# SP-100 Power System Conceptual Design for Lunar Base Applications

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# NASA

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## SUMMARY

This paper presents a conceptual design of a nuclear power system utilizing an SP-100 reactor and multiple Stirling cycle engines for operation on the lunar surface. Based on the results of this study, it was concluded that this powerplant could be a viable option for an evolutionary lunar base.

The design concept consists of a 2500-kWt (kilowatt thermal) SP-100 reactor coupled to eight free-piston Stirling engines. Two of the engines are held in reserve to provide conversion system redundancy. The remaining engines operate at 91.7 percent of their rated capacity of 150 kWe. The design power level for this system is 825 kWe. Each engine has a pumped heat-rejection loop connected to a heat pipe radiator.

Power system performance, sizing, layout configurations, shielding options, and transmission line characteristics are described. System components and integration options are compared for safety, high performance, low mass, and ease of assembly. The powerplant has been integrated with a proposed human lunar base concept to ensure mission compatibility. This study should be considered a preliminary investigation; further studies are planned to investigate the effect of different technologies on this baseline design.

## INTRODUCTION

Future lunar bases with a permanent human presence would have high power requirements to support such activities as scientific experimentation, in situ mining and processing, astronomical observation, and surface exploration. In addition, some form of a power-intensive, closed-loop life support system would probably be in place.

This study offers a potential design concept for a nuclear powerplant that could be used in this lunar base scenario. The objective was to integrate Stirling engine energy conversion with a baseline SP-100 nuclear reactor in a design that would be compatible with a human-tended lunar base. In selecting a reference concept, system components and integration options were compared for maximum mission compatibility.

This design is a result of a request by the Office of Aeronautics and Space Technology (NASA Headquarters, Code RP). The lunar base concepts were coordinated with the Office of Exploration (Code Z), which is involved in the evaluation of long-range scenarios for human exploration of the solar system. The task was performed in-house through a combined effort by the Advanced Space Analysis Office and the Power Systems Integration Office at NASA Lewis Research Center. This manuscript documents the results to date. Further studies have been initiated to better define the "optimal" design concept.

## LUNAR BASE ASSUMPTIONS

For this study, an evolutionary lunar base, growing from a small initial outpost to a larger base with extensive resource processing, is assumed. A top view of the proposed lunar base layout is shown in figure 1. The concept for the initial outpost is derived from studies performed at the NASA Johnson Space Center. This outpost would consist of a space-station-type habitat module integrated with a lunar lander and connected to an inflatable spherical habitat (ref. 1). The spherical habitat would be partially buried and sufficiently shielded with lunar soil for protection from solar and cosmic radiation. A 1-m thickness of lunar soil "sandbags" over the inflatable module was estimated to provide shielding from the worst recorded solar flare. A concept for the inflatable habitat is presented in figure 2. The power system for this initial outpost is assumed to consist of an advanced photovoltaic power system with a regenerative fuel cell energy storage system.

Other facilities will be required as the base grows (fig. 1). A science laboratory could be added adjacent to the original habitat module. This structure would provide a pressurized shirt-sleeve environment for experimentation and research. Like the habitat module, it would utilize the inflatable concept and would be protected from space radiation by lunar soil shielding.

A rover storage and recharging facility would also be located near the original habitat. This facility would consist of a simple, open-ended arched structure to protect the rovers from micrometeoroids and solar flares. It would also house the equipment to recharge rover batteries and perform periodic maintenance. Recharging power requirements for this facility may be substantial and would depend on the number of vehicles that rely on fuel cell or battery power systems.

A soil processing plant would be located at a distance of 5 km from the core base. After the soil has been mined from a nearby excavation, it would be transported to this central facility for processing. Oxygen for propellant production and life support would be the most likely product of such a plant, but other resources such as helium and hydrogen might also be considered for processing. This plant would have the highest power requirements of the entire base in supporting such activities as soil handling, material separation, and cryogenic refrigeration and storage. A lunar oxygen processing plant concept is shown in figure 3 (ref. 2).

A landing/launch pad would be located approximately 1 km from the processing facility. The proximity of the launch pad to the processing plant would enable oxygen for propellent to be easily delivered to orbit for use in chemically propelled space transfer vehicles.

A substantial rover fleet would be required to construct and maintain a base of this magnitude. Specific construction requirements for this conceptual lunar base necessitate rovers for excavation, hauling, mining, and transportation.

# INITIAL OUTPOST POWER

A solar photovoltaic (PV) power system with a regenerative fuel cell energy storage system is assumed to meet the power requirements of the initial outpost. A solar PV power system was selected for the initial outpost because of its relatively quick and easy installation. As activities increase and a nuclear reactor power system becomes necessary, this initial PV system will remain available as a redundant power supply.

In addition to this central PV solar power system, several portable power units would be available for localized construction or experimentation. These systems may include small nuclear reactors, isotope conversion units, erectable PV blankets, and/or regenerative fuel cell carts. The number and size of these portable units are dependent on the speed at which the base is constructed and the amount of experimentation.

The photovoltaic system for this conceptual base consists of amorphous silicon semiconducting cells on a kapton substrate. Amorphous silicon is the preferred cell material because of its durability and ease of retraction. The cells are mounted on a flexible Sun-tracking array structure that allows the blankets to be repeatedly rolled and unrolled. Damage to the solar cells due to solar and cosmic radiation and micrometeoroid bombardment may be avoided by rolling up the amorphous silicon blankets when they are not being used. This will prolong the life and performance of the cells. It is predicted that these cells are capable of obtaining 15 percent efficiency at a specific power of 300 W/kg (ref. 3).

The 354-hr lunar night necessitates the use of a reliable energy storage system to work in conjunction with the photovoltaic arrays, and mass limitations require that this storage system be lightweight. Regenerative fuel cells (RFC) utilizing high-pressure filament wound storage tanks are assumed for this application. These RFC's have an estimated round-trip storage efficiency of 60 percent and an energy density of 1000 Wh/kg (ref. 3).

Power requirements for the initial outpost are estimated to be in the 25 to 100 kWe range. An amorphous silicon/RFC power system capable of meeting these requirements would weigh from 16 to 67 metric tonnes (t). At power levels beyond this range, the storage system would become very massive. At the 825-kWe power level, a 100-percent duty cycle solar PV system with RFC's would have an overall mass 28 times that of the nuclear reactor power system offered in this report. (A 100-percent duty cycle indicates continuous power operation throughout the lunar day and night.) The complete performance and mass estimates of the initial outpost solar PV power system at various power levels are shown in table I. As shown, the mass of the energy storage system dominates the total mass, and the energy storage system mass increases dramatically with higher power level.

# NUCLEAR REACTOR POWER SYSTEM CONCEPT

In this section, the nuclear reactor power system conceptual design is presented and described. The power system consists of the nuclear reactor, human-rated shielding, Stirling energy conversion engines, heat rejection radiators, and a power management and distribution system.

## Reactor and Primary Heat Transport

This conceptual nuclear power system is driven by a SP-100 reactor rated for 2500 kWt. SP-100 is a joint DOE/DOD/NASA program to develop safe nuclear power systems for use in space. This nuclear power system design is a derivative of the reference SP-100 flight system configuration. The reference configuration uses thermoelectric conversion to deliver 100 kWe with the same 2500-kWt heat source. The advantage of replacing the thermoelectrics with Stirling engines is an eight-fold increase in thermal to electric efficiency. This reactor is designed for a 7-yr lifetime at full power. The current SP-100 reactor power system configuration for orbital applications is shown in figure 4.

A schematic of the reactor and Stirling engine combination for the lunar base application is shown in figure 5. The SP-100 reactor utilizes uranium nitride (UN) fuel pins cooled by liquid lithium. In this conceptual design, the lithium exits the reactor at 1350 K and is pumped to the Stirling engines by an electromagnetic pump. A torus-shaped manifold with a 4-m major diameter transfers the lithium from the reactor to the eight Stirling engines. The engines are fed via an intermediate heat exchanger that is coupled to the manifold through a nonweld field connection. The opposing side of the heat exchanger is prewelded to the Stirling heater head. An instrument-rated radiation shield is inherent in the reactor design for protection of the drive motors and instrumentation from radiation.

