone is approximately 6.5 m from the upper end. The heat rejection radiator panels are again in a daisy wheel configuration and approximately 6.8 m long. They fold down onto the reactor while in the stowed position and are self deployable (via hinges) to the horizontal orientation for operation.

Siting this reactor may require a block and tackle arrangement -- with suspended cable -- positioned over a large man-made or natural crater as shown in Figure 13. The thrust behind this concept is to eliminate all internal power processing equipment set-up and to minimize the amount of lunar regolith handling for an excavation emplacement option. The complete SP-100 assembly is brought to the edge of the crater and hoisted up towards the suspended overhead cable until it is high enough to clear the lip of the crater. The SP-100 assembly is then allowed to slide down the overhead suspended cable until it is positioned directly over the center of the crater. Once centered, the SP-100 unit is lowered into the crater by the hoist until it hits bottom. The unit is then leveled and its radiator panels and power cable subsequently deployed.

Like the "four pi" integral shield option of Section 5.5, crater shielding also lends itself well to the direct flight lunar lander concept. The crater shielded lunar lander reactor would also have the advantage of not being required to carry an integral four pi shield and thus the space craft would be approximately 5,000 kg lighter than the Section 5.5 lunar lander.

5.6.2.2 Task Breakdown Description. The following tasks must be accomplished in the emplacement of this power system option.

1) Lift stowed SP-100 reactor with integral retaining wall from the lunar lander, place reactor on a lunar surface transportation vehicle, and transport system to power plant emplacement site.

2) Orient reactor in the vertical position and set reactor assembly at the edge of the crater.

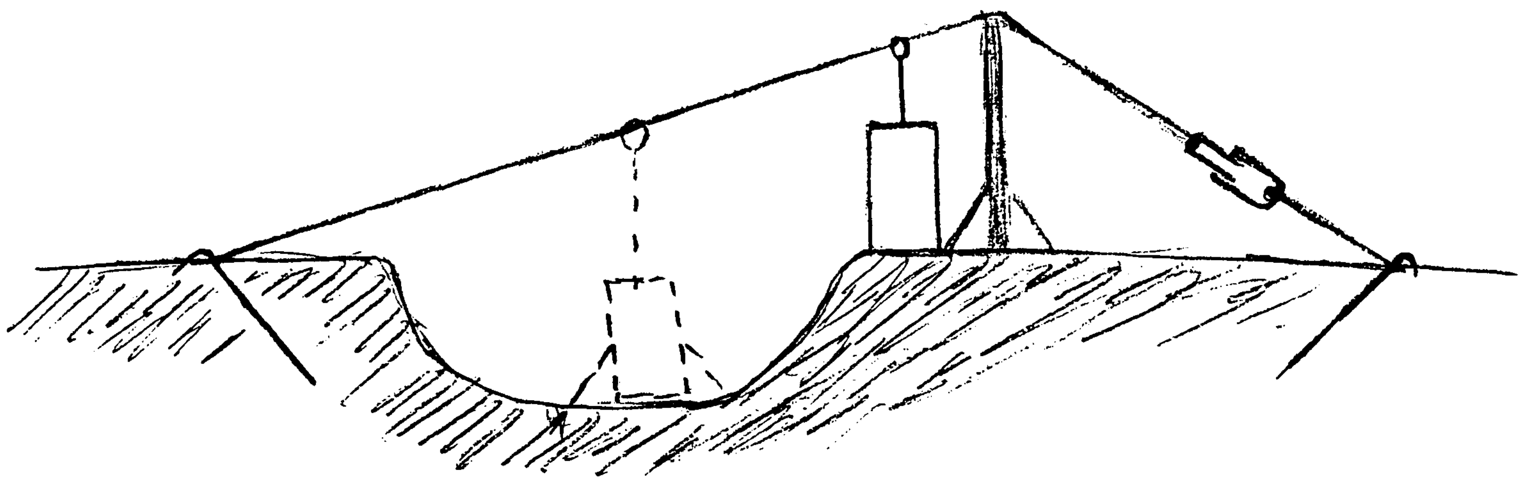


Figure 13. Crater Emplacement Rigging for Small SP-100 Reactor

3) Set up overhead suspended cable and pole. Anchor and secure ends of cable in the lunar regolith and apply approximately 5,000 lbs tension.

4) Connect reactor assembly hoist line to the overhead suspended cable and lift reactor assembly high enough for bottom of assembly to clear the lip of the crater (when the unit is ready to be slid down the overhead cable).

5) Slide the reactor assembly down the overhead suspended cable until it is located over the center of the crater.

6) Lower the SP-100 reactor assembly down to the bottom of the crater with the hoist line and deploy the assembly's standing legs.

7) Automatically deploy the SP-100 radiator panels. Ensure panels are locked in place.

8) Deploy control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position.

9) Initiate automatic reactor thaw and start-up.

5.7 LARGE 550-825 kWe NUCLEAR REACTOR (SEPARATE DYNAMIC ENGINES)

This emplacement concept uses the same 2.5 MW thermal nuclear reactor that is standard for the SP-100 class systems described in Sections 5.2 through 5.6 above. However, this option uses higher thermal efficiency dynamic engines (e.g., Stirling or Brayton) to achieve higher electrical power output (approaching 6 to 8 times the SP-100 thermo-electric power output) for the same thermal input. In order to achieve these higher electrical power outputs, the heat rejection radiators -- when connected to dynamic power conversion systems -- must operate at much lower temperatures than when they are operated in conjunction with thermal electric (TE) converters -- which is the case for the options described in Sections 5.2 through 5.6 above. As a consequence, the radiator areas for the 550-825 kWe nuclear reactor system must be greatly expanded from those designed for the baseline SP-100 device. Hence, these radiators will most likely be delivered as separate packages to the lunar surface for subsequent assembly and connection to the nuclear reactor system; they will not be integrally attached to the reactor for automatic deployment as is the case in the options described in Sections 5.2 through 5.6 above.

5.7.1 Scope

The basic design for the 550-825 kWe nuclear reactor (with separate dynamic engines) option is the concept advanced by Mason et al. (Ref. 5). The basic reactor system is shown in Figure 14. It consists of approximately 23 separate packages to be flown to the lunar surface and assembled at the site -- as opposed to one to three packages for the small SP-100 reactor systems described in Sections 5.2 through 5.6 above. The 23 packages are:

1) one 2.4 m diameter by 4.2 m high cylindrical reactor bulk head enclosure weighing approximately 680 kg;
2) one 1.8 m diameter by 3.8 m high SP-100 reactor assembly weighing approximately 2,390 kg;
3) one 4.0 m diameter by 0.2 m high Stirling inlet/outlet manifold weighing 420 kg;
4) four 5.4 m by 3.1 m by 0.1 m engine support platforms weighing approximately 250 kg each;
5) eight 3.1 m by 2.2 m by 1.1 m Stirling engines weighing approximately 1,040 kg each; and
6) eight 5.0 m by 1.0 m by 2.3 m radiator panel packages weighing approximately 780 kg each.

Total weight of all 23 packages is about 19,000 kg.

The large 550-825 kWe nuclear reactor with separate dynamic engines option requires the most work of any of the power system options for set-up. As shown in Figure 14, the reactor and its bulkhead enclosure is located below grade in a 2.4 m diameter by 4.0 m deep excavation. The eight Stirling engines are placed above grade along with the eight accordion radiator panels. Nuclear radiation operating doses well below 5 rem/year at a distance from the reactor of 1000 m should be feasible. In fact this option could probably enable the SP-100 reactor to be within 100's of meters of the lunar habitat.

5.7.2 Requirements

5.7.2.1 Emplacement Characteristics. This option utilizes a buried reactor concept with above grade energy conversion units. It is the most complex of

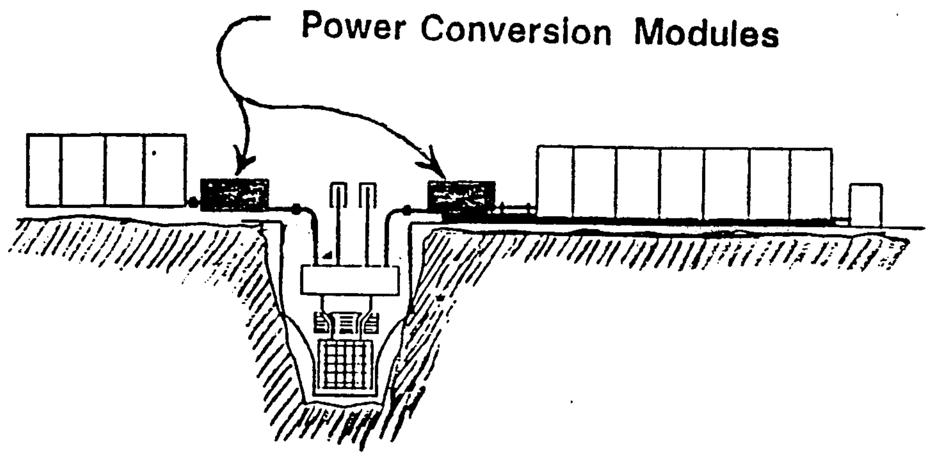


Figure 14. Large SP-100 Lunar System - Surface Dynamic Engines

all nuclear reactor option emplacement concepts currently being considered and could require a major construction/assembly activity.

