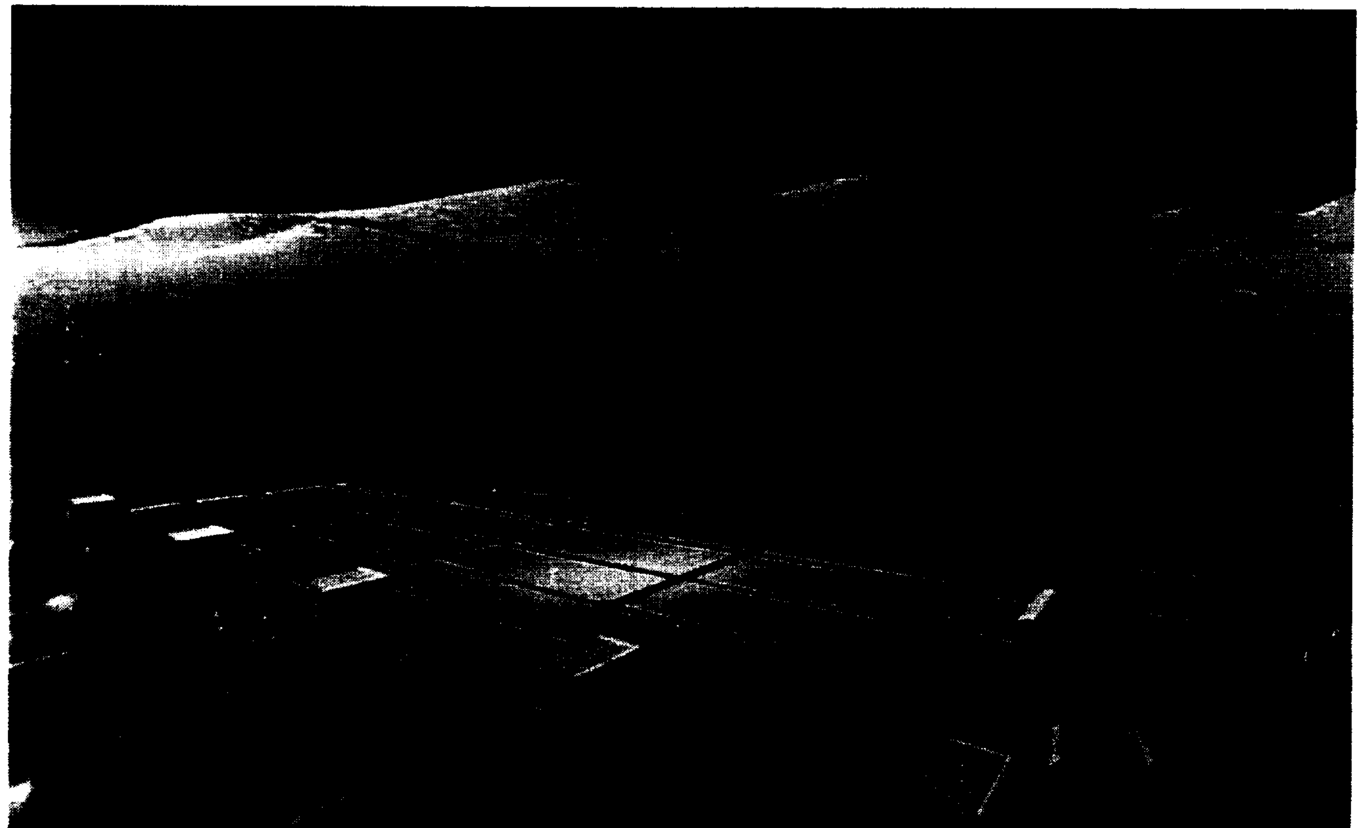
NASA CR-172086

LBSS

Conceptual Design of a Lunar Base Solar Power Plant



(NASA-CR-172086) CONCEPTUAL DESIGN OF A LUNAR BASE SOLAR POWER PLANT LUNAR BASE SYSTEMS STUDY TASK 3.3 (Eagle Engineering) 60 p CSCL 10B

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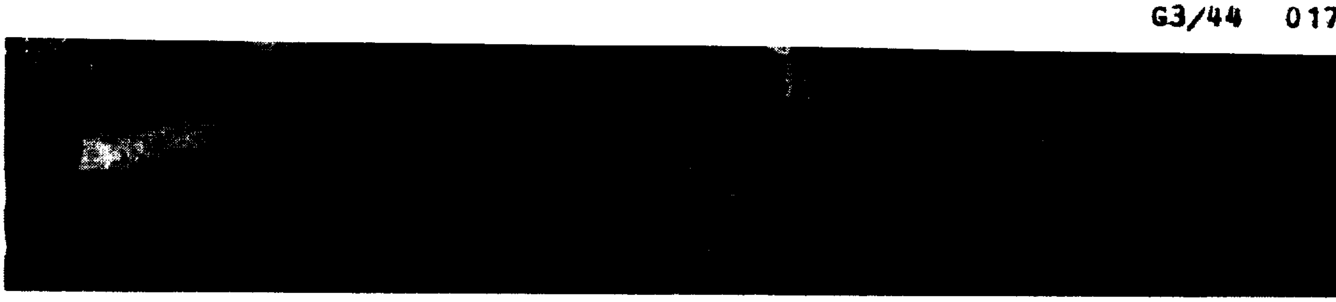

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August 14, 1988

EAGLE

Conceptual Design Of A
Lunar Base Solar Power Plant
Lunar Base Systems Study Task 3.3

Prepared under NASA Contract NAS9-17878 for the

Advanced Programs Office

Engineering Directorate

NASA Johnson Space Center

By

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Houston, Texas

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Task 3.3 Report

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FOREWORD

This report was prepared during April - July, 1988. It's objective is to establish as conclusively as possible the merits of the best static and dynamic power plant concepts applicable to the lunar surface using solar energy, and to select from those analyses recommended concepts for establishing a lunar base in the early 2000's.

Dr. John Alred was the NASA JSC technical monitor for this contract. The NASA task manager was Mr. Michael Roberts.

Mr. Bill Stump was the Eagle Project Manager for this contract. Mr. Hoyt McBryar was the Task Leader for the study and was responsible for the static concept. Mr. Richard Ferguson was a co-participant and responsible for the dynamic concept. Other participants included Mr. Pat Rawlings, Mr. John Lowery and Mr. J. Michael Stovall.

FIGURES

TABLES

1.0 EXECUTIVE SUMMARY

The objective of this study was to determine the viability of a solar powered lunar base. Study guidelines required that power plant growth occur incrementally with an ultimate capacity of 100 kW continuously. The latitude of the base was given as 18° South based upon criteria other than power systems siting.

The study required selection of the most rational static and dynamic conversion systems for comparison. Based upon trade-off analyses, one of these was to be selected for a more in-depth analysis of the impacts of a solar power system on a lunar base development.

Several photovoltaic cell technologies were investigated in several configurations of fixed and tracked arrays. From these trade studies, a fixed flat array of gallium arsenide cells was selected for comparison with a solar dynamic system. Lunar night energy is supplied from a Regenerative Fuel Cell (RFC) system with H_2 and O_2 stored at pressures up to 20,673 kpa (3,000 psi).