## Shielding

The reactor would be installed in a pre-excavated cylindrical hole which provides human rated shielding from gamma and neutron radiation. The use of lunar soil eliminates the need to transport heavy terrestrial shielding materials to the lunar surface. The reactor is enclosed by a Boral bulkhead with a domed cap which maintains a dust-free environment while reducing lunar soil neutron scattering. The hole is sized to maintain safe radiation levels in all directions outside the bounds of the power system.[1] The excavated shield design also allows for short-term periodic maintenance to be performed on the power system's radiator panels. The time required to excavate a suitable hole for the reactor was estimated to be from 2 to 3 hr given the proper machinery.[2]

This shielding concept was selected for the reactor after evaluation of several other shielding options. These shielding options are presented in figure 6. The first option used terrestrial materials to form a shield spanning a 360° azimuth and consisting of alternating layers of tungsten and lithium-hydride in a circumferential configuration surrounding the reactor (fig. 6(b)). This option was rejected because it required that over 20 t of shielding materials be transported from Earth.

Another shielding option that was evaluated was to "bulldoze" soil circumferentially around the reactor. For this design, 7 m of lunar soil would be required to attenuate radiation to safe levels (ref. 4). This corresponds to

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[1]A.C. Klein, NASA Lewis Summer Intern Report.
[2]Personnal communication from J. Alred, NASA Johnson Space Center.

730 $m^3$ of soil being moved (fig. 6(c)). By comparison, only 38 $m^3$ of soil would have to be moved for the excavated shielding concept (fig. 6(a)). In addition, bulldozing of soil on the lunar surface may be difficult because of the electrostatic nature of the soil.[2] The 7 m thickness of soil would also necessitate the use of very long heat transport piping from the reactor to the Stirling engines. For these reasons, this option was dismissed.

## Stirling Engines

The advantages of Stirling cycle energy conversion include high efficiency with low radiator area, and the potential for long operating life (ref. 5). High efficiency is attributed to the similarity of the Stirling thermodynamic cycle to that of the Carnot cycle. Temperature-entropy diagrams of the Stirling and Carnot cycles are shown in figure 7. The attractiveness of the Stirling engine over most dynamic power cycles is that it can achieve high efficiency at relatively low temperature ratios ($T_{hot}/T_{cold}$). Operation of heat engines at low temperature ratios can substantially reduce required radiator area.

The prediction of long life is based on the fact that free-piston Stirling engines have only two moving parts, a power piston and a displacer, which are separated by gas bearings (ref. 5). Hermetic sealing of the engine will also extend life by eliminating the problem of lunar dust contamination. A schematic of a 150 kWe Stirling engine design is presented in figure 8.

In this conceptual design, eight free-piston Stirling engines extend radially from the reactor manifold. The engines are located outside of the excavated hole and are supported by carbon-carbon platforms which form an annulus around the excavation. A cutaway of the reactor subsystem and the placement of the Stirling engines in relation to the reactor is presented in figure 9.

The Stirling engines are rated at 150 kWe per engine. Two of the engines are held in reserve for conversion system redundancy. The six active engines operate at 91.7 percent of their rated capacity to produce the 825-kWe design point power level. This design point power level assumes the power plant to be located at the equator and to be operating when the Sun is at its highest point. Higher power levels would be achieved through the lunar night when the radiator is exposed to lower sink temperatures. The variance of power for this system over the lunar day/night cycle is presented in figure 10.

NASA Lewis is responsible for coordinating NASA's Stirling engine development program under the High Capacity Power element of the Civilian Space Technology Initiative (CSTI). Contracts are in place to develop a 25-kWe, 1050-K Stirling engine for ground demonstration by 1992. This effort will eventually be extended to examine the feasibility of higher temperature (1300 K) Stirling engines in order to more fully utilize the proposed SP-100 reactor outlet temperature. The advantage of using higher temperature engines is a substantial radiator area reduction while maintaining the same (or higher) thermal-to-electric efficiency. The reactor and Stirling system specific mass (including radiators) at inlet temperatures of 1050 and 1300 K for a range of power levels is shown in figure 11. The difference between the two curves can be attributed to radiator mass.

The number of engines selected for this conceptual design is based on an upper power limit of 150 kWe per Stirling engine. The 150 kWe Stirling engine power limit is based on current growth projections for this energy conversion technology. If there were no upper power limit on Stirling engine technology, it was determined that three engines (with one spare) would be the preferred configuration from a mass and reliability perspective. Scaling studies are planned to determine the feasibility of higher powered engines.

The Stirling engines considered in this conceptual design operate at a temperature ratio of 2.2 with an inlet temperature ($T_{hot}$) of 1300 K. This design point corresponds to an overall 33-percent thermal-to-electric efficiency. This design point was chosen for low mass, high power output, and subsystem compatibility. The minimum specific mass point (kg/kWe) for a 1300-K Stirling cycle occurs at a temperature ratio of 2.0 (see fig. 11). However, the higher temperature ratio (2.2) leads to higher conversion efficiency, and thus, higher power levels, with only a minimal increase in specific mass. Subsystem compatibility can be maintained because the 2.2 temperature ratio yields an appropriate rejection temperature for traditional radiator materials.

Each Stirling engine is equipped with its own ac-to-dc converter and parasitic load resistor (PLR). The 150-kWe engines utilize internal linear alternators designed to deliver 200 V at 200 Hz ac. In this conceptual design, the ac output is converted to dc (externally from the engine) so that each engine can be operated independently and autonomously. Without individual converters, the engines would require complex synchronizing instrumentation to ensure phase lock. In addition, the output voltage would be increased to the 1-kV range to reduce the mass of the long transmission lines required for this conceptual lunar base. The function of the PLR is to reject any power generated by the system which is not required by the base. This component enables the power conversion system to follow changes in the electric load without changing the reactor or Stirling system operating parameters.


Heat Rejection

The thermal energy that is generated by the reactor head source but is not converted to electrical power must be rejected through waste heat radiators. Candidate systems for waste heat rejection in space include heat pipes and pumped loops. Advanced radiator concepts such as liquid droplets and moving belts do not appear to be viable alternatives for this application because of the presence of lunar gravity. The function of these systems is to transfer heat by radiation from the energy conversion system to the external environment. For lunar surface applications, this environment includes the lunar surface, the lunar sky, and deep space.

Radiator panels consisting of modular heat pipe sections were selected for this conceptual design. This type of heat rejection system offers built-in redundancy because of the multitude of individual heat pipes employed in each radiator panel. In essence, each heat pipe acts as a small, separate radiator. If micrometeoroids penetrate an individual heat pipe, the overall radiator panel will be largely unaffected in its ability to meet the heat transfer requirements. Heat pipes are also quite compatible with the constant rejection temperature Stirling engines.

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Spare heat pipes were specifically designed into the system to allow for any losses during the radiator life. These heat pipes are in addition to those required for design point heat rejection. Analyses indicate that the addition of spare heat pipes is preferred over protective armoring from a mass perspective. The manifold that feeds the individual heat pipes would be buried under lunar soil for protection against micrometeoroids.

The heat pipe radiators in this conceptual design are vertically oriented and form panels which extend radially from the Stirling engines. The eight radiator panels and Stirling engines form a spoked wheel around the reactor. An artist's rendering of the entire power system is presented in figure 12. In this illustration, the reactor power system is shown in the foreground, the core base (habitat, science lab, and rover facility) is shown in the upper right corner, and the resource processing plant and launch/landing pad are shown in the upper left corner.

Waste heat rejected from the Stirling engines is transferred to heat pipe radiators by a secondary heat transport loop with either liquid sodium or sodium-potassium (NaK) as the heat transfer fluid. The secondary heat transport loop manifold is attached to the Stirling engine by a nonweld field connection (see fig. 5). Each engine has its own individual manifold and heat pipe radiator panel. A shared manifold was considered for the waste heat transport loop but was rejected because of its complexity and size. The heat pipe fluid options are mercury or high-pressure water.

Several radiator panel configurations were examined. These consisted of vertically oriented panels arranged in a spoked wheel, a pinwheel, and a segmented field as shown in figures 13 (a), (b), and (c), repectively. Horizontal radiators positioned on the lunar surface were also considered for comparison. The horizontal configuration was rejected because of the larger area required for one-sided heat rejection. Furthermore, the heat rejection capability of the horizontal configuration was adversely affected by solar insolation throughout the lunar day.

Several constraints were used to arrive at the final radiator design. These included the requirements that the radiator panel be less than 2 m high for the vertically oriented configurations. This constraint was imposed to allow the radiator panels to be easily handled and assembled by astronauts. Also, the field coverage area required of the entire power system was kept to a minimum to reduce pumping power requirements on the secondary heat transport system.