For siting this reactor option, PSS Operations must provide a cylindrical hole 2.4 m in diameter by 4.0 meters deep. Also PSS Operations will be required to perform numerous intricate assembly procedures for connecting and unfolding (where required) the 23 individual packages together.

5.7.2.2 Task Breakdown Description. The following tasks must be accomplished in the emplacement of this power system option (see also, Figure 15).

1) Excavate a large cylindrical hole in the lunar regolith that is 2.4 m in diameter and 4.0 meters deep.

2) Place the following auxiliary equipment -- liner and liner cooling system -- in hole and backfill as required.

3) Lift the stowed SP-100 reactor (with its primary cooling system module) from the lunar lander, place reactor on a lunar surface transportation vehicle, and transport reactor to power plant emplacement site.

4) Orient reactor in the vertical position and with a bridge and crane assembly, pick reactor up 0.5 m and place entire reactor assembly over the excavation centerline.

5) Lower reactor (with its primary cooling module, control rod assembly, and bulkhead) into the excavation; cover bulkhead with lunar regolith material.

6) Set-up and deploy vertical radiator panels and their reflective ground aprons.

7) Set-up and install power conversion modules (i.e., the Stirling or Brayton engines) and their related power conditioning equipment.

8) Connect all piping and coolant loop plumbing hardware. Inspect all connections to ensure there are no cracks or mis-fitted connections which could possibly leak.

9) Deploy control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position.

10) Initiate automatic reactor thaw and start-up.

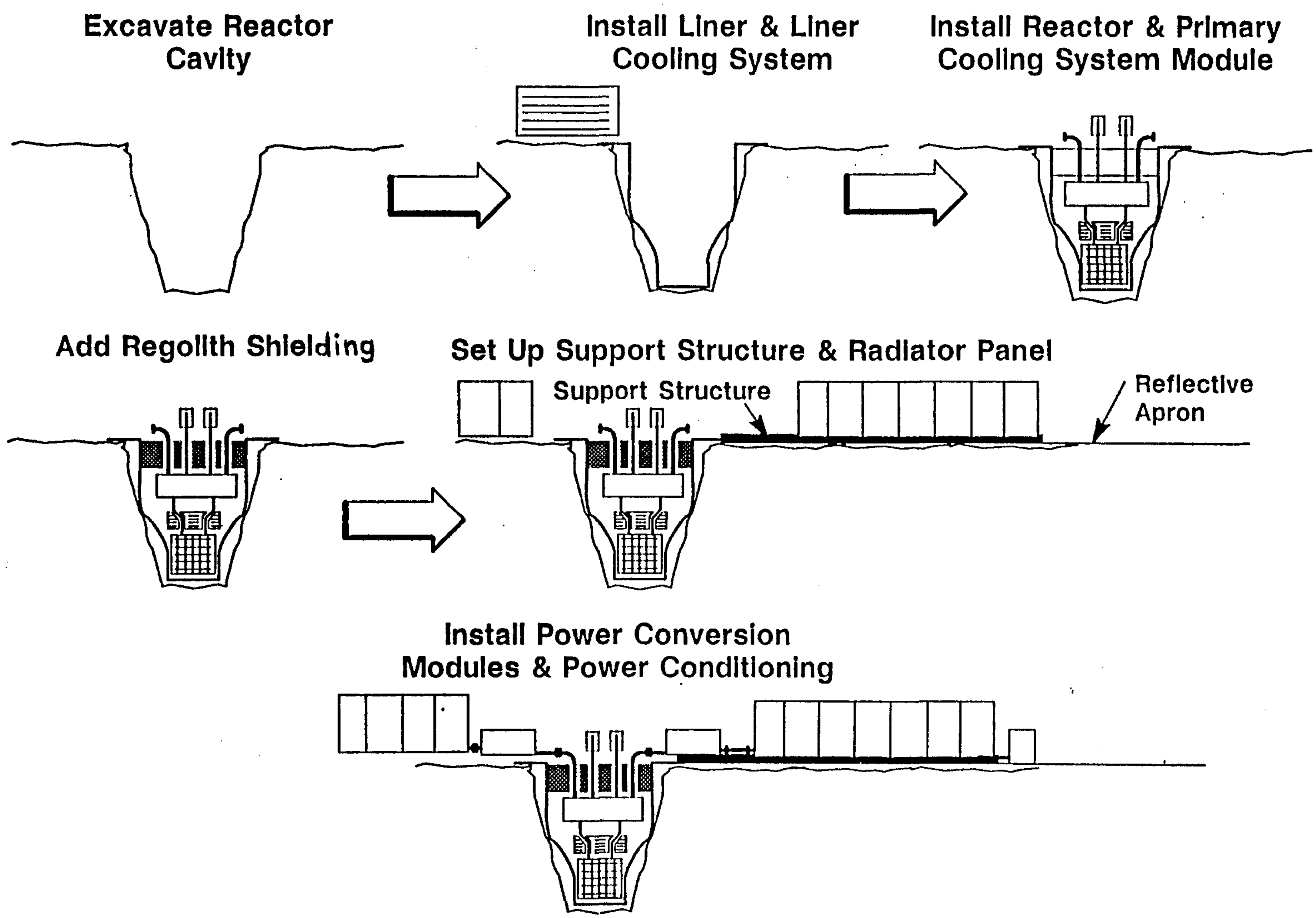


Figure 15. Large SP-100 Lunar System - Emplacement Task Breakdown

5.8 LARGE 550-825 kWe NUCLEAR REACTOR (INTEGRATED DYNAMIC ENGINES)

This emplacement concept is essentially the same concept described in Section 5.7 above for the large nuclear reactor using "separate dynamic engines" except that this reactor design includes the power conversion modules with the nuclear reactor assembly. Hence, the ability to maintain and replace the plant's power conversion modules is lost, but the scope of the construction/assembly task is reduced.

5.8.1 Scope

The basic design for the 550-825 kWe nuclear reactor (with integrated dynamic engines) option is shown in Figure 16. This concept is similar to that described in Section 5.7 above except that the eight power conversion engine packages (Brayton or Stirling) are designed as an integral part the main reactor structure.

A Brayton cycle power conversion system (for example) would typically be designed so that the reactor assembly package will only double in weight from 2,390 kg to approximately 4,800 kg. These engines would be packaged to form the radiation shielding cover for the reactor core as shown in Figure 16. Such packaging should minimize the amount of regolith and/or dedicated reactor shielding required to cover the excavation from that shown for the Section 5.7 option. However, depending upon how the reactor assembly packages, the excavation depth may have to be increased from 4.0 m.

5.8.2 Requirements

5.8.2.1 Emplacement Characteristics. This option is the same as the Section 5.7 concept except that step number 7 -- set up and install power conversion modules -- need not be performed.

5.8.2.2 Task Breakdown Description. The following tasks must be accomplished in the emplacement phase of this power system option.

1) Excavate a large cylindrical hole in the lunar regolith that is 2.4 m in diameter and over 4.0 meters deep.

