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NASA Technical Memorandum 105925

Power Requirements for the First Lunar Outpost (FLO)

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Prepared for the
Tenth Symposium on Space Nuclear Power and Propulsion
sponsored by the University of New Mexico
Albuquerque, New Mexico, January 10–14, 1993

(NASA-TM-105925) POWER REQUIREMENTS FOR THE FIRST LUNAR OUTPOST (FLO) (NASA) 11 p

N93-15523

Unclas

G3/44 0136522

NASA

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Abstract

NASA's Exploration Program Office is currently developing a preliminary reference mission description that lays the framework from which the nation can return to the Moon by the end of the decade. The First Lunar Outpost is the initial phase of establishing a permanent presence on the Moon and the next step of sending humans to Mars. Many systems required for missions to Mars will be verified on the Moon, while still accomplishing valuable lunar science and in-situ resource utilization (ISRU). Some of FLO's major accomplishments will be long duration habitation, extended surface roving - both piloted and teleoperated and a suite of science experiments, including lunar resource extraction. Of equal challenge will be to provide long life, reliable power sources to meet the needs of a lunar mission.

INTRODUCTION

The baseline mission is to send a crew of four on a nominal 45-day stay encompassing one lunar night and two lunar days. The crew will live in a completely outfitted habitat that is delivered on the first cargo flight. Subsequently, the piloted flight will be launched between 2 and 6 months later. This timeline is based on a one launch pad scenario and the time required to refurbish the pad and process the launch vehicle. However, this does allow ample time to ready the habitat prior to the crew's arrival. Once the crew has established residence in the habitat, they will begin conducting science and exploration.

The major science objectives include establishing astronomy stations, exploratory geoscience and the demonstration of extracting valuable resources from the lunar regolith. The crew will deploy remote science stations about 10 kilometers from the habitat which are baselined to operate autonomously for ten years. The crew will traverse the lunar surface in a rover similar to the Apollo LRV (Lunar Roving Vehicle), only larger, configured to accommodate up to four crewmembers or the equivalent in cargo mass. The crew will be paired into two teams, alternating work days inside the habitat and on rover EVA (extravehicular activity). While crew teams are performing EVAs, they will collect samples from diverse sites for both geologic testing and feedstock for the ISRU demonstration unit located next to the habitat.

One of the significant exploration achievements will be the extended presence on the Moon far exceeding any Apollo mission. FLO will be the first step in the learning process for extended lunar stays and eventual Mars missions. We will experience for the first time the challenges of long term, remote operations coupled with the harsh environments of space.

Of particular significance to power system designs is providing power over the long lunar night. The Apollo missions occurred only during the lunar daytime and were of such a short duration that primary batteries were adequate to meet mission needs. FLO, however, demands comparatively high power levels during the lunar night and the robotic deployment of solar arrays and radiators. Immediately upon landing, power must be available to the habitat to maintain its critical functions which include; health monitoring, temperature control, communications/avionics and maintenance of consumables. The outpost main power system will power the habitat, the ISRU demonstration unit and recharging rovers if required. Each of the major segments of the FLO will be discussed in greater detail with special emphases on those requirements that affect power system design.

SPACE TRANSPORTATION SYSTEM

The space transportation system is comprised of the following elements: heavy lift launch vehicle (HLLV), trans-lunar injection (TLI) stage, lander/descent stage, and crew module/ascent stage. A HLLV is baselined with a shroud diameter of 10 meters by 18 meters in length and a lifting capability of about 240 Mg. The HLLV, TLI stage and lander are designed to accommodate both the cargo and piloted missions. Both cargo and piloted mission phases require about 33 Mg of payload to the surface of the Moon to accomplish a 45 day stay with a crew of four. In the cargo configuration, the lander will deliver the habitat, crew consumables and the initial power system for the outpost. No cargo offloading capabilities are planned for the first mission, therefore, the habitat and power system must remain on the lander approximately 7 meters above the lunar surface.