The heat rejection analysis took into account several conservative factors. These involved a 65-K temperature drop from the Stirling cooler head to the outside radiator surface. This results in an effective rejection temperature of 525 K. In addition, two correction factors were used on the calculated prime radiator area to account for redundancy (a factor of 1.28) and surface efficiency (a factor of 1.10) of the radiator. These terms account for the difference between a theoretical area value and an actual radiator configuration. The redundancy factor used was added to establish the size of a minimum mass system with regard to micrometeoroid survival. Previous studies indicate that the optimum redundancy value for a minimum mass system is 28 percent (ref. 6). A specific mass of 7 kg/m$^2$ was assumed for the stainless steel radiator material selected.

The analysis varied the radiator length as well as the starting location of the radiator panels with respect to the reactor vertical centerline. Radiator height was calculated to meet the required heat load for the three different heat sinks (lunar surface, lunar sky, and deep space) with their respective view factors. View factors for the vertical configurations were based on panel geometry, distance from the reactor, panel height, and panel length. The temperatures of the sinks were chosen to represent the worst case situation for a lunar surface design. The sky temperature that was used in this analysis assumed incident solar radiation on those radiator panels which were not aligned with the Sun's path across the sky. Another radiator design, which had all radiator panels oriented with respect to the ecliptic in such a way as to minimize incident solar flux, was rejected because of the difficult heat transport plumbing requirements. The lunar surface temperature that was used represented a noon-time worst case of 375 K.

Because of the relatively high lunar surface heat-sink temperature, the 2-m panel height requirement prohibited a reasonably sized radiator field. The high surface temperature of the Moon when the Sun is overhead is due in most part to the high solar absorptivity (0.90) of the lunar soil. This problem was resolved by placing an aluminized plastic apron between the radiator panels. This apron would reduce the solar absorptivity of the surface to approximately 0.12. A value of 4 was selected for the apron's solar absorptivity to thermal emissivity ratio ($a_s/e_{th}$). This ratio determines the equilibrium temperature of the apron and, thus, the effective sink temperature of the lunar surface (222 K). The result is a reduction in the effective overall lunar sink temperature to 247 K (ref. 7).

Table II compares radiator area, panel height, and field coverage area of the three vertical configurations for a series of starting locations for the two different heat sinks. The comparison indicates that the spoked and pinwheel arrangements yield the smallest radiator area, followed by the segmented field configuration. Despite the superiority in field coverage area of the pinwheel design, the spoked-wheel configuration was selected for this conceptual design because of its relatively simple arrangement. Figure 14 illustrates the effect of the lunar apron on the radiator area of the spoked-wheel design as a function of power system field coverage area. The final design point was selected based on minimum radiator area, minimum field coverage, and a maximum panel height of 2 m.


## Power Distribution

The predominant electrical load for this conceptual lunar base is the oxygen production plant. This plant would perform a hydrogen reduction process on lunar ilmenite using basalt feedstock. The resulting byproduct of water is electrolyzed into hydrogen and oxygen. The hydrogen is recycled for future reduction processes. The oxygen is liquified and stored for eventual delivery to low lunar orbit to be used as a propellant for space transfer vehicles. A small portion of the oxygen would be alotted for life support.

Seventy-five percent of the nuclear power system output (619 kWe) would be distributed to the processing plant. This would provide enough power for an oxygen production capability of 249 t/yr (ref. 2). This capability assumes a 90-percent processing duty cycle and a 35-percent mining duty cycle. The electrical power would be used for the mining, beneficiation, processing, and

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refrigeration required of a full-up production plant.  The mining power requirements would consist of a recharging station for mobile mining equipment similar to the rover recharging facility at the core base.  The predominant power consumer of the plant is the electrolysis subsystem (approximately 39 percent of the processing plant electrical requirements).  The thermal energy requirements would be provided by electrical resistance heating.  Oxygen production capability as a function of the hydrogen reduction process electrical power requirements is shown in figure 15 for two different lunar feedstocks.  For this study, the basalt feedstock option was chosen over the soil feedstock option because of its lower power requirements.

The remainder of the base could be powered redundantly by both the original PV system and the excess nuclear system output.  The habitation and laboratory life support requirements were estimated to be approximately 51 kWe for an 18-person crew.  This power level is based on a partially closed-loop life support system comparable to that being planned for Space Station Freedom.  Of the 51 kWe, 40 percent is devoted to environmental control.  Other life support subsystems requiring power include lighting, system monitoring, module heating and cooling, and meal preparation.  The life support power requirements are presented in table III.  The abundant power available from a nuclear reactor power system could also be used to implement a completely closed-loop life support system.

The 156 kWe of remaining power would be shared between the rover recharging facility and the science laboratory.  The laboratory power profile would be dependent on the extent and magnitude of experimentation taking place.  The rover recharging requirements would depend heavily on the quantity of surface exploration and construction.  It was estimated that one-third of the remaining power would be used for the laboratory and two-thirds would be available for rover recharging.  A breakdown of the power requirements for all the elements of this conceptual lunar base is presented in figure 16 for two cases of solar PV availability.  One case assumes a 50-kWe continuous output from the PV system.  The other case assumes that the PV system is stowed, and thus not producing power.

For the lunar base layout previously illustrated in figure 3, a total of 5051 m of transmission cabling would be required.  This is based on the assumption that the oxygen production plant must be a minimum of 5 km from the habitat area.[2]  Although the excavated shielding concept essentially eliminates radiation outside the bounds of the radiator panels, the nuclear reactor power plant has been placed 1 km from the habitats.  This ensures a safe buffer zone between the reactor and the crew.

The transmission lines for this conceptual power plant utilize multiple insulated wiring for redundancy.  They are geographically separated to avoid shorting.  Candidate materials include copper or aluminum.  The high voltage dc output from the nuclear powerplant keeps transmission line mass to a minimum (ref. 4).  In this power system conceptual design, the transmission lines have been buried or covered with lunar soil.  Buried lines offer a safer design than suspended lines.  Further studies are required in the area of transmission line deployment to determine the safety and thermal implications.  The efficiency of the power management and distribution system was assumed to be 92 percent.

## SYSTEM MASS AND PERFORMANCE

The nuclear reactor power system mass breakdown is presented in table IV.
The total system specific mass was calculated to be 24.2 kg/kWe. The eight
Stirling engines and the system radiators are the heaviest of the subsystems.
It should be noted that the Stirling system mass estimates include the two
standby engines and their accompanying hardware. A less conservative design
using only one redundant engine would decrease the system mass by nearly
10 percent. The use of advanced materials and technology improvements could
further reduce the system mass. In general, the mass estimates shown for this
conceptual design are based on conservative technology projections. These mass
estimates are not necessarily indicative of the mass goals of the High Capacity
Power element of the NASA CSTI program. That program is focused on the devel-
opment of advanced power system technologies for use on spacecraft. Also, the
lunar base concept requires several additional components not required in a
spacecraft design.

A summary of the nuclear reactor power system performance is shown in
table V. Each of the six operating Stirling engines produces 137.5 kWe for a
total power output of 825 kWe. This power level corresponds to 69 percent of
the full operating capacity of the eight Stirling engines. The total thermal-
to-electric efficiency of the system is 33 percent. As stated earlier, this
is accomplished with a Stirling temperature ratio ($T_{hot}/T_{cold}$) of 2.2 and
an inlet temperature of 1300 K. A total radiator area of 780 $m^2$ configured in
a spoked-wheel geometry is required to reject the 1675 kWt of waste heat.

## DELIVERY TO THE LUNAR SURFACE

A follow-on study was performed to determine how this nuclear power system
might be packaged for transport to the lunar surface. The power system was
divided into two packages to accommodate the payload capacity of a NASA Marshall
Space Flight Center derived lunar descent vehicle (LDV) (ref. 8). The first
package would consist of the reactor and bulkhead, the eight Stirling engines,
the engine support platforms, and the primary heat transport system. Powerplant
construction would begin following the delivery of this package to the sur-
face. The second package would contain the radiator panels and transmission
cabling. Table VI provides a packaging breakdown of the elements in this
nuclear reactor power system conceptual design.

The two packages, each attached to a separate LDV, would be launched to
low-Earth orbit via a 91 t (200 000 lb) capacity heavy-lift launch vehicle
(HLLV). A second HLLV would transport the propellant required for one round-
trip mission of a lunar transfer vehicle (LTV). In this scenario, the first
package and its LDV are mated to an LTV docked in low-Earth orbit at a propel-
lant depot. The LTV is tanked at the depot and proceeds on its mission to low
lunar orbit. The LDV then separates and descends to the lunar surface with the
first reactor package. After the LTV completes its delivery, it returns to
low-Earth orbit for mating with the second package. A third HLLV would launch
the propellant for the second round-trip LTV mission. The second package would
be delivered in a manner similar to the first. A complete scenario description
was presented at NASA Lewis (M.W. Mulac, oral presentation).