Rankine, Brayton and Stirling cycle engines were considered as dynamic candidates. Operation of any of these engines during the Lunar night with thermal energy storage was determined to be impractical if the storage media is required to be transported from the earth. As a result, energy storage is based on the use of an RFC which would be identical to that required for the photovoltaic system. Alternator output would be required to be converted to DC for the RFC. Based primarily on weight, the Stirling cycle was selected for comparison with the photovoltaic system.

The primary obstacle to the successful use of solar power systems on the lunar surface is the extremely long period in each cycle in which solar energy is unavailable. As a result, the energy storage system constitutes over 90 percent of the photovoltaic and over 50 percent of the dynamic system weights. The photovoltaic power generation portion of the system would weigh approximately one-eighth that of the corresponding Stirling generation equivalent, and is therefore the logical candidate for the initial Lunar Solar Power Plant.

The first power plant module to be deployed would carry a portion of the reactants as gaseous H_2 and O_2. The amount that would be necessary would be determined after operational timelines were developed. The total mass to be transported would remain constant and the first 25 kW module would only require 12.5 MT and 60 m^3 of payload capacity. Landed mass for a 100 kW continuous power system is 50 MT. The most difficult part of the power plant installation appears to be the placement and burial of the reactant tanks which is required for thermal and micrometerorite protection. Equipment handling and trenching machinery must be landed prior to the first power plant module.

The cover illustration (the same as the color rendition on the following page) depicts a roll-out, flat-plate solar array configuration for a 100 kW (net) system. The fuel/electrolysis cell modules and associated tanks are sized for 25 kW each, a size well suited for logistics and incremental power plant buildup. A fifth segment is shown being deployed illustrating power plant growth. There are no known limitations to the size of a power plant so constructed. Being modularized allows for flexibility in siting individual segments so that "mini" power plants may be located closer to the users. Thus it seems reasonable to consider the photovoltaic/regenerative fuel cell power system for lunar surface applications into the multi-megawatt power range or until nuclear sources become available.

2.0 INTRODUCTION

The purpose of this study is to conceptualize a 100 kW power plant for the Lunar surface based upon solar energy conversion. Two concepts for energy conversion were specified for trade studies, viz., static and dynamic, with appropriate energy storage. The concept selected from the analyses is shown in the drawings, Figures 11 & 12. Growth capability into a multi-megawatt system is to be considered.

Guidelines for the study included modularizing the system to enhance gradual buildup of the base because full power capability during the lunar night in the early stages of establishing base operations was not considered practical. Guidelines for compatibility with transport vehicles were 4.58 m and 9.15 m diameter heavy lift vehicle shrouds and a 25 metric ton payload limit for the lunar lander vehicle.

Clearly, the strongest driver in establishing a lunar solar power plant is the energy storage requirement for the long lunar night. If the site selected was at one of the poles, the energy storage requirement could approach zero because continuous exposure to the sun could be achieved, except for short periods of eclipse. The rotational axis is inclined from the ecliptic plane by 1.5°, therefore a tower about 600 meters high (less if a natural feature with good elevation was available for the construction site) would have clear exposure to the horizontal sun's rays throughout the lunar cycle. The solar panels would rotate on the vertical axis of the tower to track the sun at normal angle for maximum power output. The array sizing would be dictated by the basic station power level of 100 kW. This may be as low as 12% of the size required for of an equatorial siting where the peak generation requirement may be 800 to 1,000 kW, depending upon the design selected, i. e., tracking, fixed flat plate, etc. For the polar case, assume a photovoltaic collector and using the derated (net) output of gallium arsenide cells of 235 W/m^2:

$$100{,}000\ W \div 235\ W/m^2 = 425\ m^2$$

or approximately 20 x 20 m, a modest dimension.

The mass difference between polar and equatorial siting may be even more pronounced. Preliminary studies have established the photovoltaic portion of a lunar power plant at about 8 kg/kW and the storage portion to be about 750 kg/kW. At equatorial siting, the array must be sized to accommodate energy storage and therefore peak power of 800 kW may be required. At the pole, the array would be sized for 100 kW. Assuming the photovoltaic portion would be increased by a factor of 10 (to 80 kg/kW) to include the mass of the tower structure at the pole, the total mass of the polar system would be only about 10% of the mass of a plant requiring nighttime energy storage. If differences of this magnitude can be verified (80 kg/kW vs. 750 kg/kW) by detailed analysis of tower structure requirements, polar siting may be a viable option for a lunar base (Ref. 1).

The primary site selection was established at 18° South, 35° West. Assuming a "sun tracking" panel configuration and in order to achieve full normal sun angle, the south end would need to be elevated 3.1 meters per 10 meters of panel length. Without elevation, the effectivity of the panels would be proportional to the cosine of 18° or 95 percent of the energy associated with normal sun angle. In the initial buildup stage of power plant construction, this may be a reasonable trade-off against the additional mass and labor required to effect elevation. The slight tilt of the moon's axis of 1.5° relative to the ecliptic plane produces no seasonal changes of consequence, only 0.034% of incident energy. As the cells degrade, or at such time as additional power is required, the panels could be elevated to normal (90°) sun exposure and thus increase the power output by 5%. Likewise, in the initial power plant construction, a flat plate layout of the array would be less mass and labor intensive. Thus in order to increase array power output as the base grows, upgrading to a tracking configuration may be feasible after the base activity settles into routine operation. The integrated electrical energy increase of a perfect tracking array over the flat plate orientation would be the gain of that energy lost due to the cosine law effect, or 57.5%.

3.0 POWER PLANT SIZING

The basic power requirement to be delivered to the power conditioning equipment was established at 100 kW continuous. This requirement to be met throughout the lunar night increases the size of the solar energy conversion equipment dramatically in order to provide the energy storage, either by a secondary battery system, a regenerative fuel cell system, or a heat storage system. A battery system for example, typically operating at 70% cycle efficiency, would require a photovoltaic array sized for a net output of approximately 180 kW over the basic 100 kW for the base, making the total array area 280% of the size required for daylight power only. With the regenerative fuel cell system operating at approximately 56% cycle efficiency approximately 225 kW array area is dictated or 325% over the daylight-only array requirements. These numbers assume a tracking array configuration providing maximum efficiency of the solar cells. With a less efficient orientation such as a flat plate, the peak power sizing requirements of the array are further increased.

For the purpose of this study, it was assumed that the angle of the sun with respect to the solar panels, whether photovoltaic or concentrator, for base power would be essentially ineffective before 10° after sunrise and after 10° before sunset. In the case of a multiple-row tracking array this assumption accounts for early and late shadowing. In the case of a flat plate array, this assumption provides for the low angle of incidence of sunlight.