To minimize lunar regolith ejected onto the habitat by the piloted lander's engine exhaust gases, the baseline minimum landing distance from the habitat is 1 km (suggested by Katzan 1991). The piloted lander will have its own power system and not rely on receiving power from the outpost's power system. For example, one alternative would be to connect a power cable from the piloted lander to the outpost power system. This method requires that the piloted lander to habitat separation distance be no greater than the cable length. Obvious risks are involved if the lander does not meet its landing objective. Once the outpost is expanded, various other options can be employed to utilize surface assets to provide such services (90 Day Study 1989).

The lander, in the piloted configuration, will carry the crew module, ascent stage (with the trans-Earth injection system), about 5 Mg of cargo and a self-contained power system. The power system is required to support all the transportation elements for about 9.5 days of Earth-Moon-Earth transit, the 2 days on the lunar surface (while preparing for surface egress to the habitat and pre-ascent launch preparations) and the 45 days in a shut-down mode. Power is required in the shut-down mode for vehicle health monitoring and heating the ascent stage propellant tanks during the lunar night. The estimated power level, duration, and energy during each mission phase for both the cargo and piloted mode are given in Table 1 and displayed graphically in Figure 1. A significant portion of energy is required during the lunar night for the ascent vehicle and thus will have an impact on the lander's energy storage system mass.

TABLE 1. Transportation System Power and Energy Requirements for Piloted and Cargo Fights

MISSION PHASE	DURATION (hours)	POWER (kWe)	ENERGY (kWe-h)	MISSION
EARTH SURFACE TO EARTH ORBIT	1.47	2.57	3.76	Piloted and Cargo
EARTH ORBIT TO LUNAR ORBIT	96.1	1.88 to 2.52	1.83	Piloted
EARTH ORBIT TO LUNAR ORBIT	120.0	1.88 to 2.52	228	Cargo
LUNAR ORBIT TO LUNAR SURFACE	1.92	2.52 to 2.59	4.84	Piloted and Cargo
ON LUNAR SURFACE (Day)	672	0.48 to 2.66	403	Piloted
ON LUNAR SURFACE (Night)	408	2.10	858	Piloted
LUNAR SURFACE TO LUNAR ORBIT	3.23	2.51	8.12	Piloted
LUNAR ORBIT TO EARTH ORBIT	96.7	1.83 to 2.51	177	Piloted
EARTH ORBIT TO EARTH SURFACE	0.533	2.34 to 2.36	1.25	Piloted
NOMINAL (Piloted)		1.3	1639	
NOMINAL (Cargo)		1.9	236	

The piloted lander requires significantly more energy than in the cargo mode. As shown in Figure 1, about 2.3 kWe is needed for 48 hours while the crew prepares the ascent vehicle/crew module for the 45 day quiescent period and egress to the habitat and the 24 hours prior to departure. Health monitoring of all vehicle systems is required and estimated to total about 500 We for the lunar day period. During the lunar night the storable propellants will need thermal management. The electrical heaters are estimated to require 2.1 kWe to keep the propellants from freezing.