## MULTIPLE REACTOR SYSTEMS

The reactor power system in this conceptual design study is modular and can be replicated to meet increasing power requirements. It would also be possible, and perhaps desirable, to replicate this system design and operate the two systems at reduced power levels. If one reactor power system needed to be shut down, the other system could compensate for the loss in power. As power requirements increase, the capacity of the systems could be gradually increased to meet the higher power levels.

The benefit of this scenario arises from the added redundancy of multiple reactors. Redundancy is specifically designed into the power conversion system, the heat rejection system, and the distribution system; however, there is only one reactor heat source. Although there is only a remote possibility that the reactor would shut down irreversibly during its design life, a system design which includes multiple reactors would be advantageous.

## CONCLUSIONS

The results of this study indicate that nuclear power systems can be made compatible with a human-tended lunar base. This nuclear power system conceptual design offers safety, high performance, low mass, and easy assembly. The excavated cylindrical hole provides adequate, human-rated nuclear radiation shielding. The eight Stirling engines coupled with the reference 2.5 MWt SP-100 reactor produce 825 kWe with considerable system redundancy. The thermal apron between the vertical heat pipe radiator panels significantly reduces required radiator area for waste heat rejection. Mass is relatively low at 20 t for the entire system, and delivery to the lunar surface can be accomplished in a series of two packages. Once there, the system is designed such that a majority of the installation can be performed by astronauts.

The benefits of nuclear power include increased power for more extensive surface operations and substantial mass savings over solar power alternatives. It is inevitable that as the lunar base matures, greater power requirements will prescribe the use of nuclear reactor power systems. At some point in time, it is conceivable that the power needs of an advanced lunar colony would warrant the use of a complete power grid similar to what is found in our terrestrial cities.

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TABLE I. - PHOTOVOLTAIC POWER SYSTEM SIZING

| User power, kWe | Array area, $m^2$ | Array mass, kg | RFC[a] mass, kg | PMAD[b] mass, kg | Total mass, kg |
|---|---|---|---|---|---|
| 25 | 397.6 | 241.5 | 16 033 | 500 | 16 774 |
| 50 | 795.2 | 483.1 | 32 065 | 1000 | 33 548 |
| 75 | 1192.8 | 724.6 | 48 098 | 1500 | 50 322 |
| 100 | 1590.4 | 966.2 | 64 130 | 2000 | 67 097 |

[a]Regenerative fuel cells (RFC) for 100 percent night power (354-hr lunar night).
[b]20 kg/kWe power management and distribution (PMAD) specific mass.

TABLE II. - RADIATOR CONFIGURATION AREA COMPARISON

| Distance to first panel,[a] m | Radiator configuration | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Spoked wheel[b] | | | Pinwheel[b] | | | Segmented field[c] | | |
| | Total radiator area, $m^2$ | Panel height, m | Field coverage area, $m^2$ | Total radiator area, $m^2$ | Panel height, m | Field coverage area, $m^2$ | Total radiator area, $m^2$ | Panel height, m | Field coverage area, $m^2$ |
| Soil heat sink; surface temperature, 375 K | | | | | | | | | |
| 5 | 984 | 2.46 | 2827 | 990 | 2.48 | 1616 | 1028 | 3.36 | 1963 |
| 10 | 938 | 2.35 | 3848 | 936 | 2.34 | 2407 | 1028 | 2.40 | 2827 |
| 15 | 742 | 1.86 | 5027 | 742 | 1.86 | 3355 | 1028 | 1.87 | 3848 |
| Apron heat sink; surface temperature, 222 K | | | | | | | | | |
| 5 | 780 | 1.95 | 2827 | 785 | 1.96 | 1616 | 821 | 2.68 | 1963 |
| 10 | 754 | 1.89 | 3848 | 756 | 1.89 | 2407 | 821 | 1.91 | 2827 |
| 15 | 598 | 1.49 | 5027 | 598 | 1.49 | 3355 | 821 | 1.49 | 3848 |

[a]From reactor centerline.
[b]Radiator panel length, 25 m.
[c]Four rings, 5-m spacing.

TABLE III. - POWER REQUIREMENTS FOR A PARTIALLY CLOSED

LIFE SUPPORT SYSTEM

| Subsystem | Scaling factor | Power,[a] kW |
|---|---|---|
| Crew systems | | |
| Lighting | 0.40 kW/module | 1.2 |
| Perishable storage | .10 kW/person | 1.8 |
| Crew accomodations | .33 kW/person | 5.9 |
| System monitoring | .01 kW/person | .2 |
| Health maintenance | .27 kW/module | .8 |
| Life support systems | | |
| Envionmental control | 1.10 kW/person | 19.8 |
| Active cooling and heating | .07 kW/person | 1.2 |
| Food preparation | | |
| Single meal heating | .56 kW/person | 20.2 |
| Total | | 51.0 |

[a]18-Member crew.

TABLE IV. - NUCLEAR POWER SYSTEM MASS BREAKDOWN

| Systems and components | Mass, kg |
|---|---|
| Reactor and shield subsystem | |
| Reactor | 755 |
| Instrumentation and control | 359 |
| Instrument shields | 931 |
| Primary heat transport subsystem | |
| Pumps, piping, joints, and thaw heat pipes | 342 |
| Inlet and outlet manifold | 423 |
| Power conversion subsystem | |
| Stirling engines, alternators, hot heat exchangers, and piping | 5 871 |
| Heat rejection subsystem | |
| Pumps, accumulators, and piping | 832 |
| Heat pipe radiator (including fluid) | 6 240 |
| Power management and distribution subsystem | |
| ac-to-dc converters and parasitic load resistors | 1 650 |
| Transmission cabling (5 km) | 917 |
| Surface structure | |
| Reactor excavation bulkhead | 679 |
| Engine support platforms | 1 005 |
| System total | 20 004 |

## TABLE V. – DESIGN POINT PERFORMANCE RESULTS

```
Reactor thermal power, kW  . . . . . . . . . . . . . . 2500
Reactor lifetime (at full power), yr . . . . . . . . . .  7

Electrical output (6 of 8 engines), kWe  . . . . . . .  825
Electrical output/operating engine . . . . . . . . . 137.5
Rated electrical output/engine . . . . . . . . . . .  150
Percent of full operating capacity, percent  . . . . . . 69
Thermal-to-electric efficiency, percent  . . . . . . . . 33

Stirling heater temperature, K . . . . . . . . . . . . 1300
Stirling temperature ratio . . . . . . . . . . . . . . . 2.2
Stirling cooler temperature, K . . . . . . . . . . . .  591

Waste heat to reject, kW . . . . . . . . . . . . . . . 1675
Radiator surface temperature, K  . . . . . . . . . . .  525
Lunar surface temperature (w/apron), K . . . . . . . .  222
Lunar sky temperature, K . . . . . . . . . . . . . . .  267
Total radiator area, m²  . . . . . . . . . . . . . . .  780
```

## TABLE VI. – NUCLEAR POWER SYSTEM PACKAGING BREAKDOWN

| Subsystems and packaging | Mass, kg | Volume, m³ | Stowed configuration, (all dimensions in meters) |
|---|---|---|---|
| Lunear Descent Vehicle (LDV)1 | | | |
| Reactor bulkhead enclosure | 679 | 19.0 | Cylinder (2.4 diam by 4.2 height) |
| 2.5-MWt SP-100 reactor | 755 | | |
| Instrument shield | 931 | | |
| Primary Heat transport | 342 | | |
| Instrumentation and control | 359 | | |
| Total (1 package) | 2 387 | 9.8 | Cylinder (1.8 diam by 3.8 height) |
| Stirling inlet/outlet manifold | 423 | 2.5 | Cylinder (4.0 diam by 0.2 height) |
| Engine support platform | 126 | | |
| 2 platforms (1 package) | 251 | 2.0 | Box (5.4 by 3.1 by 0.1) |
| Total (4 packages) | 1 005 | 8.0 | |
| Stirling engine[a] | 734 | | |
| Radiator interface[b] | 104 | | |
| Power conditioning[c] | 206 | | |
| 1 engine (1 package) | 1 044 | 7.2 | Box (3.1 by 2.2 by 1.1) |
| Total (8 packages) | 8 351 | 57.3 | |
| Lunear Descent Vehicle (LDV)2 | | | |
| Radiator panel section[d] | 156 | | |
| 5 sections (1 package) | 780 | 11.3 | Box (5.0 by 1.0 by 2.3) |
| Total (8 packages) | 6 240 | 90.2 | |
| Transmission cabling (5 km) | 917 | 3.1 | Cylinder (2.0 diam by 1.0 height) |
| Total (24 packages) | 20 004 | 189.9 | |

[a]Including hot heat exchanger.
[b]Including piping, electromagnetic pump, and accumulator.
[c]Including ac-dc converter and parasitic load resistor.
[d]Including heat pipes and inlet/outlet manifold.