A "lunar night" of 394 hours was therefore established as follows to derive the total kWh of energy required to be stored:

Lunar cycle = 29.53 days x 24 hrs/day = 708.72 hrs (Ref. 2)

$$\frac{200^\circ}{360^\circ}(708.72 \text{ hrs}) = 394 \text{ hrs. (storage)}$$

$$\frac{160^\circ}{360^\circ}(708.72 \text{ hrs}) = 315 \text{ hrs. (regen)}$$

Thus base power and energy storage for nighttime use must be provided during 315 hours of effective sunlight. The amount of energy required to be supplied during the dark period is determined as follows:

100 kW x 394 hrs = 39,400 kWh

The efficiency of the storage and conversion system, and the dark/light ratio determines the total power system size:

$$Pwr_t = Pwr_b + \frac{(Pwr_b \times dk/lt)}{eff_c} = 100 + \frac{(100 \times 394/315)}{eff_c}$$

Thus for the 100 kW continuous power system with a typical electrochemical energy storage system cycle efficiency of 70% (energy out vs. energy to recharge), and the dark/light ratio of 1.25, the solar power system average output requirement is determined as follows:

$$Pwr_t = 100 \text{ kW} + \frac{(100 \text{ kW} \times 1.25)}{0.70} = 278.6 \approx 280 \text{ kW}$$

3.1 STATIC CONVERSION SYSTEMS

Three technologies were considered for the solar static conversion; thermionics, thermoelectrics and photovoltaics. Thermionics was deleted due to the high temperatures required and the resulting impact brought about by the manufacturing precision requirements on the concentrators. Thermoelectrics would operate within the temperature range of interest but the resultant efficiency does not exceed the efficiency achievable using the simpler photovoltaic array. Thus the photovoltaic system was selected as the static strawman in this study.

3.1.1 PHOTOVOLTAICS

Five types of solar cells were given consideration for use on this application, viz., crystalline silicon, amorphous silicon, gallium arsenide, gallium arsenide/germanium, and indium phosphide.

Crystalline silicon is the workhorse of space solar energy conversion and can be used to construct very reliable, predictable space power plants. Several companies are active in the development and manufacture of this type cell and the performance has been remarkably improved, yielding operating efficiencies for the space environment to about 13.5%.

Amorphous silicon is "the new kid on the block" and promises to make an important contribution to solar energy conversion requirements in both the space and terrestrial environments. The cells can be made very thin and when placed on flexible backing, can be rolled up for transport much like a window shade or carpet. On the lunar surface it seems feasible to simply deploy the rolled panel on the terrain as is, assuming the contour is acceptable, or by minimal surface preparation, such as terracing, to achieve proper orientation to the sun as relates to latitude (Ref. 3). It is reported that the cells are very tough and flexible, making them very forgiving of rough handling. Predictable efficiencies are given as about 9 to 12% in the array configuration assuming a development effort similar to what has been applied to crystalline silicon. Present array performance is reported to be about 6%.

Gallium arsenide cells are presently the best type for the lunar application from an efficiency and overall performance standpoint, yielding the lowest loss due to radiation and temperature effects. Present-day efficiency in the array form is given at about 20.5% with 22 to 25% realistically achievable with development. However, the cell is brittle and may not be as forgiving to mishandling as silicon. A unique concept in the development stages is that the cell material is chemically deposited to a thickness of about 10 microns on a germanium backing of about 0.4 mm thick, then the germanium backing reduced in thickness to about 0.1 mm by chemical milling. This gives the effect of a "multiple band gap" cell with higher voltage and hence higher power density and greater efficiency. The cell cost is projected to be about midway between that of silicon and gallium arsenide.

Finally, indium phosphide cells were considered but because of the early developmental status, characteristics were not sufficiently established to make a case in this effort. The potential is great, however, because the conversion efficiency is given to be about 20.5% and the radiation degradation effect is apparently negligible (Ref. 4).

3.1.1.1 ARRAY SIZING

Solar insolation for Air Mass "0" (AMO) is variously reported to be 1,350 to 1,372 W/m^2, a difference of 1.6%. For these analyses the value of 1,350 W/m^2 is used.

Three effects on the performance of the cell must be considered in order to derive the net output to the electrical grid:

Conversion efficiency

Resistance with increasing temperature

Radiation degradation

Table 1 shows the values for each of the effects and the net output to be used to derive the overall array size.

Table 1

Solar Cell Performance Characteristics

Cell	Gross Pwr, W/m^2	Conv. Eff.%	Temp. Res.	Avg.%	Rad. Deg.	Avg.%	Net Eff.%	Net Pwr.W
Si	1,350	13.3	.45%/°C	-20	2%/yr	-10	9.6	130
GaAs	1,350	20.5	.25%/°C	-10	1%/yr	-5	17.5	235

The conversion efficiency is characteristic of a cell when new. The lunar surface temperature varies from approximately -157°C to 102°C. Solar cells operate more efficiently when cold than when hot. At a temperature increase of approximately 75° C (from the normal measurement temperature of 25° C to approximately 100°C) an output loss from the norm is experienced at the stated rates. The cells were thus derated for the temperature effect by an average of -20% and -10% as indicated. The radiation damage is cumulative and varies with the solar flare cycle of about 11 years. The net power output values take into account these effects and project the performance level at the end of 5 years assuming normal sun angle which may be achieved with a tracking mechanism.

The driver in defining the power plant model is the amount of energy required to power the base throughout the lunar night of 394 hours at the 100 kW level - 39,400 kWh. This energy must be provided and stored during the 315-hour daylight portion of the lunar cycle. The best near-state-of-the-art battery system is the NiH_2 type which is baselined for the Space Station. At 80% Depth-Of-Discharge (DOD) this battery is rated at approximately 35 Wh/kg. The stored energy weight would be:

$$39{,}400 \text{ kWh} \times 1000 \text{ W/kW} \div 35 \text{ Wh/kg} = 1{,}130{,}000 \text{ kg}$$

or 1,130 metric tons, an altogether unreasonable mass to consider. The cycle efficiency is about 80%. The Regenerative Fuel Cell system (RFC) energy density is greater by over an order-of-magnitude, approximately 385 Wh/kg, as determined in previous, preliminary studies, for a stored energy weight of:

$$39{,}400 \text{ kWh} \times 1000 \text{ W/kW} \div 385 \text{ Wh/kg} = 102{,}338 \text{ kg (102.4 MT)}$$

or 9.1% of the weight of the battery system. The best of the RFC types exhibits a cycle efficiency of approximately 56%. While this would require an array size approximately 16% larger, the massive battery system (approximately 1,000,000 kg heavier) dictates the RFC as the storage system of choice. At a payload capability of 25 MT, a total of 45 trips to the lunar surface would be required for the battery system.

With the performance parameters of the RFC established, the solar array can be designed. Because of the superior performance of the gallium arsenide cell over the long term, it is selected to establish array dimensions using the requirements of the RFC.