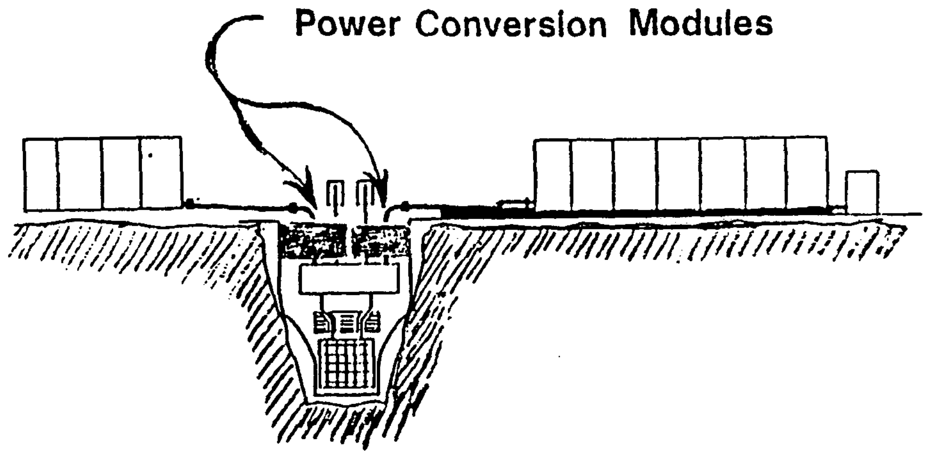


Figure 16. Large SP-100 Lunar System - Bur
Dynamic Engines

2) Place the following auxiliary equipment -- bulkhead and cooling module -- in hole and backfill as required.

3) Lift stowed SP-100 reactor from the lunar lander, place reactor on a lunar surface transportation vehicle, and transport reactor to power plant emplacement site.

4) Orient reactor in the vertical position and with a bridge and crane assembly, pick reactor up 0.5 m and place entire reactor assembly over the excavation centerline.

5) Lower reactor and its control assembly into the excavation, enclose the bulkhead and cover with lunar regolith material.

6) Set-up and deploy vertical radiator panels and their reflective ground aprons.

7) Connect all piping and coolant loop plumbing hardware. Inspect all connections to ensure their are no cracks or mis-fitted connections which could possibly leak.

8) Deploy control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position.

9) Initiate automatic reactor thaw and start-up.

5.9 DEPLOYABLE RADIATOR/PV PANELS (FOLDING ACCORDION)

The folding accordion panel design can be used for either the heat rejection radiator panels utilized in Sections 5.7 and 5.8, or they can be used for the photovoltaic (PV) solar cell panel design. They are fashioned to be readily storable in the cargo bays of the various space transportation vehicles while being as near automatically self-deployable as possible on the lunar surface.

5.9.1 Scope

These panels are shown in Figure 17 for thermal heat rejection radiator applications. They are basically contained as a collapsible box with a top and bottom 2-track system for ease of deployment. The radiator panels are hung within these two tracks. The top and bottom tracks are in-turn connected to two expandable A-frames on each end as shown. Hence, these panels are set-up by: first opening the A-frames to their fully extended position; expanding the top and bottom tracks by pulling the two A-frames apart; and sliding the radiator panels across the tracks in a "shower curtain" fashion until they fully enclose the tracks from both ends of the A-frame.

The flexibility between any two adjacent radiator panels is provided by hinged-bellow joints. These joints have two pipe bellows for transporting heat transfer coolant fluid from the power conversion engine to each radiator panel and back again in a pumped loop. Heat is distributed over each individual radiator panel surface by a number of parallel vertically oriented heat pipes.

When this concept is used to support photovoltaic solar cell panels, the two tracks are supported and allowed to swing from the vertical plane into the horizontal plane for optimum tracking and panel surface orientation to the sun as shown in Figure 18. For tracking purposes the A-frame would come equipped with a tracking motor, chain and sprocket assembly, and automatic control system for maintaining optimum panel angles.

In all cases, the folding accordion radiator/PV panel system would be made as self-deployable as possible. There will probably be internal motors and pulleys for spreading panels and tracks so as to minimize robotic and EVA requirements.

5.9.2 Requirements

5.9.2.1 Emplacement Characteristics. The weight of each panel assembly should be less than approximately 800 kg. The stowed volume should be about 18 m^3 contained within a 3 m by 3 m by 2 m box. Its deployed rectangular cross-section (from 5 radiator panels) is estimated to be approximately 15 m long by 3 m high. The panel assembly is entirely freestanding; there should be no lunar regolith penetrations. Nearly all unfolding design forces should be less than 10-lbf.

5.9.2.2 Task Breakdown Description. The following tasks must be accomplished in the emplacement of this radiator/PV panel option.

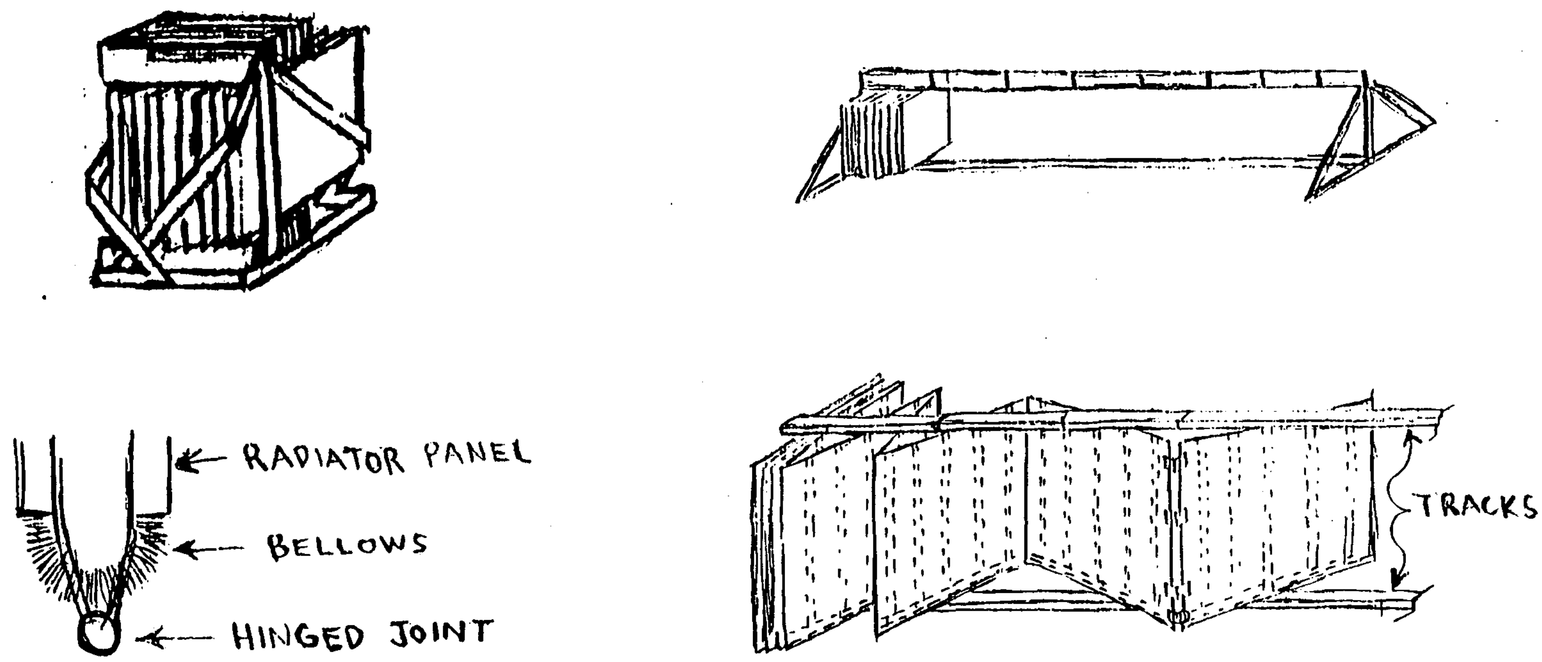


Figure 17. Detached Radiator Panel Deployment

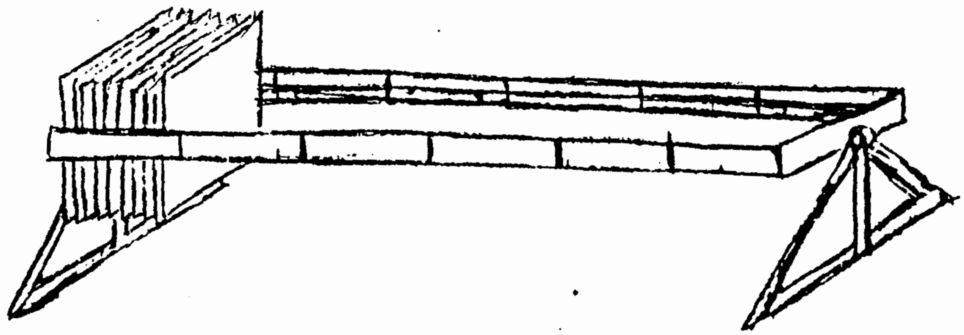


Figure 18. Photovoltaic Array Panel Deployment

1) Lift the stowed radiator/PV panel from the LEV, place on lunar surface transportation vehicle, and transport to power plant emplacement site.