**PHOTOVOLTAIC POWER SYSTEM**

INITIAL OUTPOST

ROVER

SPACE–STATION–TYPE HABITAT

INFLATABLE HABITAT

SCIENCE LABORATORY

VERTICAL RADIATOR PANELS (8)

1 km

5 km

ROVER STORAGE AND RECHARGE

SWITCHING STATION

0.50 km

REACTOR POWER SYSTEM

LANDING PAD

OPERATIONS FACILITY

0.50 km

SOIL PROCESSING PLANT

0.75 km

PROPELLANT TANKS

MINING AREA

**LEGEND**

REACTOR

POWER MAINTENANCE AND DISTRIBUTION

PHOTOVOLTAIC ARRAYS

STIRLING ENGINES

LUNAR SOIL SHIELDING

THERMAL APRONS

Figure 1. – Lunar Base Layout. (All dimensions in kilometers; figure not drawn to scale.)



RADIATOR SUN SHIELD

1 – m RADIATION SHIELD

16 – m INFLATABLE HABITAT

SOLAR PANELS

FLEXIBLE TUNNEL

DUST-OFF AREA

AIR LOCK

LUNAR SURFACE
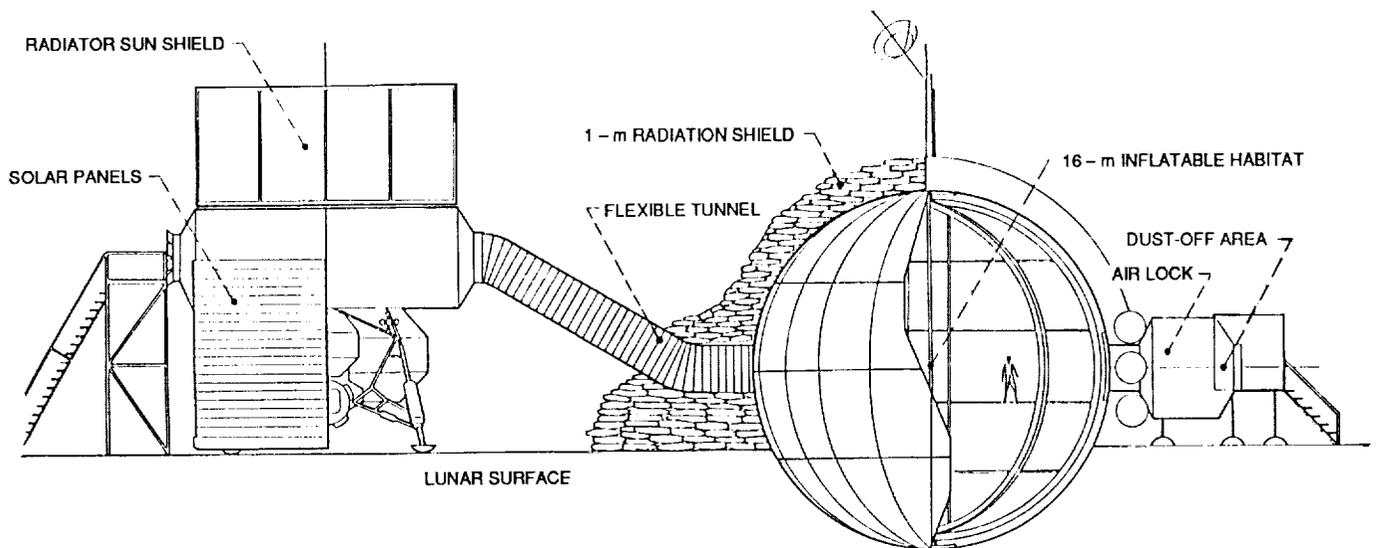
Figure 2. – Inflatable habitat concept.

15
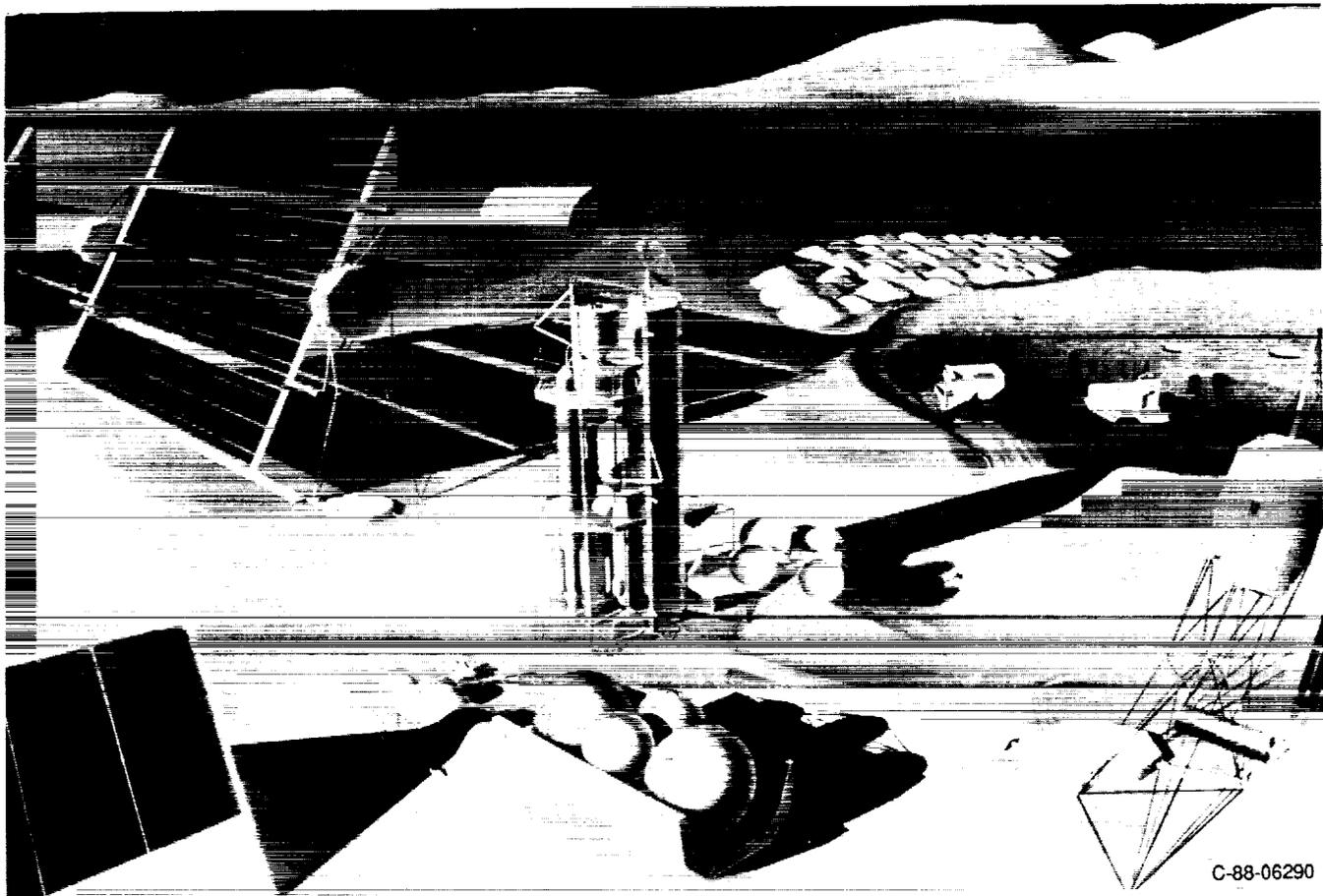
Figure 3. – Lunar oxygen processing plant concept.