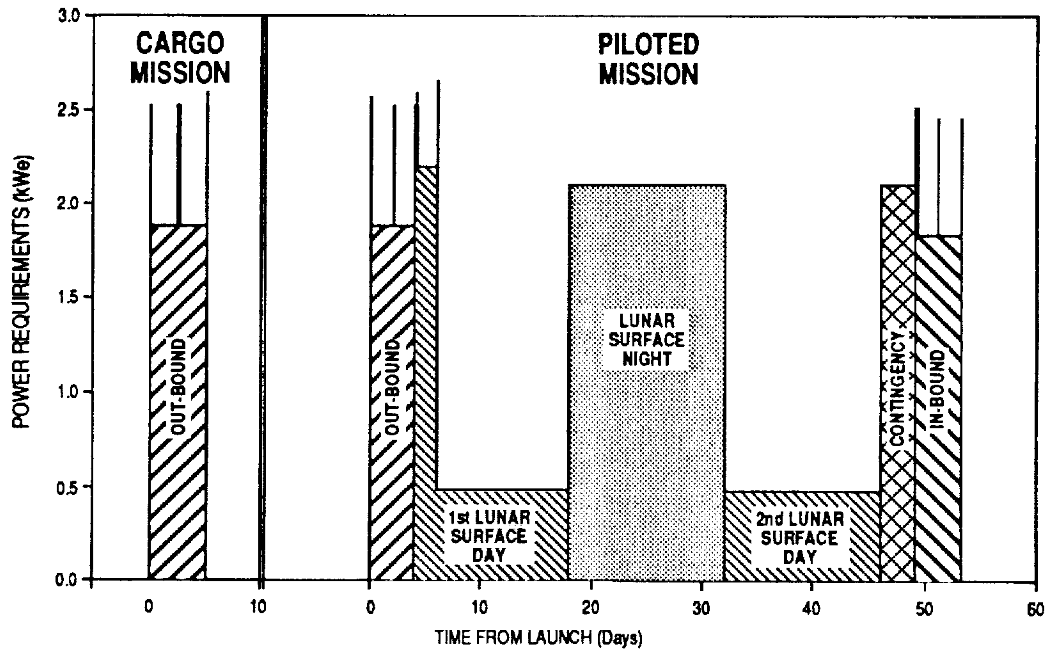

FIGURE 1. Transportation Elements Power Requirements

The outpost power system will provide power to the lander during the cargo mission to eliminate extra mass, volume and cost of an additional dedicated power system. The energy requirements during lunar transfer are small compared to the power system's capacity. Thus, the power system must be able to supply power during lunar transfer and descent to the surface as well as keep alive power for the habitat. The habitat will require continuous power until the habitat is no longer needed and decommissioned.

HABITAT

The habitat will provide all the living and working quarters for a crew of four. The baseline habitat design (10 meters in length and 4.5 meters in diameter) is a scaled down version of the Space Station Freedom HAB Module. The habitat will be situated horizontally on top of the cargo lander about 7 meters above the lunar surface. An airlock, sized to accommodate the crew in lunar suits, provides ingress/egress to the habitat and can function as a pressurized safe haven in the event of a habitat breech. The airlock must also be designed for multiple EVAs, dust removal and for the eventual joining of other pressurized volumes. The airlock support equipment requires almost 600 We on average each day that EVA are conducted. Currently the only days that EVA are not planned are several days centered about lunar noon and midnight, due to extreme temperatures and insufficient earthshine, respectively.

The habitat power requirements are shown in Table 2 and depicted graphically in Figure 2. Once the habitat is in lunar transit it will require power. All the consumables for the crew's use is delivered in the habitat and therefore must be maintained. The transit housekeeping power is 500 We, however, 2.0 kWe is needed while on the surface of the Moon. The 2 kilowatts provides power for habitat functions like thermal control, health monitoring and other control functions to insure the habitat will be habitable upon crew arrival. Thus, the power system must be deployed shortly after landing. When the crew occupies the habitat for the 45 day stay, the power required is a nominal 10 kWe during the day and 9 kWe during the night. The power allocations are as follows; crew systems, 6.0 kWe; avionics, 1.8 kWe; laboratory science experiments, 1.0 kWe.