2) Unfold each of the two A-frame truss structures until their A-frame shapes are fully developed.

3) Lift up the A-frame -- which is not directly attached to the track containing the collapsed panels -- 0.5 m off the ground and move this frame back from the other A-frame 15 m in order to completely unfold the individual tracks. Lock all tracks in place.

4) Slide panels along tracks until they completely enclose the space between each track in a "shower curtain" fashion. Lock all panels into place.

5) In the case of a PV panel system, activate the automatic sun tracking system which will tilt the panels from the vertical plane up into the horizontal direction.

5.10 DEPLOYABLE RADIATOR/PV PANELS (ROLLED-UP RUG)

The rolled-up rug panel design can be used for either the heat rejection radiator panels or the photovoltaic/PV panels similar to the folding accordion design described in Section 5.9 above. The rug design is to be capable of storage in space transportation cargo bays without the use of additional structural supports while being rapidly deployable on the lunar surface in a rug roll-out fashion.

5.10.1 Scope

The roll-out rug panel design is shown in Figure 19. It is basically a series of hinged panels which are sized to roll-up into a six-sided hexagon for storage. The width of the panels in the center of the hexagon is smaller than those at further distances from the center so that the rug maintains its desired shape in the stowed position.

In addition to the hinges, adjacent panels are connected by two pipe bellows -- in the thermal radiator panel case -- for transporting coolant fluid between the panels in a pumped loop. Heat pipes are also used to distribute the waste thermal energy across the face of each individual panel. The last outside panel is designed to connect to the exterior coolant pumping system coming from the power conversion engines. Only one side of these panels are designed to be active surfaces in rejecting waste heat or receiving solar energy. Since these panels lay on the ground in the horizontal position and in direct contact with the lunar regolith soil, it is assumed that keeping the surfaces of these panels reasonably clean will require more maintenance than the vertically oriented panels described in Section 5.9 above.

5.10.2 Requirements

5.10.2.1 Emplacement Characteristics. The weight of these panel assemblies is estimated to be less than 1,500 kg. The stowed volume should be approximately 48 m^3 contained within a 3 m long by 4.5 m diameter cylinder. Each rolled up rug assembly is designed to contain a minimum of three rugs -- each rug being 3 m wide by 15 m long.

5.10.2.2 Task Breakdown Description. The following tasks must be accomplished in the emplacement of this radiator/PV panel option.

1) Lift the stowed radiator/PV panel rug assembly from the LEV, place on lunar surface transportation vehicle, and transport to power plant emplacement site.

2) Position the rug at one of the panel final resting positions and unroll the first 15 m of panel.

3) Pick up the remaining rolled-up rug and position the assembly at the next final resting position and then unroll the next 15 m of panel.

4) Repeat step 3 until all 15 m panel assemblies have been located in their final resting places.

5) Connect panel assemblies to each other and/or power generation equipment.

5.11 HT PIPING CONNECTORS (O-RING SEAL BAYONET)

Producing leak tight piping connections on the lunar surface will be an extremely important and difficult task -- particularly if these connections are produced robotically in the field. In order to automate this procedure as simply as possible, a number of designs have been considered. First and foremost of these designs is the O-ring metal seal bayonet connection.

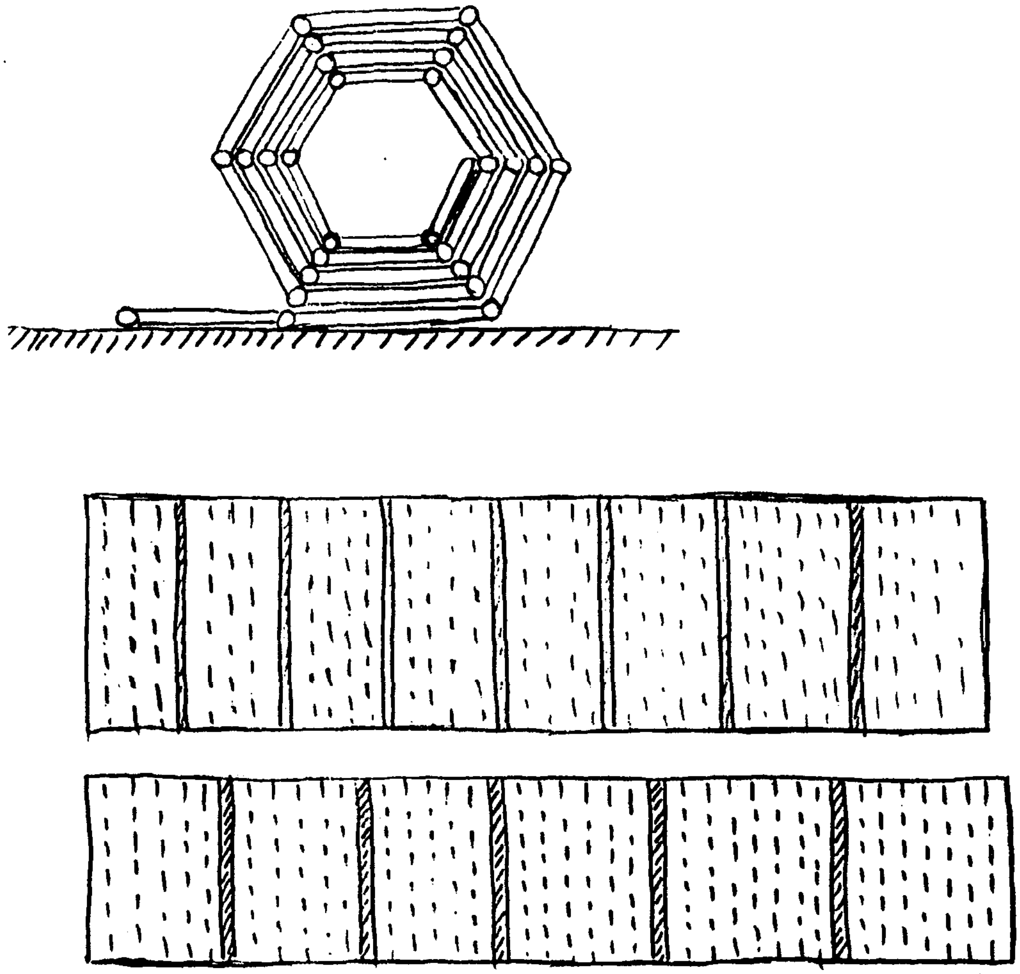


Figure 19. Detached Rug Radiator Panel Deployment

5.11.1 Scope

The O-ring metal seal bayonet connection is shown in Figure 20. It is composed of two metal rings which provide the sealing surfaces. The entire connection is held in place by a compression ring located on the outer surface of the inside pipe.

5.11.2 Requirements

5.11.2.1 Emplacement Characteristics. This type of O-ring bayonet connection should be capable of use on pipes ranging from 1/2 inch to 3 inch. These connections should be capable of being placed together with less than 20-lbf of compressive force. Both the male and female sections of these connectors are covered with a throw away wrapper in order to prevent internal piping and sealing surfaces from being contaminated with lunar dust prior to assembly. These wrappers are removed before connecting the two ends together. Axis alignment of the male and female ends should be within 0.125 inch prior to compressing the two ends together. These fittings should be hydro-statically leak checked to approximately 300 psia with a gas such as nitrogen prior to filling with its working fluid.

5.11.2.2 Task Breakdown Description. The following tasks must be accomplished in the connection of this fitting.

1) Remove fitting wrappers and expose sealing surfaces for quick inspection. Ensure that no dust or other foreign material is on internal surfaces. Clean if necessary.

2) Axially align the male and female ends with one another and slide the male fitting into the female end with approximately 20 lb of compressive force in order to collapse the outer retaining ring.

3) Check the fitting for leaks by pressurizing the piping system to a few hundred psia.