EQUIPMENT
MODULE

SHUNT
DISSIPATOR

SEPARATION
BOOM

POWER
CONVERTER
ASSEMBLIES

AUXILLARY COOLING
LOOP RADIATOR

THERMAL    MISSION
SHIELD     MODULE

REACTOR
SHIELD

RE-ENTRY
SHIELD

THERMOELECTRIC
ELECTROMAGNETIC
PUMPS

DEPLOYED
RADIATOR
PANELS

REACTOR

MUX UNITS
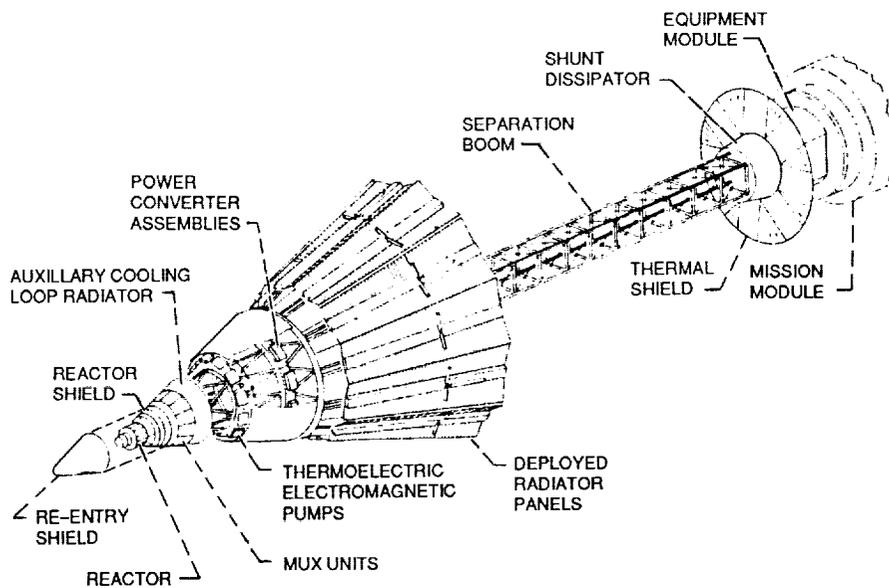
Figure 4. – SP–100 Power for spacecraft applications.
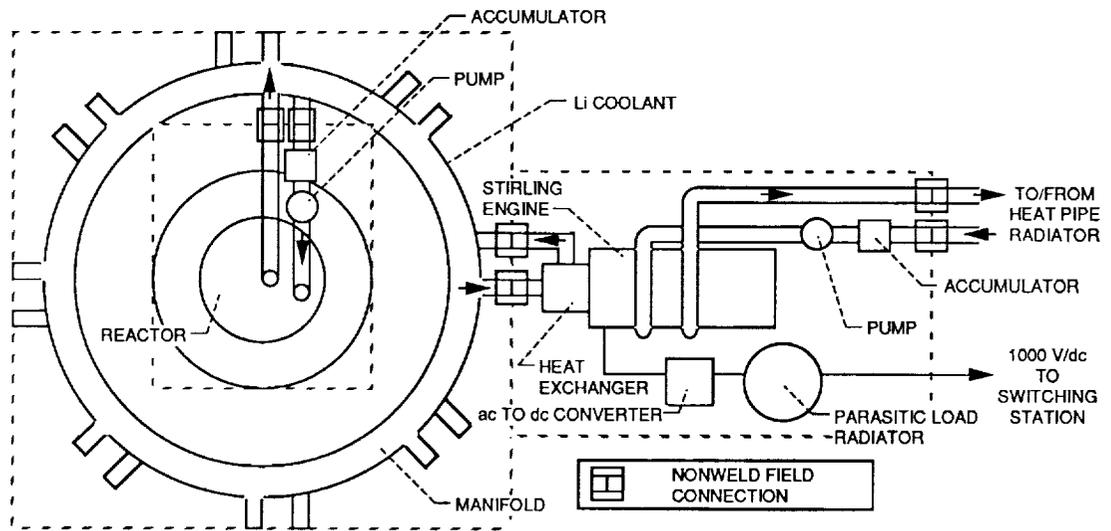
Figure 5. SP-100 Reactor and Stirling engine schematic.
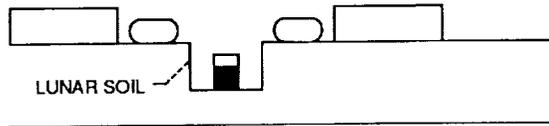


| | |
|---|---|
| CYLINDER DIAMETER, m | 2 |
| CYLINDER HEIGHT, m | 4 |
| VOLUME OF SOIL MOVED, cm$^3$ | 38 |
| MASS OF SOIL MOVED, t | 45 |

(a) EXCAVATED CYLINDER LUNAR SOIL SHIELD.
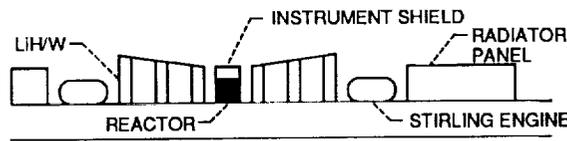
| | |
|---|---|
| LiH THICKNESS (2 LAYERS), cm | 35.2 |
| W THICKNESS (3 LAYERS), cm | 19.8 |
| TOTAL THICKNESS, cm | 55.0 |
| TOTAL SHIELD MASS, t | 22 |

(b) 360° CIRCULAR LiH/W SHIELD (FROM EARTH).
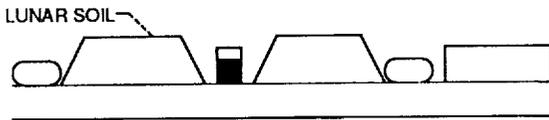
| | |
|---|---|
| SHIELD THICKNESS, m | 7 |
| SHIELD HEIGHT, m | 3 |
| VOLUME OF SOIL MOVED, m$^3$ | 730 |
| MASS OF SOIL MOVED, t | 870 |

(c) 360° CIRCULAR LUNAR SOIL SHIELD.

Figure 6. Reactor shielding options. Assumptions: Power capacity, 2500 kW; Radiation, 5 rem/mo at radiator panels; lunar soil density, 1.2 g/cm$^3$
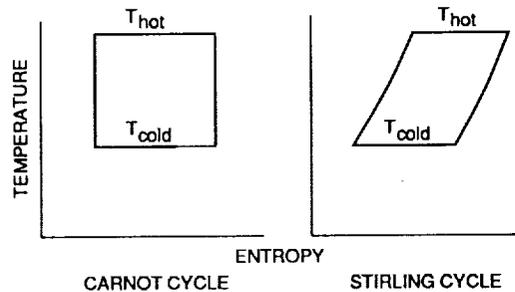


Figure 7. – Carnot cycle/Stirling cycle temperature–entropy diagrams.