The RFC system consists of a fuel cell to convert the chemical energy of H_2 and O_2 into electrical energy and H_2O during the lunar night portion of the cycle and an electrolysis cell to regenerate the H_2 and O_2 from H_2O during the active generation portion of the cycle. Approximately 4.9 kWh is required to electrolyze 1 kg of H_2O or .204 kg per kWh. The fuel cell consumption rate of H_2 and O_2 is approximately 0.364 kg per kWh of electrical output. Therefore, the weight of the reactants required is determined as follows:

$$39{,}400 \text{ kWh} \times 0.364 \text{ kg/kWh} = 14{,}342 \text{ kg } (H_2 + O_2)$$

The input energy to the electrolysis is:

$$14{,}342 \text{ kg} \times 4.9 \text{ kWh/kg} = 70{,}275.8 \approx 70{,}000 \text{ kWh}$$

For the generation period of the cycle of 315 hours, the power input requirement for the RFC would be:

$$70{,}000 \text{ kWh} + 315 \text{ hrs} = 222.2 \text{ kW} \approx 222 \text{ kW}$$

Adding this to the baseload, the array output would be:

$$222 \text{ kW (storage)} + 100 \text{ kW (base)} = 322 \text{ kW}$$

which is the net power output required of the solar array at normal sun angle utilizing a sun-tracking system. Using the net power density of gallium arsenide cells, the array area would be:

$$322{,}000 \text{ W} \div 235 \text{ W/m}^2 = 1{,}370 \text{ m}^2$$

Three additional array configurations were analyzed and the results are presented in Table 2.

Table 2

Gallium Arsenide Array Configuration

Conf'g'n	Effectivity	Power,kW	Area, m^2
Tracking	1.0	322	1,370
30° Incremental Tracking	.983	328	1,393
Flat Plate	.635	507	2,158
60^{o} "A" Frame	.46	700	2,979

It is seen that the power requirements of a photovoltaic array and hence area of the installed array can vary by over a factor of 2 depending upon the chosen option of orientation.

The Tracking array would be mounted on panels about 3 x 3 m and placed in 5 rows about 92 m long, spaced about 15 m apart. Thus, after 10° past sunrise and up to 10° before sunset, no shadowing would occur for full output of the array. The panels would be gimballed and synchronized with the sun's relative movement of about 1.97 hrs/degree. At sunset the panels could be reversed for resetting to sunrise or designed to rotate

360°. The latter would provide an opportunity for regolith settlings (if any occur) to fall off, thus helping to maintain a clean surface.

The 30° Incremental Tracking array would be spaced similarly, and set at 15° elevation at sunrise and either manually or automatically adjusted in 30° steps, 6 times per lunar day or every 59 hours. Thus the incident angle of the sun's rays would continuously vary over +/- 15° for an average affectivity of 98.3%. This is inherently a much simpler mechanism to incorporate, and costs a very small penalty. Operations could be conducted by remote, manual control.

The Flat Plate configuration is the simplest of all, but has a 57% larger area penalty over a tracking configuration. The effectivity of 63.5% applies if the south end of the rows are elevated appropriately for the 18° South siting. Without elevation, an additional penalty of 5% in performance would apply, raising the peak power rating of the array to 534 kW and the area to 2,272 m^2. Several methods have been proposed to clean the array periodically, such as brushing with plastic brooms or blowing with moderate pressure gas.

The 60° "A" Frame configuration would be elevated at the south end and arranged in 5 rows 50 m long, spaced 15 m apart to minimize shadowing for the first and last 10° of the solar arc. Again, elevation of the south end applies.

Figure 1 presents a plot of the solar flux applicable to each of the configurations, and Figure 2 illustrates the layout of each.