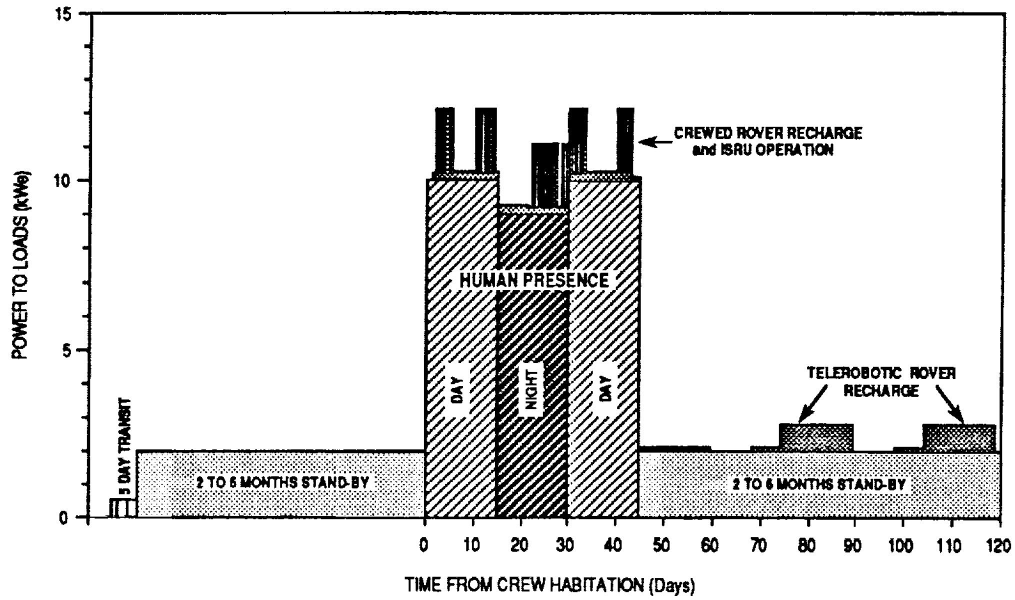

FIGURE 2. Habitat /ISRU/Rover Recharge Power Reqiurements

TABLE 2. Outpost Power and Energy Requirements.

MISSION ELEMENTS	Daytime POWER (kWe)	Daytime ENERGY (kWe-h)	NIGHTtime POWER (kWe)	NIGHTtime ENERGY (kWe-h)
OUT-BOUND	0.5	62	N/A	N/A
DEPLOYMENT	2	48	N/A	N/A
ON-SURFACE				
Stand-By	2	712 per month	2	712 per month
Crewed	10	7120 per stay	9	3204 per stay
ROVER RECHARGE				
Crewed Rover	1.4	< 20 per recharge	1.4	< 20 per recharge
Telerobotic Rover	0.1	< 14 per recharge	0.8	< 269 per recharge
ISRU POWER				
Stand-By	0.2	120	0.2	71
Operational	2	80	N/A	N/A
NOMINAL FOR CREWED PHASE	10.8	7660 per stay	9.7	3448 per stay
NOMINAL FOR UNCREWED PHASE (~ 4 months)	2.0	2904	2.8	3924

The power system must also provide power for both the ISRU demo unit and the recharging of rovers (discussed later). Rover recharge time is baselined at 14 hours, which provides a full charge for the next day's operation. The addition of these elements to the habitat load are seen in Figure 2. Peak power requirements increase to about 12.0 kWe during the daytime and 11.0 kWe at night.

SURFACE TRANSPORTATION

The need for powered surface transportation was identified during the early Apollo 11-14 missions. The maximum distance from the lander that the Apollo crew walked was about 1 km. However, with the use of the Lunar Roving Vehicle (LRV), the Apollo 15-17 crews extended their exploration capability to a 9 km radius from the landing site. It is clear that capable rovers will enhance both exploration and scientific return of future missions.

The FLO rover shall have a payload capability to transport 1 to 4 crew members and/or cargo not to exceed 1 Mg. Potential uses for the rover include; crew EVA in suits, deployment of science equipment and logistics resupply of cargo from the piloted lander to the habitat. Science stations will be deployed up to 10 km from the outpost. Also, samples will be collected from various sites and returned to the habitat for analysis and possible feedstock for the ISRU demonstration unit. The nominal rover speed is 7.3 km/h, which is based on LRV experience. However, the higher total mass of the rover compared to the LRV (1240 kg verses 406 kg, less power system) (Morea 1971) combined with advances in rover mobility subsystems could allow an increase in speed beyond the 7.3 km/h nominal limit and still remain stable.

The rover's range is also limited by EVA suit constraints and the allowable metabolic energy expenditure of 2600 kcal during return to the habitat following any rover failure. While the crew is seated in the rover, the suit's Personal Life Support System (PLSS) will be powered from the rover instead of from the PLSS's power supply. This reduces the PLSS power system mass which is desirable for the crew in lowering the suit mass. The PLSS power capability could therefore be reduced from a nominal 10 hours to that required for walk-about doing science and emergency return to the habitat (Kissinger 1992).