17
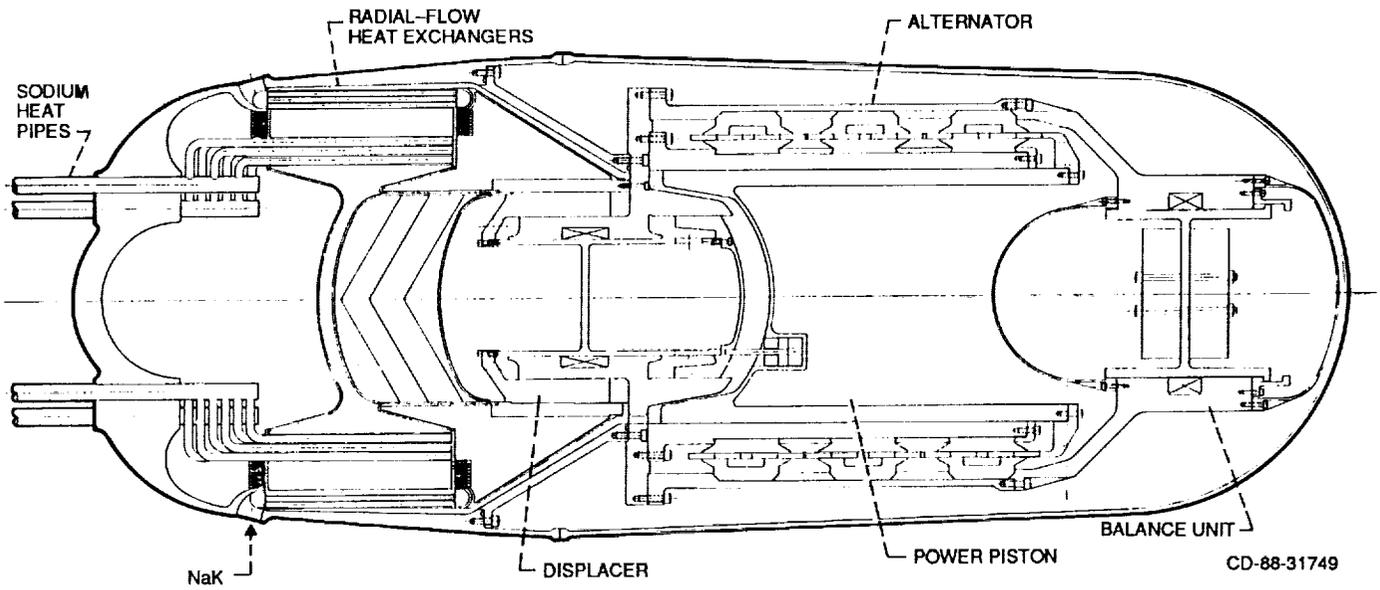
Figure 8. – 150 kWe Stirling engine schematic. Diameter, 30 in. (76 cm); Length, 78 in. (198 cm).
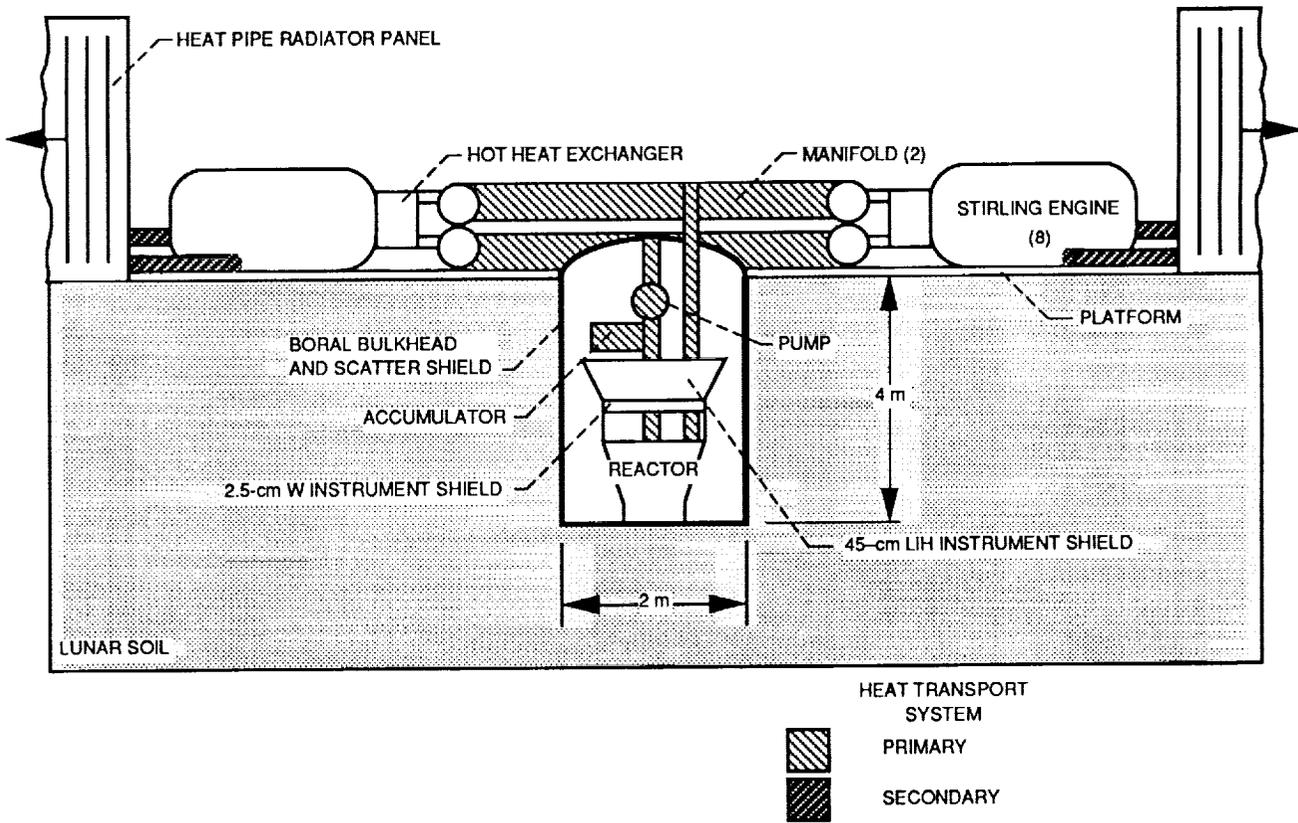


Figure 9. – Nuclear power system cutaway view.
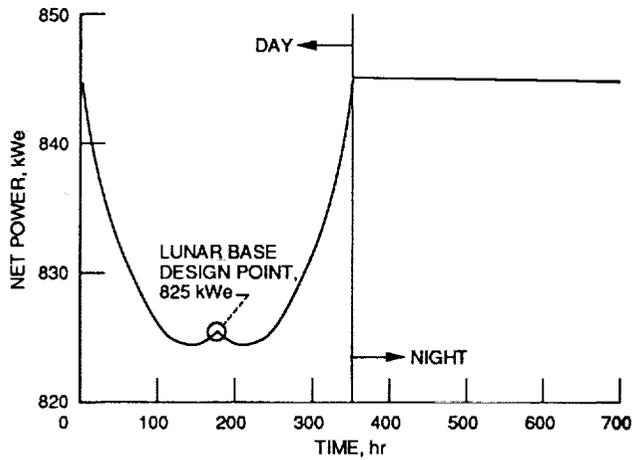
Figure 10. – Power variance over a lunar cycle.
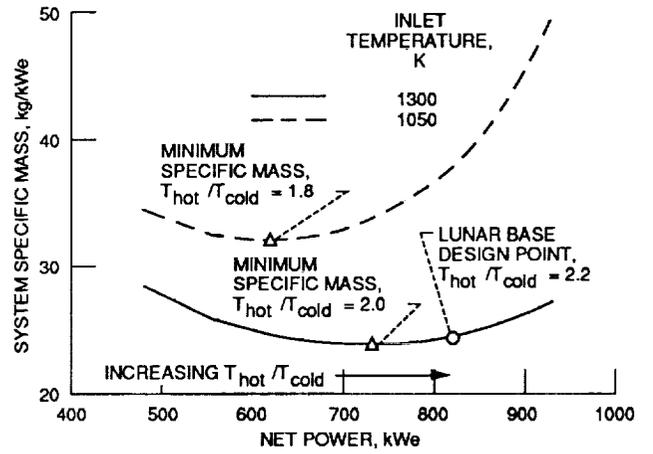