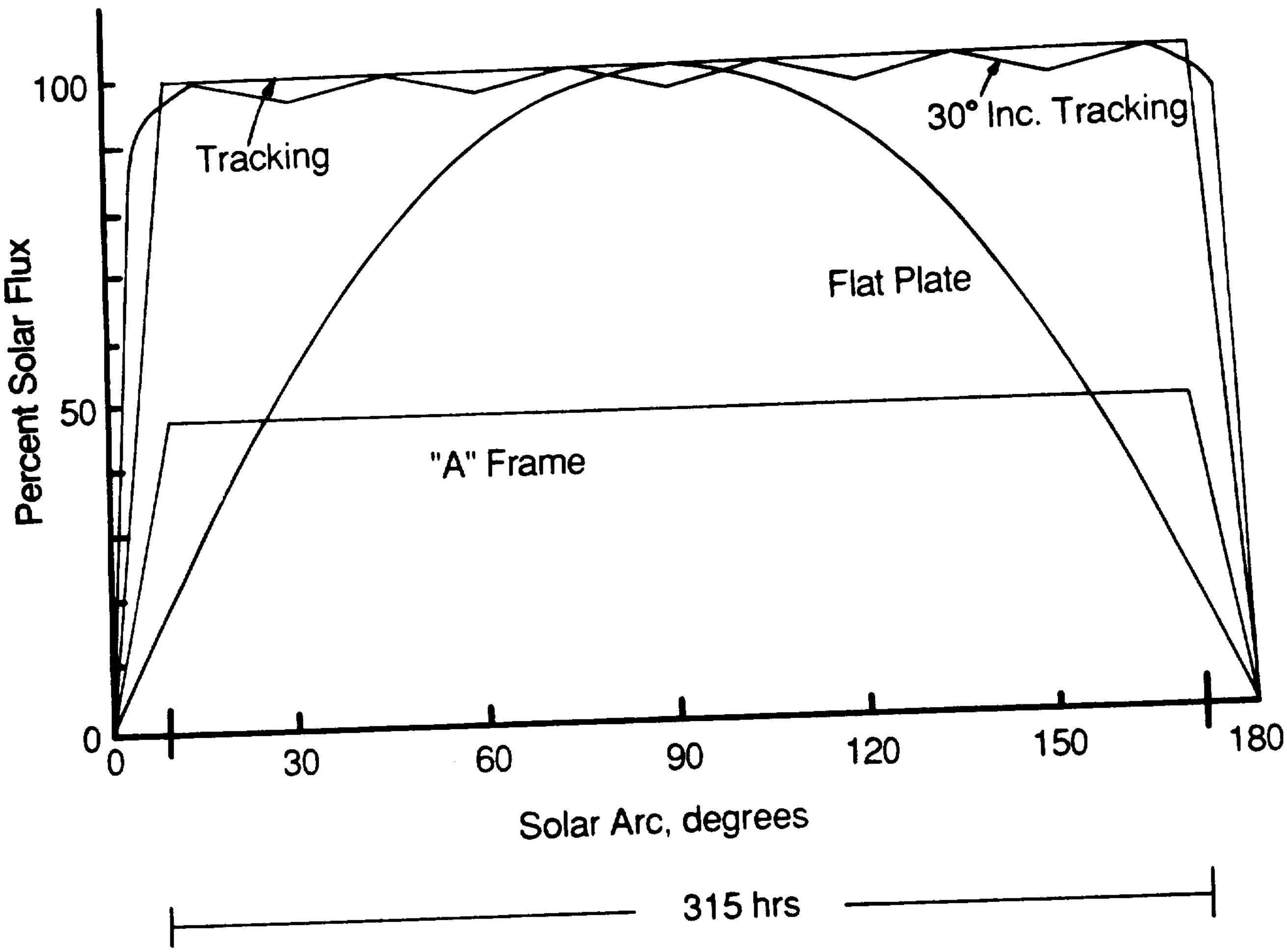


Figure 1

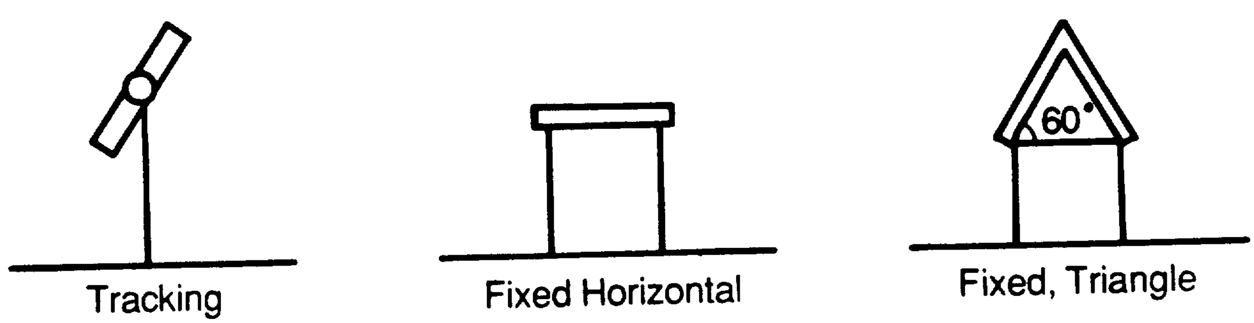


Figure 2

3.1.1.2 ENERGY STORAGE

Preliminary calculations using state-of-the-art energy density data for both NiH_2 batteries and regenerative fuel cells clearly excluded the battery system as an option for the Lunar Solar Power Plant. The weight of the storage system alone would be 11 times greater than for the RFC system, requiring 45 landings to deliver it at a landing payload limit of 25 MT.

From previous studies on modularization of fuel cells, it has been established that any size up to 25 kW is feasible and practical. It was found that a 25 kW module met the weight and volume constraints given above and has been selected for this application.

The RFC energy storage system is made up of two basic components, the energy conversion system - fuel cell and electrolysis cell, and the reactant storage system - H_2, O_2 and H_2O tanks. The tankage system is both the weight and volume driver.

3.1.1.2.1 REACTANT STORAGE SYSTEM

Two fuel cell/electrolysis cell concepts were examined for this application, viz., the acidic Proton Exchange Membrane (PEM) type, a derivative of that used on the Gemini program, and the alkaline Capillary Matrix (CM) type, the same as is used on the Shuttle. Both types have been in development for 30 years and have demonstrated life capability equal to the Lunar Base requirement which is approximately 25,000 hours over a 5-year period. Because of the differences in efficiency, the CM type was chosen for this application. An example of the difference in efficiency is given by the energy (kWh) required to electrolyze a quantity of water which is 30% greater for the PEM type over the CM type. This translates proportionately to the solar array area requirements and somewhat disproportionately to the heat rejection load, being about 13 times greater than for the CM type.

In deriving the reactant tank size requirements, a conservative factor of approximately 25% in the reactant consumption rate of the fuel cell was utilized in order to account for the effects of variations in load placed on the fuel cell. Thus the consumption rate was set at 0.455 kg of H_2 and O_2 per kWh of electrical output at the ratio of 1/8. An additional factor of 10% was added to account for residuals in the tanks as undeliverable at the minimum operating storage pressure:

H_2: 0.0455 kg/kWh x 25 kW x 394 hrs x 1.1 =	493 kg
O_2: 0.409 kg/kWh x 25 kW x 394 hrs x 1.1 =	4,433 kg
H_2O:	4,926 kg

Two maximum gas storage pressures were considered. The above values were converted to standard volume and the storage tanks were sized for 6,891 kpa (1,000 psi) and 20,673 kpa (3,000 psi) for the H_2 and O_2. A pressure of 413 kpa (60 psi) was used for the H_2O tank. A graphite/epoxy filament-wound tank with a 0.64 cm aluminum liner was used for the gases, and the .064 cm aluminum-only was used for the H_2O tank. The results are given in Table 3.

Table 3

Reactant Tanks

1,000 psi	H_2	O_2	H_2O	Total(Wt)
Dia., m	5.49	4.58	2.07	-
Weight, kg	3,744	1,874	5,657$^{(1)}$	11,274
3,000 psi				
Dia., m	3.81	3.17	2.07	-
Weight, kg	2,898	1,739	5,657$^{(1)}$	10,294

(1) Includes weight of H_2O, tank, and structure at 15% of total for transport.

The 20,673 kpa (3,000 psi) system was selected because the tank diameters of the 413 kpa (1,000 psi) system exceeded the 4.58-m (15-ft.) diameter limit and the weight is about 10% heavier.

3.1.1.2.2 ENERGY CONVERSION SYSTEM

The alkaline Capillary Matrix fuel cell and electrolyzer technology is essentially the same fundamentally, differing primarily in the oxygen electrode composition. Indeed, a cell structure is quite feasible that performs both functions, a reversible cell, which in certain applications is the preferred design. The cell would operate somewhat less efficiently because of the catalyst compromises required in the electrode, and the system would be somewhat more complex. For large applications such as the Solar Lunar Power Plant, dedicated cells are indicated.

The design is derived from the Space Shuttle Fuel Cell technology which has been quite well proven.

The 25 kW (net) fuel cell module was sized to deliver 25 kW to the bus which indicated 30 kW power capability at the fuel cell terminals when new. Thus the cell degradation losses are accounted for. Likewise, the electrolysis module is sized to regenerate all the reactants consumed during the lunar night of 394 hours by the fuel cell during the lunar day of 315 hours. The features of the system are presented in Table 4.

Table 4

25 kW Regenerative Fuel Cell System Features

Feature	Electrolyzer	Fuel Cell
No. Cells	288 (2 substacks)	214 (2 substacks)
Cell Size, m^2	.093	.093
Cell Voltage, V	1.65	0.96
Current Density, A/m^2	14	14
Power, W	55,555	30,816
Waste Heat, W	5,400	15,200
Unit Wt., kg.	560	215
Unit Vol., m^3	.85	.38
Operating T., ^oC	82.2	82.2
Operating P., kpa	20,673	413

The cell configuration of the fuel cell stack may be arranged to provide DC voltage to the power conditioning equipment at 100 or 200 volts, depending upon series or parallel arrangement of the stacks. The electrolysis system can accept either 220 or 440 volts DC, also depending upon series or parallel arrangement.

The thermal control loops would be integrated with a common heat exchanger so that the temperature of the inoperative unit would be maintained at optimum conditions by the rejected heat of the operating unit and thus avoid wide swings in temperature and potential thermal cycling problems. The radiator size is dictated by electrolysis, in spite of the fact that the waste heat load from the fuel cell would be 15.2 kW for the 25 kW module, while the corresponding electrolysis load would be 5.4 kW. The radiators baselined for the RFC would only require a total of 72 m^2 of radiating surface and the corresponding radiator weight would be 485 kg for the 100 kW system.