5.12 HT PIPING CONNECTORS (COMBUSTION WELD)

Combustion welding is one alternate method to be considered for completing quick in-the-field welds with a minimum of effort. However, it

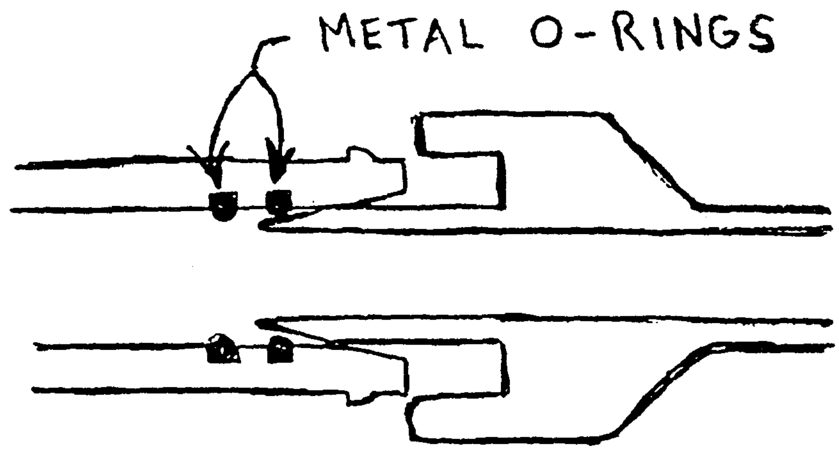


Figure 20. O-ring Seal Bayonet Pipe Connection

appears that this technique has not been extensively used and therefore some development effort would be required to ensure that such a fitting could be reliably connected -- particularly in a lunar or Mars environment.

5.12.1 Scope

The combustion weld pipe connector is shown in Figure 21. This connection is composed of a male and female end in which the female connector contains a pre-mixed fuel/oxidizer solid compound for subsequently producing the heat required for welding the two ends together. Both ends are covered in a removable protective wrapper to prevent lunar dust from contaminating internal surfaces. The solid reactants are designed to begin instantaneously burning after being brought into contact with a 2,000 °F ignition source. The products of this combustion process are hot gases which rapidly disperse from the welding site after giving up some of their sensible heat to the site. Hence, this type of connector is like having a built-in oxy-acetylene welding torch.

5.12.2 Requirements

5.12.2.1 Emplacement Characteristics. This type of connector should be theoretically capable of being used on pipes of any size. An electrical ignition source -- producing a brief 2,000 °F thermal zone within the solid reactants -- should be considered for igniting this mixture. Axis alignment of the male and female ends, prior to inserting the two ends together and welding, should be approximately 0.063 inch. A special jig or tool may be required for this accuracy. An alternate approach may be to taper the sleeve so that the fittings go together in an easier fit prior to welding. Subsequently, this fitting can be checked either hydro-statically with an inert gas for leaks or by x-ray inspection for voids.

5.12.2.2 Task Breakdown Description. The following tasks must be accomplished in the connection of this fitting.

1) Remove protective wrapper from the male and female fittings. Inspect both connector parts to ensure that no dust or other foreign material is on internal surfaces. Clean if necessary.

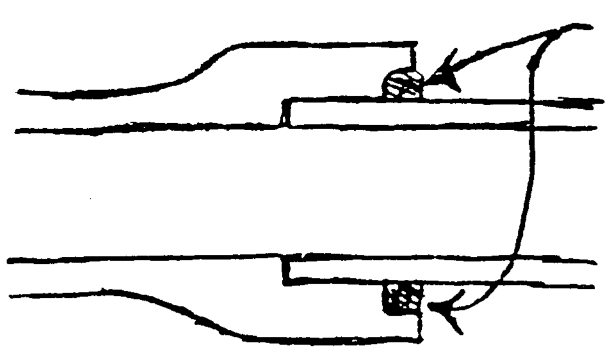


Figure 21. Chemical Combustion Weld Pipe Connection

2) Axially align the male and female ends with one another and slide the male fitting into the female end.

3) Connect the electrical leads from the ignitor to an electrical power source.

4) Close electrical ignitor switch and initiate the welding process.

5) After welding is complete, let the fitting cool and then subsequently check the fitting for leaks by pressurizing the piping system to a few hundred psia or by performing x-ray inspection techniques.

5.13 HT PIPING CONNECTORS (ELECTRICAL ARC WELDING)

Electrical arc welding is another alternate method to be considered for completing in-the-field pipe connections. However, this technique is probably the most complicated method for lunar applications in assembling piping systems together. This method requires the use of an inert gas supply for arcing, a separate coolant system for the welding machine's head, and a separate welding machine itself.

5.13.1 Scope

The portable arc welding method for pipe connections is shown in Figure 22. The head of the machine is designed to be clamped onto the pipe and automatically rotated 360 degrees around the pipe's circumference during welding. All gas, coolant, and electrical current are supplied to the head through an umbilical cord from the central body of the machine. A motor and wheels are an integral part of the welding head in order to provide the rotation about the pipe.

5.13.2 Requirements

5.13.2.1 Emplacement Characteristics. This type of portable welding machine weighs approximately 70 kg within a 1 m^3 volume envelope. It requires approximately 2 kW of electrical power at 10 amps. In order to clamp the machine's head onto each of the two pipes to be welded, it is estimated that the pipes themselves need to be radially aligned to within 0.063 inch and angularly aligned to within 2 degrees for good finished joints.

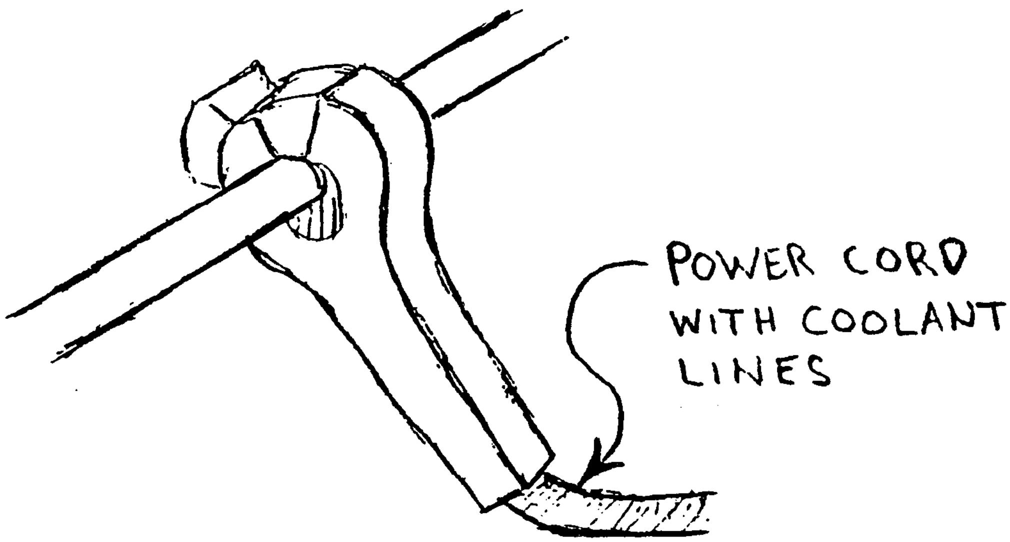


Figure 22. Portable Automatic Arc Weld Pipe Connection

5.13.2.2 Task Breakdown Description. The following tasks must be accomplished in the connection of this fitting.

1) Remove pipe end wrappers and inspect the ends of both pipes to be welded to ensure that no dust or other foreign material is on or near surfaces to be joined. Clean if necessary. Also ensure that pipe ends are tapered properly.

2) Axially align the two pipes and attach them into the welding machine's head. Ensure that the head of the machine is securely fashioned to both pipes.

3) Activate the welding machine's control panel which will automatically begin inert gas and coolant supply flows to the head of the machine. After a given delay, electrical power will be delivered to the head as the head itself is rotated for welding the two pipes together.

4) After welding is complete, let the fitting cool and then remove the welding machine's head. Subsequently check the fitting for leaks by pressurizing the piping system to a few hundred psia or by performing x-ray inspection diagnostics.

5.14 HT PIPING CONNECTORS (HEAT PIPE)

Rather than using forced convective pumped coolant loops for transporting heat between power system components, these connections could possibly be made by inserting self-contained heat pipes directly into these devices. By utilizing heat pipes, there becomes no need for ensuring that welds are leak tight or that seals will not wear out. However, unless the pipe is somewhat flexible, alignment of the heat pipe into the recesses of the various power system components could be quite difficult -- particularly if piping runs are long and contain a number of bends, or power system hardware to which these pipes mate is heavy and not easily moveable.

At this time no specific heat pipes -- for thermally connecting power system hardware together -- have been studied. Further conceptual design efforts should be pursued to determine whether such connections are feasible and the types of working fluids to be utilized for the various power system applications.

5.15 HT PIPING CONNECTORS (EXPANSION BELLOWS)

Perhaps one of the most important infrastructure components for connecting power system components together -- at least as far as thermal hydraulic interfaces are concerned -- is the fluid pipe expansion bellows. This device is most important for: taking up the mis-alignment between power system components (both axial and circumferential); isolating vibration; relieving thermal and/or mechanical stresses; and allowing flexibility in piping and hardware components between their stowed and fully deployed configurations.