The FLO current baseline for total rover driving distance is 50 km; 20 km outbound, 10 km traverse, and 20 km inbound. The theoretical roving outbound leg distance limit with a single rover is about 20 km based on a 8 hour walk back rate of 2.5 km /h average walking speed. Table 3 and Figure 3 depict the power required for the rover in this single rover scenario. Nominal power is 1.6 kWe with peak values of 2.2 kWe.

TABLE 3. Rover Power and Energy Requirements.

TYPE OF SORTIE	FUNCTION	POWER (kWe)	ENERGY (kWe-h)	COMMENTS
CREWED ROVER	Mobility	1.35	9.3	• Estimated 14- hour rest period after return to habitat
	Housekeeping (Mobile)	0.30	3.0	• Day and night roving capability
	EMU/PLSS	0.50	3.4	• Estimated 50- km traverse (20 km max. radius)
	Science	0.50	1.0	• Maximum speed of 7.3 km/h
	NOMINAL	1.62	16.7	• 0.1 kWe during rest for health monitoring
	MAXIMUM	2.15	---	
RESCUE ROVER	Mobility	1.35	11.1	• Possible second crewed rover for rescue mission
	Housekeeping (Mobile)	0.30	3.0	• 2 crew outbound; 4 crew inbound
	EMU/PLSS	0.50	6.2	• Estimated 14- hour rest period after return to habitat
	Science	0.00	0.0	• Day and night roving capability
	NOMINAL	2.03	20.3	• Estimated 60 km traverse at maximum speed of 7.3 km/h
	MAXIMUM	2.65	---	• 0.1 kWe during rest for health monitoring
TELEROBOTIC ROVER	Mobility	0.10	20.0	• Estimated 20- day rest period after return to habitat
	Housekeeping (Mobile)	0.10	22.0	• Daylight roving only
	Telerobotics	0.30	66.0	• Estimated 200- km traverse at maximum speed of 1.0 km/h
	Science (Mobile)	0.10	20.0	• 0.1 kWe during rest for health monitoring
	Science (Stationary)	0.60	12.0	
	NOMINAL	0.64	140.0	
	MAXIMUM	1.00	---	