The electrolysis module would be sealed in a pressure vessel so that critical seals in the unit would not be subjected to large deferential pressures. The gases produced from electrolysis of H_2O will be electrochemically pumped into the storage vessels without the necessity of mechanical compressors. Likewise, the product H_2O from the fuel cell is condensed and stored in the H_2O tank at a pressure equal to or lower than the fuel cell operating pressure. The transport of H_2O from the storage pressure of 350-400 kpa as product H_2O from the fuel cell, to the operating pressure of the electrolysis cell is accomplished by a mechanical pump and a small H_2O accumulator which is pressure referenced to the O_2 tank. A schematic of the system is presented in Figure 3. The overall concept of the reactor assemblies is illustrated in Figure 4.

Energy Conversion/Storage System

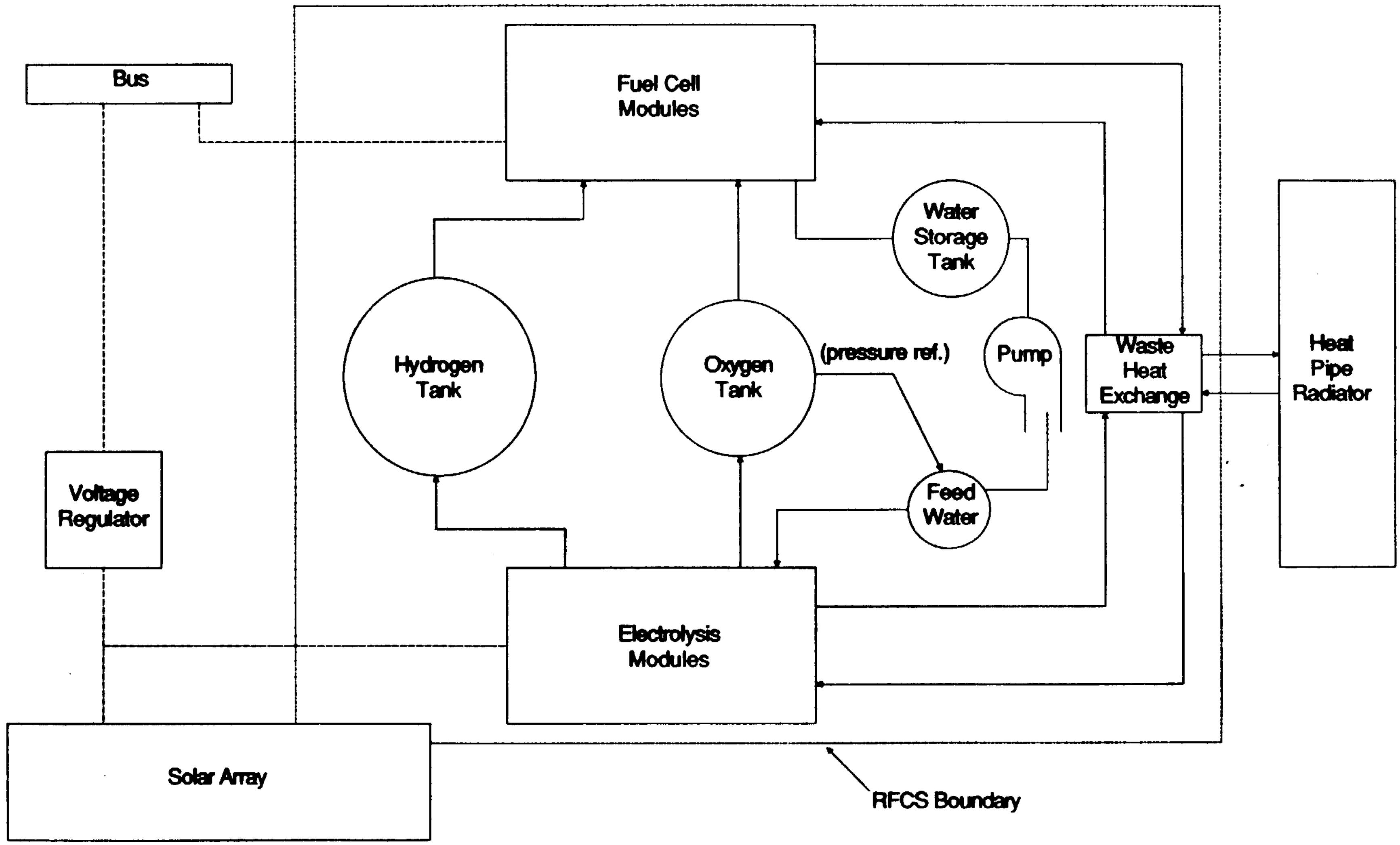
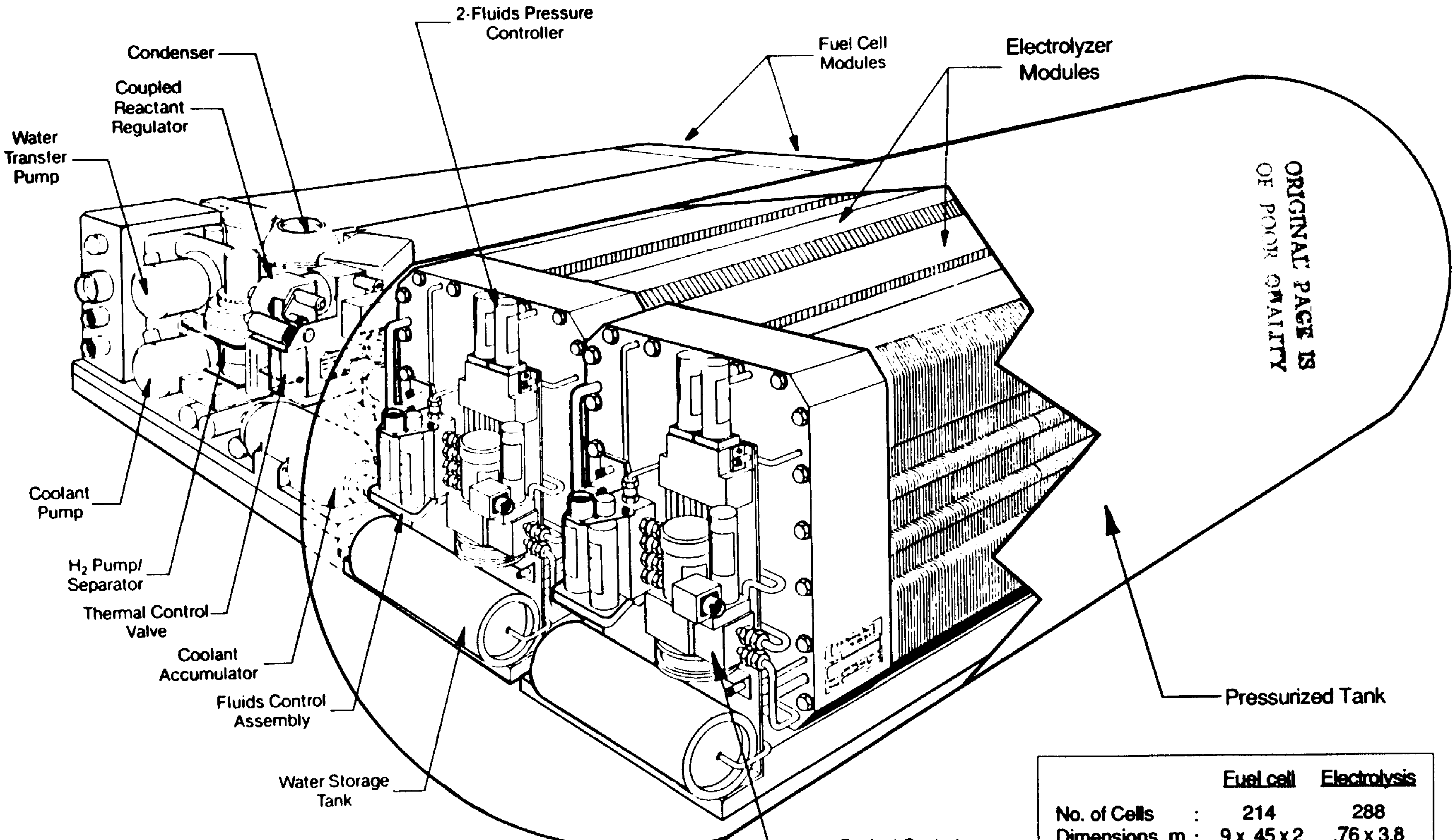