5.15.1 Scope

The expansion bellows to be used for lunar surface applications range from those which are designed to expand and contract no more than 1/4 inch in the axial direction, to those which can bend a complete 180 degrees as seen in Figure 17. These bellows are to be made for 1/2 to 3 inch pipe applications in service temperatures ranging from -80 °F to well over 1,500 °F.

5.15.2 Requirements

The expansion bellows are to be capable of being connected to various pipes with any of the following in-the-field connections: O-ring bayonet (Section 5.11); chemical combustion welding (Section 5.12); portable arc welding (Section 5.13); or standard flange fittings (not shown).

5.16 ELECTRICAL WIRE CONNECTORS (CRIMPED CONNECTION)

Option 5a planning (Ref. 1) requires the siting of electrical power generation systems at various distances from the end users. No distance will be exactly pre-determined prior to arrival at the lunar surface. In most instances the exact site location will be dependent upon lunar surface terrain. Hence, electrical power and control cables will have to be cut to length at the site and various connectors attached to their ends.

5.16.1 Scope

The crimped connector for uninsulated single wire electrical cable is shown in Figure 23. It is designed for quick connections with a minimum amount of intricate manipulations for its attachment. One end of the connector contains a female slot for inserting the bare electrical cable; the other end contains a threaded fitting for screwing onto hardware bus board panels.

5.16.2 Requirements

In order to install this electrical connector onto an uninsulated single wire, the following is required. The axial alignment between the wire and the connector's wire slot -- prior to insertion -- is approximately 0.125 inch. The axial alignment between the connector's threaded end and the bus board fitting is also 0.125 inch. Approximately 250 lbf of crimping force and a special crimping tool will be required to adequately secure the connector to the wire. The turning torque necessary to fasten the connector to the bus board will be approximately 20 ft-lbf.

5.17 ELECTRICAL WIRE CONNECTORS (SOLDERED CONNECTION)

Another method for attaching an electrical connector to an uninsulated single wire cable is through the use of a soldered connection. This method eliminates the use of mechanical crimping force to secure the connection in favor of applied heat.

5.17.1 Scope

The soldered connector for uninsulated single wire electrical cable is shown in Figure 24. It is designed for quick connections with a minimum amount of intricate manipulations for its attachment. One end of the connector contains a female slot for inserting the bare electrical cable; the other end contains a threaded fitting for screwing onto hardware bus board panels.

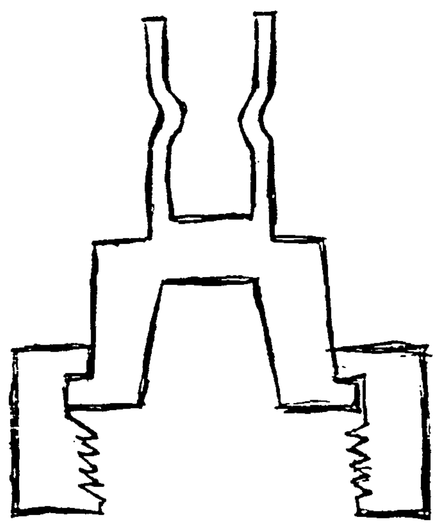


Figure 23. Crimped Connector for Uninsulated Electrical Cable

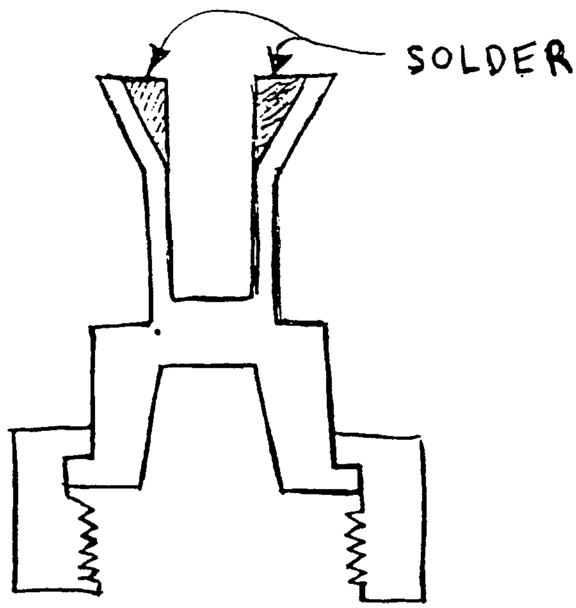


Figure 24. Soldered Connector for Uninsulated Electrical Cable

5.17.2 Requirements

This electrical connector has the following installation characteristics for the fastening of uninsulated single wire cables. The axial alignment between the wire and the connector's wire slot -- prior to insertion -- is approximately 0.125 inch. The axial alignment between the connector's threaded end and the bus board fitting is also 0.125 inch. The wire slot must be heated to approximately 1,200 °F with electrical resistance heater wire in order to cause the solder to flow into the slot and permanently hold the cable. This electrical resistance wire can either be designed for temporarily wrapping onto the connector when the soldering function is to be performed; or it can be design for permanent attachment so that no time is required for installing this resistance wire in-the-field. All soldering must be accomplished with the fitting held in the vertical direction so solder will run down into the slot upon heating -- not out of it. Finally, the turning torque necessary to fasten the connector to the bus board will be approximately 20 ft-lbf.

5.18 ELECTRICAL POWER CABLE (TRENCHED-IN BURIED)

Gordon (Ref. 39) has shown that probably the most promising method of running electrical cable from the power generation area to the various electrical power user sites is by burying that cable underground.

5.18.1 Scope

The burial method for this underground cable can be produced in a number of ways via shoveling, backhoe, dragline, etc. All methods require the excavation of an open trench for subsequently laying in the electrical cable. Once the cable has been placed into the trench, lunar regolith (removed during the excavation process) is used to cover the cable and fill the excavation.

5.18.2 Requirements

The continuous trench to be produced is to be a channel approximately 9 inches deep by 9 inches in width. Upon refilling of this excavation, the lunar regolith should be compacted to the same density which the regolith had prior to removal in order to ensure reasonable soil bearing capacity for lunar vehicles and structures which may be in close proximity. After refill, the surface of the excavation should be at grade with no depressions or humps.

5.19 ELECTRICAL POWER CABLE (COVERED MOUND BURIED)

Another method of burying electrical cable within the lunar regolith is by simply laying the cable directly on the surface of the moon and covering this cable with lunar soil from the surrounding terrain.

5.19.1 Scope

The burial method for this option requires the use of stakes which can be driven into the regolith for holding the cable and preventing it from sliding across the landscape. Once the cable is secure from lateral movement, lunar regolith can be placed over the cable by using a tractor bulldozer or scraper combination in conjunction with a roller for compaction -- among other methods.

5.19.2 Requirements

The securing of the cable from lateral motion will be obtained by driving a pair of 18 inch vertical stakes into the lunar regolith approximately every 20 feet. The lunar regolith mound to be placed over the cable should have a compacted height of approximately 10 inches directly over the cable. The slope from grade level to the top of the mound should be at an angle of approximately 20 degrees or less (particularly in areas of vehicle traffic). All regolith composing the mound should probably be compacted to match the density of the surrounding lunar soil for reasonable bearing capacity. Further analysis is required.

5.20 ELECTRICAL POWER CABLE (PLOWED-IN BURIED)

Finally, another method of burying electrical cable into the lunar regolith is with a tractor driven plow. This method -- if given a powerful enough tractor -- should be the fastest way of getting cable laid between the electrical power generation areas and the electrical power user areas.

5.20.1 Scope

The use of a plow in separating lunar regolith far enough for embedding an electrical cable a few inches below the surface terrain offers significant time advantages that such a method deserves serious attention. This method requires the least amount of regolith to be moved for getting electrical cable buried.

5.20.2 Requirements

The cable for this method should be placed approximately 6 to 9 inches below the lunar regolith grade line in an excavation having essentially no width. After passage of the tractor, plow and cable spool; the loose regolith should be compacted back to its original density with a roller.

5.21 ELECTRICAL POWER CABLE (POWER POLE SUSPENDED)

Suspending electrical power cable above the lunar surface from electrical power poles provides another method of running cable without the uncertainties associated with excavations and trenches.

5.21.1 Scope

An electrical power pole for possible use on the moon is shown in Figure 25. It is designed for quick set-up without the need of driving the pole into the ground; the design is free-standing. It uses an unfolding arm concept for the cable support cross-members along with pull-out legs for free-standing capability.