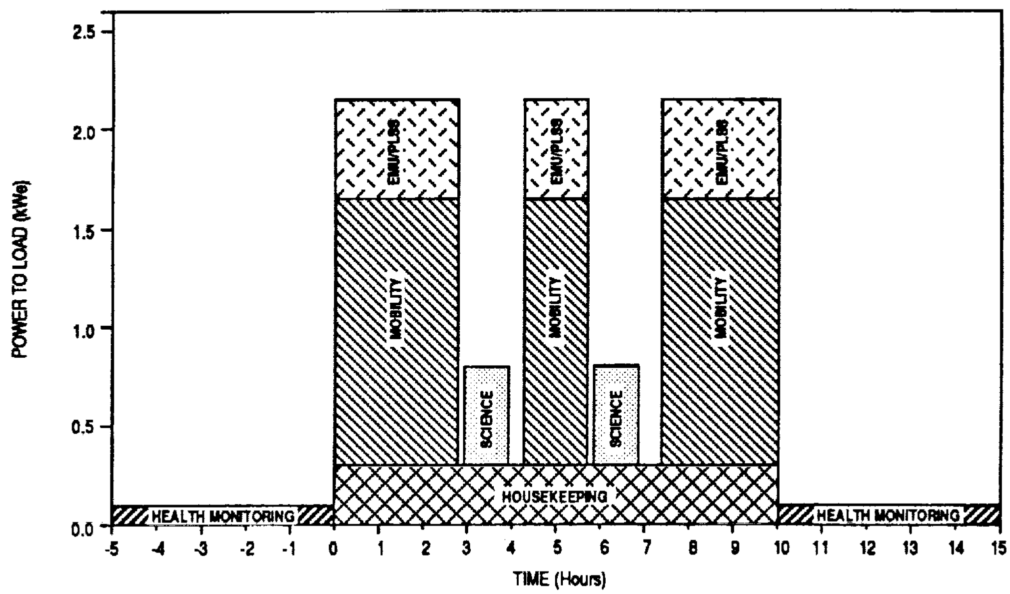

FIGURE 3. Crewed Rover Power Requirements for Single Rover Mode

The multiple rover scenario allows a greater outbound leg distance to be driven by the primary rover (30 km), because the second rover can perform a rescue mission. If the primary rover should fail, the crew can start walking back to the habitat while the second rover is dispatched. The second rover reaches the crew within 3.5 to 4 hours, and all crew members return to the habitat in the rescue rover. Since two different rovers will probably not be developed, the more severe rescue mode power requirements will be the rover power system design driver and this worst case is shown in Figure 4. The nominal power is 2.0 kWe and the maximum is 2.7 kWe with four crew members on board.

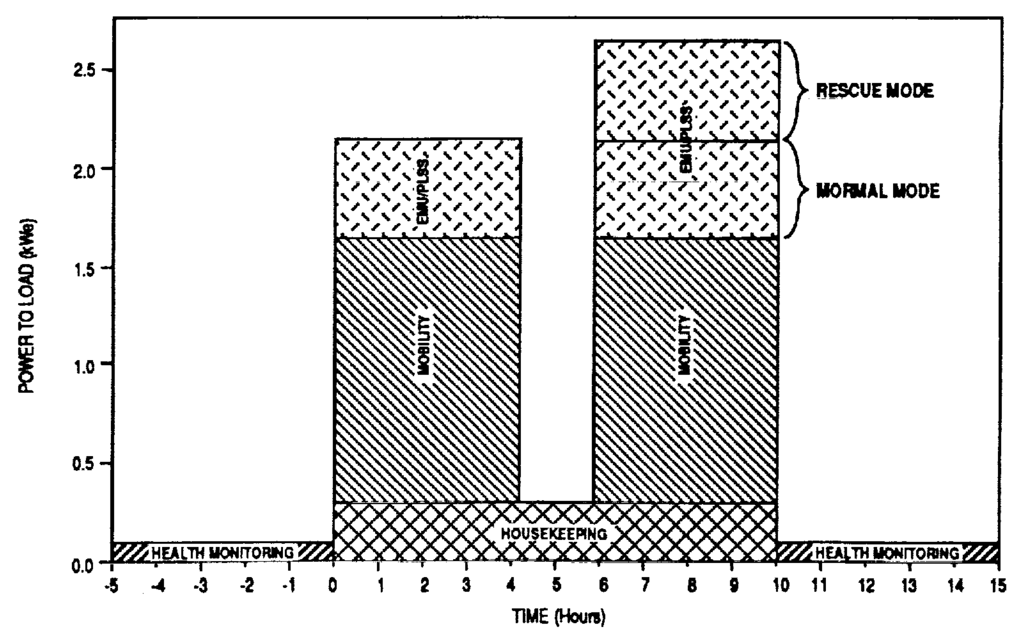

FIGURE 4. Crewed Rover Power Requirements for the Multi- Rover Mode

The lighting conditions afforded by earthshine during portions of the lunar night allow EVA to be carried out during the lunar night (Eppler 1991). In fact, it is desirable to perform nighttime EVA due to the reduced heat loading on the suit's cooling system. The rover will be required to operate during lunar night EVA except for periods centered about local midnight. This operation scenario has an impact on the outpost power system by requiring rover recharge at night if energy storage is used to power the rover.

In addition to a piloted rover, a telerobotic science rover will be used for extended explorations when the outpost is unoccupied. The anticipated total roving distance is about 200 km at a speed of 1 km/h. The longer range explorations will help identify locations of resources different from those near the outpost and to help target locations for exploration by the next crew. Power requirements are shown in Table 3 and Figure 5. The nominal power is 0.64 kWe and the maximum is 1.0 kWe.