Figure 3

30 kW REGENERATIVE FUEL CELL SYSTEM[a]



		Fuel cell	Electrolysis
No. of Cells	:	214	288
Dimensions, m	:	.9 x .45 x 2	.76 x 3.8
Volume, m^3	:	.810	1.62

Figure 4

A mass summary of the selected design of the photovoltaic/regenerative fuel cell system is given in Table 5.

Table 5

Mass Summary, GaAs Solar Array and RFC Power System

Element		25 kW Module, kg	100 kW System, kg
Solar Array 507 kW, Flat Plate, GaAs		1,014	4,056
Tankage:	H_2 O_2 H_2O	3,036 1,815 564	12,144 7,260 2,256
Fluid:	H_2O (liquid)	4,927	19,708
Fuel Cell		215	860
Electrolysis Cell		560	2,240
Radiator		121	485
TOTAL		12,252	49,009

3.2 SOLAR DYNAMIC

3.2.1 APPLICATION TO LUNAR BASE

As with solar statics, the most difficult environment to overcome is the long dark period. The power plant must continue to run during the lunar night period or it must be oversized in order to store produced energy. The continuous engine operation dictates that the solar energy must be converted into another form - thermal - and stored for later use. The problems of storing product electrical energy electrochemically closely parallels the energy storage options available to photovoltaics. The primary difference is that the dynamic engine/alternator output is AC and must be converted to DC for storage in either secondary batteries or regenerative fuel cells (RFC).

A secondary obstacle to overcome is the mid-day thermal environment at the proposed latitude. The dynamic systems are bound by the Carnot Cycle efficiency. This efficiency is the ratio of the difference between the maximum and minimum cycle temperatures to the maximum temperature. High radiator temperatures will impact this theoretical limit and will affect some actual cycle efficiencies more than others.

The objective of this section is the definition of the most logical candidate system for producing continuous power. In defining this strawman, considerable engineering judgement has been used in selecting those technologies that do not have insurmountable problems. Since this judgement is being applied to extrapolate from the 1988 base, the results presented could likely prove too conservative when viewed from a future start time period. In a later section, this strawman system is compared with the photovoltaic system, based on similar groundrules, with the intent of selecting one or the other for a more in-depth analysis of the ramifications of a solar powered lunar base with initial power demands increasing with growth up to 100 kW.

3.2.2 CONCENTRATOR/RECEIVER

Due to the lower efficiency of electrochemical storage, the concentrators for start-stop operation will be larger than for the same power plant technology operating continuously. The receiver combined with thermal storage, however, is heavily impacted by the long lunar night of 394 hours.

The moon does present a more stable and predictable platform than an earth orbiting spacecraft. For this reason higher concentration ratios, thus higher temperatures, are more practical.

The rigid truss hexagonal design (Ref. 5) was selected as a baseline for this study. While other lighter weight concepts could be considered, overall powerplant weight is not sensitive to these different technologies. The rigidized hex truss has been selected for the Space Station, and if implemented as planned, should establish a firm technology basis for use on the moon. The projected specific weight for the Space Station concentrators is approximately 6.5 kg/kW of energy transmitted to the receiver. As an example, concentrators with a total projected area of 1,000 m^2 would be capable of transmitting about 1,200 kW to the receiver. The power plant, operating at 30% efficiency, could produce 300 kW, which is sufficient to support a base load of 100 kW using electrochemical storage. The weight of the hex truss concentrators would be about 7,800 kg.

Logical thermal storage media would be limited to metallic salts such as lithium hydride or lithium fluoride. The heat of fusion of most candidate Phase Change Materials (PCM) is approximately 1,000 kilojoules per kilogram. The gases that exist at the respective melting temperatures are notoriously hard to contain. The containment weight, therefore, tends to exceed the PCM weight by a factor of three or four.

Left exposed to the thermal environment during the lunar night period, the rigid concentrators could be seriously damaged. However, a combination of a lightweight radiation shield coupled with a limited amount of heat should be sufficient to maintain these structures above the target design temperature limit of minus 29°C, which is the design limit of the Space Station concentrators. Temperatures below this limit will likely cause structural damage and permanent distortion of the mirror surfaces.

3.2.3 RADIATOR PERFORMANCE

Due to the large amount of heat that is required to be rejected during direct dynamic system operations, the hostile thermal environment seriously impacts the operating temperature range available.

In each case included in this study, the radiator was assumed to be mounted adjacent to the engine. The plane of the radiator was assumed to be in the solar plane. Due to the angle of inclination of 18°, it was further assumed that only the side of the radiator facing the nearest pole was effective.

Radiator performance was derived from a study by Wallin and Miles, for Earth orbital based dynamic power systems (Ref. 6). They determined that a radiator with an area of 103 m^2, weighing 750 kg, would dissipate 58.1 kW at an average fluid temperature in the radiator of 371° K. Their sink temperature was 185° K.

Two factors were applied to extrapolate Earth orbital performance of this radiator to performance on the lunar surface during sunlight periods. The average fluid temperature was raised to 710° K, or a temperature in excess of local surface temperature. By itself, the higher temperature will raise the radiant heat flux by 28%. However, with the view factors applied as discussed previously, only 108° of the 360° viewing band was considered effective. This reduced the radiator effectiveness to 30% of comparable Earth orbital performance. With emissivity equal to absorbtivity in the same thermal range, there would be a net heat flow from the radiator to the Lunar surface which is not taken into account, thus the approach is considered conservative.

The net effect on the referenced radiator is a reduction from 58.1 kW to 22.2 kW or 2.31 m^2/kW. The referenced radiator would weigh 14.56 kg/m^2 or the radiator weight per energy dissipated would be 33.7 kg/kW. These ratios were used for sizing radiators for all dynamic power systems.

In order to assure reasonable intermediate heat transfer surface areas, it was assumed, for the purpose of the study, that the lowest cycle temperature for any engine would be 177°C.