5.21.2 Requirements

The weight of each power pole should be on the order of 1.0 kg in a stowed cylindrical volume of 0.1 m diameter by 5 m long. The deployed volume

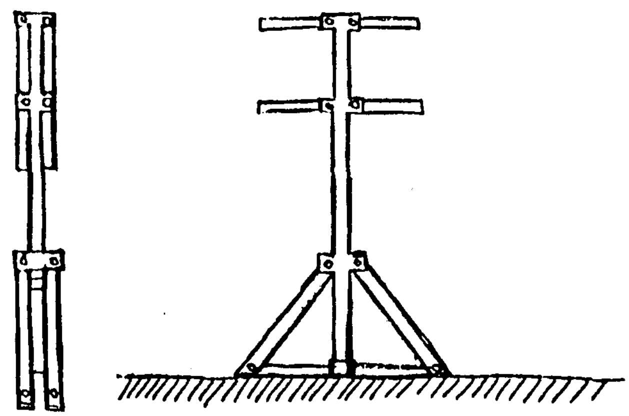


Figure 25. Electrical Power Pole Deployment

as it stands on the lunar surface should be approximately 4.5 m in height having 1 m crosses for hanging cables and a 1.5 m diameter foot print. All unfolding of power pole members (i.e., crosses and legs) should be achieved by using forces of less than 10 lbf.

Spacing of these power poles should be limited only by the amount of cable sag to be allowed by lunar base facility planners. These poles will be designed to support a wide range of cable weights to give optimum pole spacing. However, electrical designers have been investigating the use of "flat" suspended electrical power cables for improved heat transfer and improved current carrying ability. Specifications for these cables may require them to be supported in the vertical plane. Due to the instability of maintaining flat cable in the vertical direction, lateral spacing between these poles will be only about 7 m in order to provide adequate vertical support. Should round cable be used, the spacing can be much greater.

5.22 ELECTRICAL POWER CABLE (INSIDE SURFACE CONDUIT)

Another method for consideration in deploying electrical power cable across the lunar terrain is by placing this cable inside a structurally sound, electrically insulated conduit. Such a conduit could be simply set on the lunar surface with little or no burial.

5.22.1 Scope

The electrical cable emplacement method for this option involves laying the conduit on the lunar surface and securing its location by anchoring the conduit to the lunar regolith with a series of stakes. Once the conduit is set in place, sections of electrical cable are mechanically pulled through the conduit and fastened to one another at optimum lengths along the pipe until the entire distance between power generator and power user have been transversed.

5.22.2 Requirements

The electrical conduit will be composed of sections of circular pipe having a diameter of approximately 10 cm and a length of nearly 18 m. The linear weight of this conduit should be less than 0.07 kg/m. This conduit will be secured by driving a pair of 18 inch vertical stakes into the lunar regolith approximately every 40 m. Electrical cable in up to 100 m lengths should be capable of being continuously pulled through 5 connected conduit sections of 18 m each. The pulling force for sliding this cable through the conduit should be less than 300 lbf for most terrains. Splicing of this cable together -- for runs greater than 100 m -- can be accomplished by using either the crimped or soldered connectors of Sections 5.16 and 5.17 where the threaded end of these connectors have been replaced by another slotted end instead.

5.23 OTHER EQUIPMENT

The possibilities of other types of infrastructure equipment for power system deployment are limitless. Only a few examples have been described here for stimulating conceptual thinking and further consideration. None of these designs have been backed-up by either extensive calculations or testing. Certainly better designs and concepts may be possible.

6.0 SUMMARY AND CONCLUSIONS

Based upon the uncertainties associated with robotic emplacement methods and lunar regolith soil mechanics as discussed in Section 4.0, the first electrical power generation plant at the 100 kWe level that is installed on the lunar surface should be a complete self contained unit which requires no extensive assembly other than to plug-in the power cord. Most likely candidates for this 100 kWe system are photovoltaic arrays with regenerative fuel cell power storage (i.e., PV/RFC systems) or the SP-100 class nuclear reactor with thermo-electric or dynamic energy conversion. In the case of a self-contained SP-100 nuclear reactor system, serious consideration should be given to siting this hardware down into a deep crater (Section 5.6) or within a remote canyon.

Emplacement of larger nuclear electrical power generation systems -- which will require the use of lunar excavations and regolith berms -- should wait until there is a manned presence on the lunar surface and extensive construction emplacement techniques have been practiced and tested. Due to the high cost associated with EVA astronautic involvement and the launching of heavy payloads, most construction and hardware emplacement scenarios are being planned with "low power, low torque, and low weight" robotic and tele-robotic equipment. Hence, the traditional "brute-force" construction methods employed on earth for building our towns and communities (see, e.g., Merritt, Ref. 40) will not be available. Should unexpected soil and rock formations be encountered, there may not be enough power and strength to complete the job. Furthermore, using robots in the place of humans presents a whole panoply of issues regarding object identification, intelligence, and mechanical dynamic control and stability of the robotic mechanism.

Ultimately, all power plant hardware and infrastructure will be significantly driven by lunar regolith soil mechanics and robotic capabilities. Hence, it becomes imperative that extensive design, fabrication, and testing of a "most likely to be built" integrated power system by performed. The integrated system includes not only the power plant but also: the equipment which builds it, the terrain it sits on, and the auxiliary hardware which maintains and supports it. Areas of design which should be adequately addressed include: soil mechanics; robotics; reactor analysis; radiation shielding; logistics and logistics support; thermo-hydraulics; hardware dynamics; power, management, and distribution (PMAD); and launch flight loads, vibration, and packaging. Only by going through this extensive development process can it be assured that a reliable, maintainable, and successful power plant system will be delivered, emplaced, and operated on the moon.

Consideration should be given to fully implementing the program plan for developing a U.S. lunar construction capability as previously outlined by the United States Army Corp of Engineers in 1963 (Ref. 41). This plan called for the use of numerous existing laboratories (such as soils and vacuum chamber laboratories) and to-be-built development facilities -- such as the Operations and Test (O&T) and Lunar Environmental Research and Test (LERT) facilities -- where specific hardware, components, and complete systems could be checked-out and evaluated.

Certainly if the U.S. seriously expects to build and maintain a permanent manned outpost on the moon, extensive testing and detailed analyses of the hardware and integrated systems to be used in that outpost must be a part of that effort. With missions currently scheduled to begin in the year 2002, integrated hardware design, fabrication, testing, and analysis need to begin very soon. The following follow-on task orders should be considered for future funding:

1) Develop Detailed Lunar Regolith Data Base. Complete the soil descriptions for cohension coefficient and internal friction angle for various degrees of compaction and dilatancy. Determine the alignments of the stress and strain-rate tensors during Mohr-Coulomb shear, as well as the stress and strain tensor relationships in the so-called elastic regime. Finally, develop the stress and strain-rate relationships in the viscous flow regime. Provide a laboratory testing program to aid in the development of this information.

2) Dynamic Analyses of Robotic Emplacement Methods. Develop the transient dynamic modeling tools necessary for performing robotic

emplacement and construction. Transient analyses need to be developed for: (a) soils flow, (b) the mechanical loads within a nuclear reactor system package, (c) robotic mechanical joints and structures, (d) robotic motors and electrical power circuits, (e) electrical sensors, computer and electrical control circuits (information processing speeds), (f) graphical recognition of objects, and artificial intelligence (time to assimilate and understand changing physical operating environments).

3) Build and Operate Strawman Emplacement Models. Construct a lunar operations and test facility. Build nuclear reactor system package models and robotic models. Test the dynamic responses of the complete integrated nuclear system and robotic models to varying lunar environments. Develop the analytical scaling principles to be used for final hardware design.

7.0 REFERENCES

1. Anon., Reference Architecture Description Option "5a" (Option 5 with ISRU Emphasis), PSS Reference Architecture Document 90-2, Johnson Space Center, National Aeronautics and Space Administration, Houston, TX (May 22, 1990).

2. Anon., Planet Surface Systems--Study Period Summary, IZ/Lunar and Mars Exploration Office, IZ2/Planet Surface Systems Office, Johnson Space Center, National Aeronautics and Space Administration, Houston, TX (Nov. 17, 1989).

3. Anon., Status Review on Integrated Transportation System, Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, AL (Feb. 28, 1990).

4. Sluka, M., Planetary Surface Systems--PSS Elements Data Base for the 90-Day Lunar/Mars Study, Lockheed Engineering and Sciences Co., Houston, TX (Jan. 1, 1990).

5. Mason, L. S., Bloomfield, H. S., and Hainley, D. C., SP-100 Power System Conceptual Design for Lunar Base Applications, TM-102090, Lewis Research Center, National Aeronautics and Space Administration, Cleveland, OH (Jan. 8, 1989).