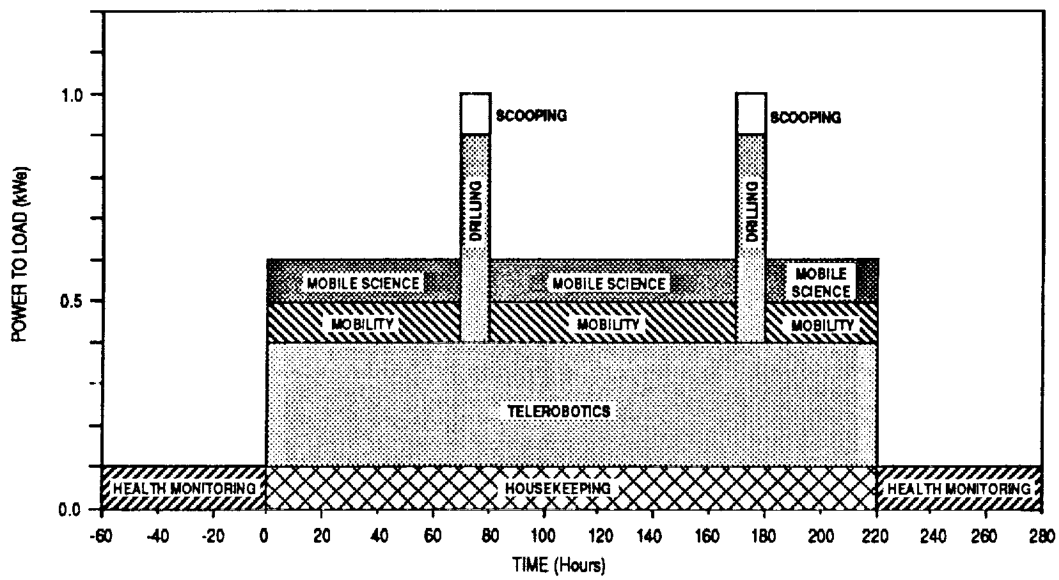

FIGURE 5. Telerobotic Rover Power Requirements

SCIENCE

The four disciplines that form the major science thrust for FLO are astronomy, geophysics, life sciences and space and solar system physics. In addition, demonstrating and validating the extraction of resources is also of scientific merit. The science payloads baselined for FLO consist of a set of astronomical instruments, a Geophysical Monitoring Package, a Solar System Physics Experiment Package, an ISRU unit, a laboratory internal to the habitat, and a Traverse Geophysical Package.

Astronomy experiment packages include three strawman telescopes; a Lunar Transit Telescope, Small Solar Telescope, and a Small Research Telescope have been baselined. These telescopes will be located at least 10 km from the outpost. The Lunar Transit Telescope operates continuously and will view stars and galaxies in the UV spectral range. The Small Solar Telescope will provide high resolution images of the Sun and will therefore only operate during lunar daytime. The Small Research Telescope operates continuously and is pointable to observe various astronomy objectives. The suite of telescopes will be operated from Earth and become a stand-alone science station with a 10 year lifetime.

The Geophysical Monitoring Package will be an enhanced version of the Apollo ALSEP science station providing data on heat flow, magnetic strength, seismic activity, micrometeorite and secondary ejecta flux and precise distance measurements to Earth. The Solar System Physics Experiment Package contains instruments to measure particles and fields and to analyze the lunar atmosphere and its variations.

The above science payloads could be located in close proximity to each other in order to benefit from one central power source. The sum of all the stationary science packages is 930 watts as shown in Table 4.

TABLE 4. Science Payload Power and Energy Requirements.

SCIENCE ELEMENTS	POWER (kWe)	ENERGY per ~ 2 WEEK PERIOD (kWe-h)	
STATIONARY SCIENCE(a)			
Lunar Transit	0.10	36	
Small Research	0.50	178	
Small Solar	0.05	18	5 watts during night
Solar System Physics	0.19	68	
Geophysical Monitoring	0.09	32	
TOTAL	0.930	332	
MOBILE SCIENCE (b)			
Traverse Geophysical Package	0.10	36	rechargeable battery or rover power
Geologic Tool Set with drill(c)	0.50	5.0	assumes 1 hole per sortie
TOTAL	0.60	NA	

NOTES: (a) Once installed operation is continuous for 10 years (can be co-located).
(b) Periodic operation on rover sorties.
(c) Assumes 1 hour per hole and maximum of 1 hole per rover sortie.