Figure 11. – Power system mass sensitivity to Stirling engine inlet temperature.
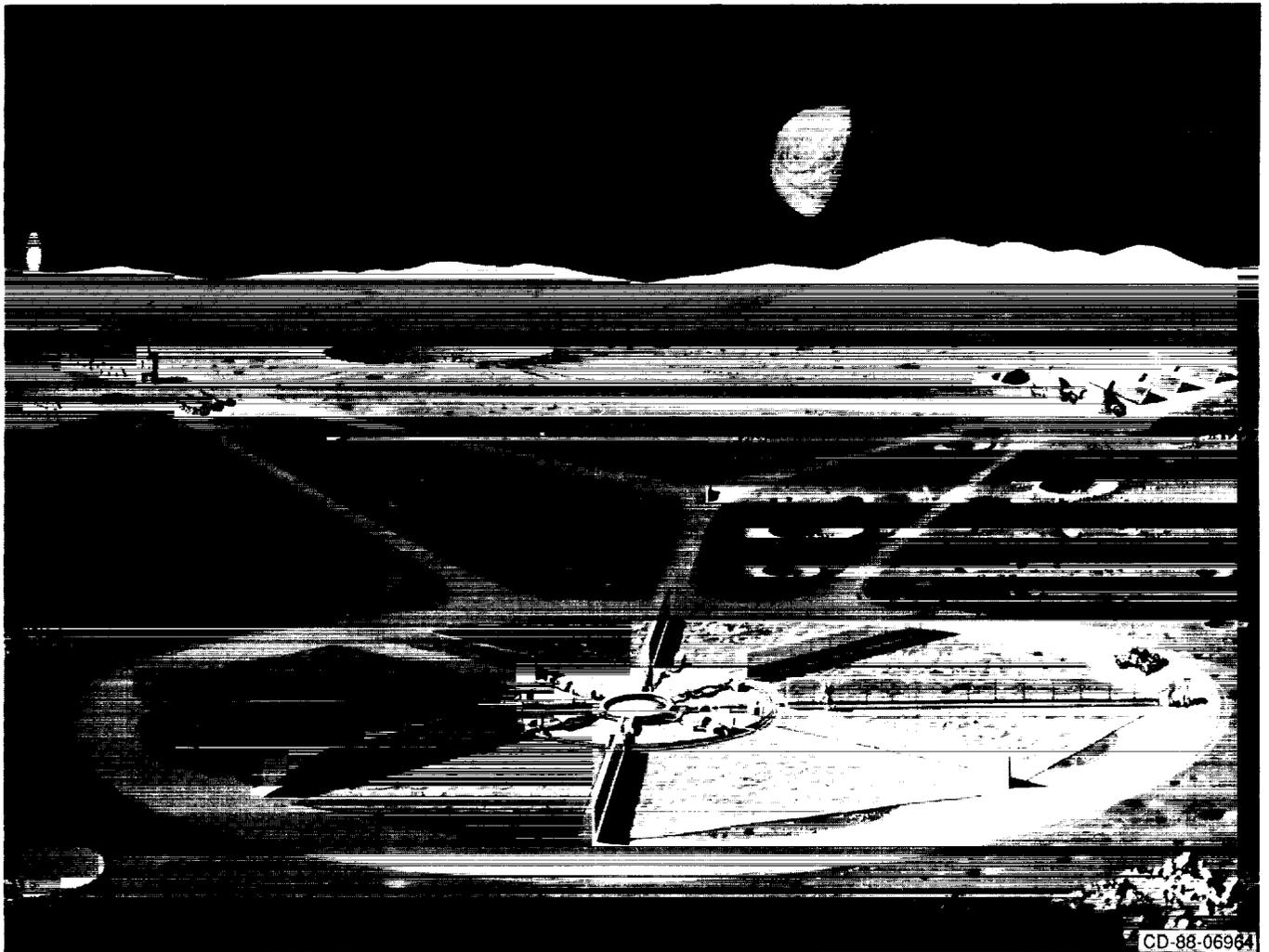


Figure 12. – Artist's rendering of integrated nuclear power system.

(a) VERTICAL RADIAL SPOKED WHEEL.  (b) VERTICAL RADIAL PIN WHEEL.  (c) VERTICAL SEGMENTED FIELD.
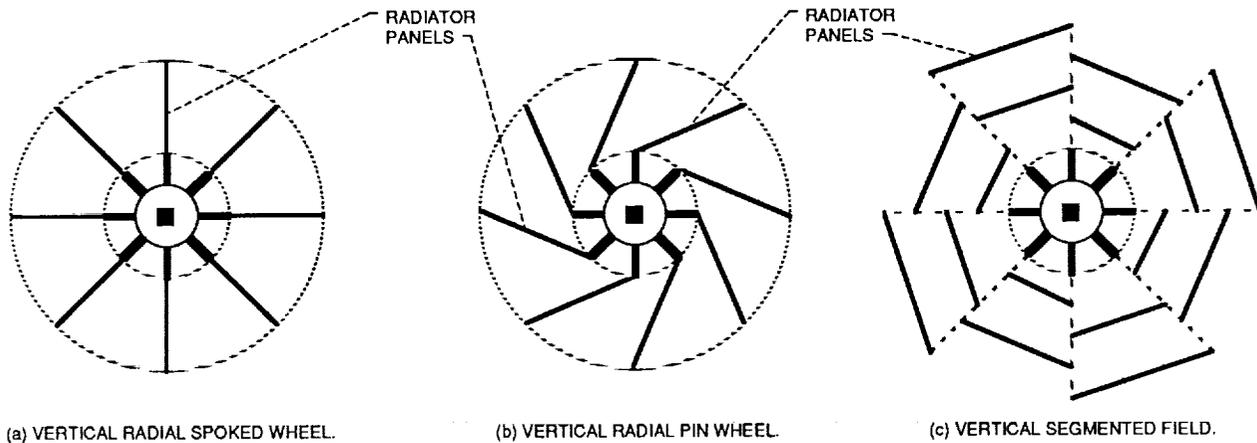
Figure 13. Radiator panel configuration options.
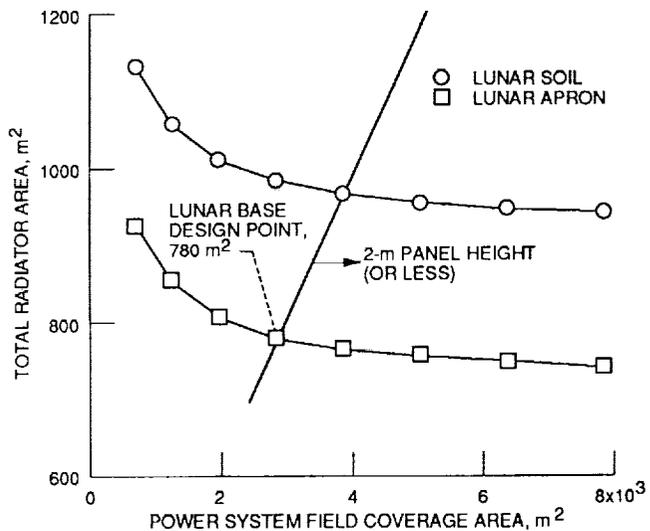


Figure 14. – Radiator area sensitivity to heat sink.
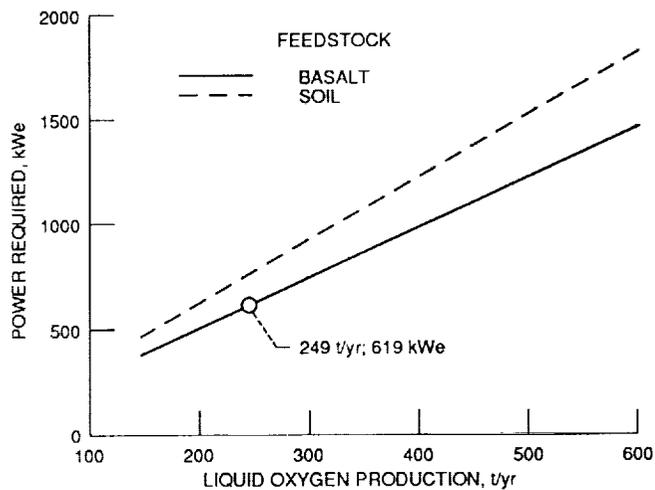


Figure 15. – Lunar oxygen processing plant production capability.
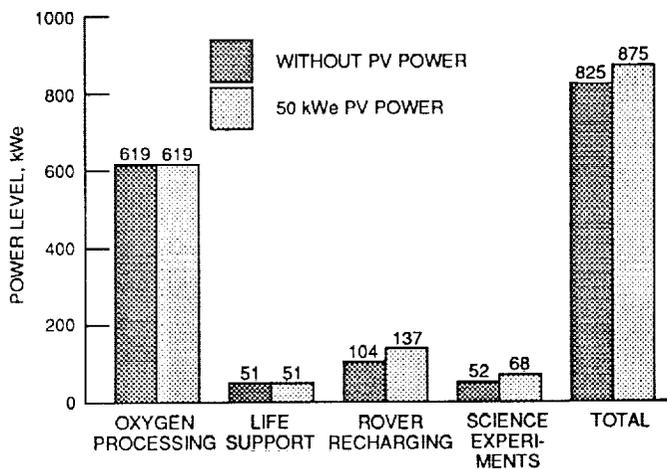


Figure 16. – Lunar base power distribution.

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| | | |
|---|---|---|
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15. Supplementary Notes

16. Abstract

This paper presents a conceptual design of a nuclear power system utilizing an SP-100 reactor and multiple Stirling cycle engines for operation on the lunar surface. Based on the results of this study, it was concluded that this powerplant could be a viable option for an evolutionary lunar base. The design concept consists of a 2500-kWt (kilowatt thermal) SP-100 reactor coupled to eight free-piston Stirling engines. Two of the engines are held in reserve to provide conversion system redundancy. The remaining engines operate at 91.7 percent of their rated capacity of 150 kWe. The design power level for this system is 825 kWe. Each engine has a pumped heat-rejection loop connected to a heat pipe radiator. Power system performance, sizing, layout configurations, shielding options, and transmission line characteristics are described. System components and integration options are compared for safety, high performance, low mass, and ease of assembly. The powerplant has been integrated with a proposed human lunar base concept to ensure mission compatibility. This study should be considered a preliminary investigation; further studies are planned to investigate the effect of different technologies on this baseline design.

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