6. Bell, L. and Boles, W., Operations Analysis for Lunar Surface Construction: Results from Two Office of Exploration Case Studies, USA-CERL Technical Report, Planet Surface Systems Office, Johnson Space Center, National Aeronautics and Space Administration, Houston, TX (April 1990).

7. Anon., Titan IV User's Handbook, Preliminary Edition, Martin Marietta Aerospace, Denver, CO (June 1987).

8. Veljovich, W. and Larson, J. E., DIPS--Conceptual Design Structural Evaluation, Supporting Document EID-00057, Rocketdyne Division, Rockwell International, Canoga Park, CA (October 1988).

9. Owen, D. and Schmidt, W. J., Dynamic Isotope Power Subsystem (DIPS) Engineering Unit (EU), Specification No. CP409R0007, Rockwell International, Rocketdyne Division, Canoga Park, CA (February 1989).

10. Goldstein, G., "Raj Reddy: Shaping the Next Generation of Robots," Mechanical Engineering, 112 (No. 6), 38 (1990).

11. Erickson, J. D., "Humans, Automation, Robotics, Telerobotics," Presentation at the Planetary Surface Systems Cycle 1 Interim Review, Johnson Space Center, National Aeronautics and Space Administration, Houston, TX (May 22, 1990).

12. Ollendorf, S., "GSFC (Goddard Space Flight Center) Preliminary HART Study Results," Presentation at the Planetary Surface Systems Cycle 1 Interim

Review, Johnson Space Center, National Aeronautics and Space Administration, Houston, TX (May 22, 1990).

13. Binder, A., Lunar Data Base, Lockheed Engineering and Sciences Co., Houston, TX (Feb. 21, 1990).

14. Drucker, D. C. and Prager, W., "Soil Mechanics and Plastic Analysis on Limit Design," Q. Appl. Math., 10, 157 (1952).

15. Drucker, D. C., "Limit Analysis of Two and Three Dimensional Soil Mechanics Problems," J. Mech. Phys. Solids, 1, 217 (1953).

16. Shield, R. T., "Mixed Boundary Value Problems in Soil Mechanics," Q. Appl. Math., 11, 61 (1953).

17. Shield, R. T., "On Coulomb's Law of Failure in Solids," J. Mech. Phys. Solids, 4, 10 (1955).

18. Drucker, D. C., Gibson, R. E., and Henkel, D. J., "Soil Mechanics and Work-Hardening Theories of Plasticity," Trans. Amer. Soc. Civil Engrs., 122, 338 (1957).

19. Jenike, A. W. and Shield, R. T., "On the Plastic Flow of Coulomb Solids Beyond Original Failure," J. Appl. Mech., 26, 599 (1959).

20. Jenike, A. W., "Steady Gravity Flow of Frictional-Cohesive Solids in Converging Channels," J. Appl. Mech., 31, 5 (1964).

21. Johanson, J. R., "Stress and Velocity Fields in the Gravity Flow of Bulk Solids," J. Appl. Mech., 31, 499 (1964).

22. Jenike, A. W., "Gravity Flow of Frictional-Cohesive Solids-Convergence to Radial Stress Fields," J. Appl. Mech., 32, 205 (1965).

23. Pariseau, W. G. and Nicholson, D. E., "Elastic-Plastic Finite Element Analysis of Hopper Filling and Flow Initiation," Mechanics Applied to the Transport of Bulk Materials, AMD - Vol. 31, Cowin, S. C., Editor, Amer. Soc. Mech. Engrs., Appl. Mech. Div., New York, NY 61 (1979).

24. Hashiguchi, K., "Constitutive Equations of Elastoplastic Materials with Elastic-Plastic Transition," J. Appl. Mech., 47, 266 (1980).

25. de Josselin de Jong, G., Statics and Kinematics in the Failable Zone of a Granular Material, Thesis, University of Delft (1959).

26. Spencer, A. J. M., "A Theory of the Kinematics of Ideal Soils Under Plane Strain Conditions," J. Mech. Phys. Solids, 12, 337 (1964).

27. Mandl, G. and Fernandez Luque, R., "Fully Developed Plastic Shear Flow of Granular Materials," Geotechnique, 20, 277 (1970).

28. de Josselin de Jong, G., "The Double Sliding, Free Rotating Model for Granular Assemblies," Geotechnique, 21, 155 (1971).

29. Spencer, A. J. M., "Critique of Mandle and Fernandez Luque," Geotechnique, 21, 190 (1971).

30. Spencer, A. J. M. and Kingston, M. R., "Plane Mechanics and Kinematics of Compressible Ideal Granular Materials," Rheol. Acta, 12, 194 (1973).

31. Mehrabadi, M. M. and Cowin, S. C., "Initial Planar Deformation of Dilatant Granular Materials," J. Mech. Phys. Solids, 26, 269 (1978).

32. Bagnold, R. A., "Experiments of a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid Under Shear," Proc. Roy. Soc. London, A, 225, 49 (1954).

33. Bagnold, R. A., "The Shearing and Dilatation of Dry Sand and the 'Singing' Mechanism," Proc. Roy. Soc. London, A, 295, 219 (1966).

34. Goodman, M. A. and Cowin, S. C., "Two Problems in the Gravity Flow of Granular Materials," J. Fluid Mech., 45, 321 (1971).

35. Goodman, M. A. and Cowin, S. C., "A Continuum Theory for Granular Materials," Arch. Rational Mech. Anal., 44, 249 (1972).

36. Jenkins, J. T. and Cowin, S. C., "Theories for Flowing Granular Materials," Mechanics Applied to the Transport of Bulk Materials, AMD - Vol. 31, Cowin, S. C., Editor, Amer. Soc. Mech. Engrs., App. Mech. Div., New York, NY 79 (1979).

37. Anon., SP-100 Reference Flight System--System Design Review, Interim Briefing, General Electric Aerospace, Valley Forge, PA (May 17-19, 1988).

38. Smith, M. A., SP-100 Reactor Technical Support for Lunar/Mars Exploration Initiative, Final Briefing on Purchase Order No. R04PAB90432028 (XL-T26-890251), General Electric Aerospace, Valley Forge, PA (December 1, 1990).

39. Gordon, L. B., Electrical Transmission on the Lunar Surface--Part 1: DC Transmission, Interim Report Under NASA Grant No. NAG-3-1055 for the Period of June 1, 1989 to April 20, 1990, Space Power Institute, Auburn University, AL (April 27, 1990).

40. Merritt, F. S., Editor, Standard Handbook for Civil Engineers, 2nd Edition, McGraw-Hill, New York, NY (1976).

41. Office of the Chief of Engineers, Special Study of the Research and Development Effort Required to Provide a U.S. Lunar Construction Capability (Vols. 1 & 2), NASA DPR W-11430, United States Department of the Army, Washington, DC (April 30, 1963).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
June 1991

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Infrastructure for Deployment of Power Systems

5. FUNDING NUMBERS
WU–953–20–0D–00
NAS3–25808, Task Order 7

6. AUTHOR(S)
Kenneth M. Sprouse

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Rockwell International
Rocketdyne Division
Canoga Park, California

8. PERFORMING ORGANIZATION REPORT NUMBER
E–12689

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR–187167

11. SUPPLEMENTARY NOTES
Project Manager, Robert Cataldo, Power and Propulsion Office, NASA Glenn Research Center, organization code 6920, 216–977–7082.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 20
Available electronically at http://gltrs.grc.nasa.gov/GLTRS
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The emplacement of an integrated surface power system and its related infrastructure on the lunar surface is an extremely important effort for the successful establishment of a permanent manned presence on the moon. These power systems and infrastructure must survive hostile launch environments from the earth's surface as well as being reasonably sited, operated, and maintained in another relatively hostile setting. This report investigates numerous emplacement options and conceptual ideas for power system hardware. It provides (among other things): very preliminary values for equipment mass and size; task breakdown descriptions for hardware emplacement; the required heat, forces, torques, and alignment tolerances for equipment assembly (where capable of reasonable estimation). Since the concepts presented in this report are very preliminary, this document spends some time detailing the important issues which must be resolved before undertaking the design of complete integrated power plants and their related infrastructure systems. For example, the shock, vibration, acoustics, and quasi-static accelerations expected to be exerted on the power plants and infrastructure hardware during their flight from launch to the lunar surface must be developed.

14. SUBJECT TERMS
Nuclear reactors; Solar array radiators

15. NUMBER OF PAGES
94

16. PRICE CODE
A05

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	