The life science laboratory located within the habitat will be designed to perform various activities including: gravitational biology experiments, physiological experiments on the nervous system and body fluids as well as thermo-regulation analyses. Geologic sample analyses will also be performed. The power needs for the laboratory is allocated within the habitat power budget at 1.0 kilowatts.

The ISRU demonstration unit will enable early demonstration and validation of basic mass production processes of oxygen and materials such as sintered bricks. Feedstocks of varying compositions will be loaded into the ISRU unit in a batch mode and analyzed for optimum oxygen extraction. A hydrogen reduction process, using imported hydrogen, produces water which is electrolyzed into oxygen and hydrogen. The ISRU unit will be operated intermittently during the lunar daytime, with approximately 10 batches run each lunar day period. Each batch will require about 2 kWe and take 4 hours to complete. A continuous 200 We is needed to maintain ISRU systems in a ready mode once the unit is initially activated. To facilitate crew ISRU operations, the unit will be located near the habitat and thus will be connected to the power system via a cable.

Several experiment packages are designed to be transported on the rover. The ability to obtain science data from a wide and diverse set of locations will provide a valuable database on the regional composition and potential resources of the Moon. The Traverse Geophysical Package is a set of instruments including: electromagnetic sounder, seismic experiments, gravimeter, magnetometer, and electrical properties experiment that will provide data on various locations. The crew will therefore transport these instruments on the rover obtaining a diverse set of data. The other payload is the Geologic Tool Set, which contains regolith sampling tools, sample containers and drills that can obtain core samples up to 3 meters deep.

The science experiments that are used in conjunction with the rover, total 600 watts with the hour long drilling operation representing the major power user as shown in Table 4. Power from the rover has been allocated to operate these science packages, either directly or to recharge small portable batteries (Figure 3).

CONCLUSIONS

Mission profiles envisioned for FLO call for continued visitation and eventual evolution to larger outposts. Thus the FLO power system must provide about 12 kilowatts to power the habitat, ISRU, and possible rover recharging while the outpost is occupied and about 2 kilowatts to keep the outpost maintained in a ready mode for the next occupancy period. The set of science instruments could be placed such that a small single 1 kilowatt power system could be used. Rover applications range from 1 to 2.5 kilowatts for a telerobotic rover and a crewed rover, respectively. The reliability and lifetimes of all systems are critical to a successful long term mission. The logistics and operations of such an endeavor as FLO mandatorily require designs that minimize resupply equipment, have reduced maintenance and are self deployable. Some of these less salient design features along with the obvious low mass and volume design features must be drivers guiding the technology programs over the up coming years. Because these criteria are factors in the mission life cycle costs, they will have a significant impact on whether the nation embarks on such an ambitious program as FLO and can strive to reach its vision of Mars.

Acknowledgments

The authors wish to thank the following individuals for their contributions; Lee Mason and J. Mark Hickman, NASA Lewis Research Center; Dallas Evans, Paul Johnson, John Gruener, Dean Eppler and John Connolly, NASA Johnson Space Center; Don Perkinson and Don Williams, NASA Marshall Space Flight Center.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
January 1993

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Power Requirements for the First Lunar Outpost (FLO)

5. FUNDING NUMBERS
WU-590-49

6. AUTHOR(S)
Robert L. Cataldo and John M. Bozek

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-7427

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-105925

11. SUPPLEMENTARY NOTES
Prepared for the Tenth Symposium on Space Nuclear Power and Propulsion sponsored by the University of New Mexico, Albuquerque, New Mexico, January 10-14, 1993. Robert L. Cataldo and John M. Bozek, Lewis Research Center. Responsible person, Robert L. Cataldo, (216) 977-7082.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 44

12b. DISTRIBUTION CODE

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

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14. SUBJECT TERMS
Lunar outpost; Power requirements

15. NUMBER OF PAGES
10

16. PRICE CODE
A02

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