Figure 5 illustrates the combined effect of temperature limits on the theoretical Carnot efficiency, the efficiency that no engine can exceed. T_h represents the highest temperature within the closed cycle while T_c represents the lowest temperature. Assuming that T_h is limited to 1,090°K, by a combination of concentrator performance and materials limitations, the Carnot efficiencies range from 52% to 70%, for effective T_c's ranging from 500 to 300° K. At a hot temperature of 1,090°K, Carnot efficiency is less sensitive to T_h than T_c. T_h would be required to be raised approximately 200°K to achieve the same performance that a reduction of T_c by 50°K could provide. Therefore, the emphasis needs to be placed on reducing the coldest cycle temperature without excessive radiator penalties.

Carnot Cycle Efficiencies

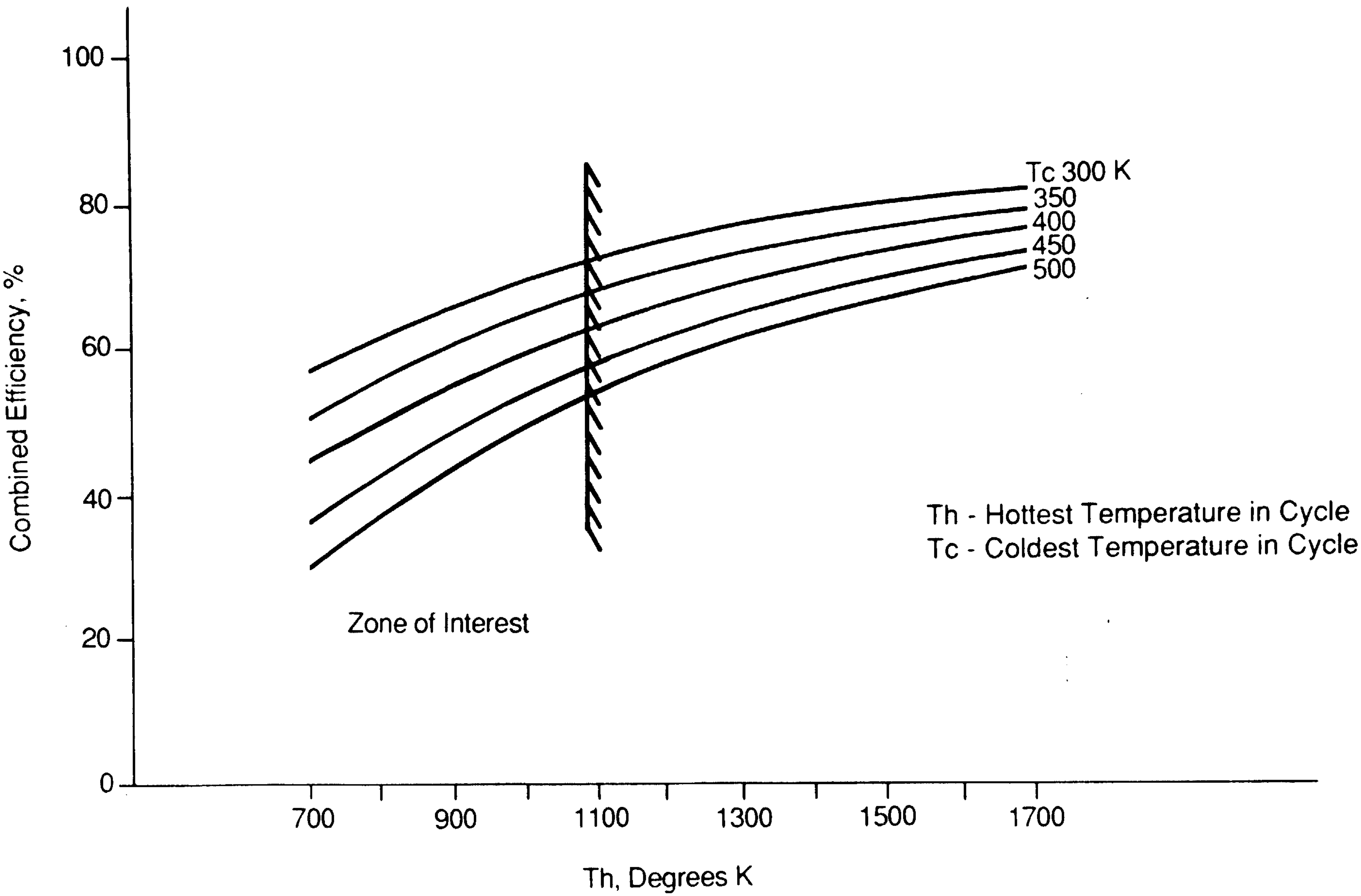


Figure 5

A heat pipe radiator design was used as a baseline throughout the study, and its selection was based on a combination of performance and ease of maintenance and replacement.

Like the concentrators, the radiators must be kept at a reasonable temperature during the lunar night. As with the concentrators, this should constitute no design barrier. Either the engines are operating continuously and heat is being rejected, or stored energy is being utilized by the fuel cells or batteries. In the latter case, excess thermal energy is readily available if adequate thermal covers are used to protect the radiators.

3.2.4 ENGINE COMPARISONS

There are three engine cycles that are candidates for the lunar base power system. These are the Rankine vapor cycle and the Brayton and Stirling single phase gas cycles. While it has never been used in space, the liquid/vapor metal Rankine cycle has been considered for applications dating back to the late 1950's. A more recent candidate has been the Organic Rankine Cycle, or ORC. The Brayton Cycle has gained much attention since the 1960's, primarily as a result of extensive development done and sponsored by Lewis Research Center. The Stirling Cycle has also been proposed for space applications from the beginning of the Space Age but lagged the other two cycles in the level of technology readiness. As a result, engineering developments required to raise the cycle to the level of the other two has only recently been applied.

3.2.4.1 CYCLE DESCRIPTIONS

All thermodynamic cycles are limited by the maximum theoretical, or Carnot, efficiency. Basically, the efficiency is limited by the following expression where:

$$\text{Eff.} = \frac{T_h - T_c}{T_h}$$

The performance of the solar concentrators and radiators and their effects on Carnot cycle efficiency are illustrated in Figure 6. The range of radiator return temperatures from 367°K to 450°K are the likely bounds that would be incorporated in this application. At a radiator return temperature of 450°K, Carnot efficiency gains with hot cycle temperatures above 1,100°K are seriously constrained and do not warrant striving for the higher ranges. Higher temperatures not only complicate the design of the concentrators, they require changes to more exotic materials on elements of the system exposed to these temperatures. As a result, cycle temperatures were considered to be limited to between 1,100°K and 450°K with a corresponding Carnot cycle efficiency of 59%.

The effects of these limits on the respective cycles are discussed in conjunction with Figure 7.

(a) <u>Rankine:</u> This cycle is depicted in the Pressure-Volume (P-V) diagram by (1-2) liquid pressurization or pumping, (2-3) evaporation and superheating at constant pressure, (3-4) expansion work, and (4-1) cooling and condensation. Since little work is required to pump liquids, the cycle efficiency of the cycle is generally represented by the work output divided by the amount of energy added in the

Carnot Efficiency Limitations

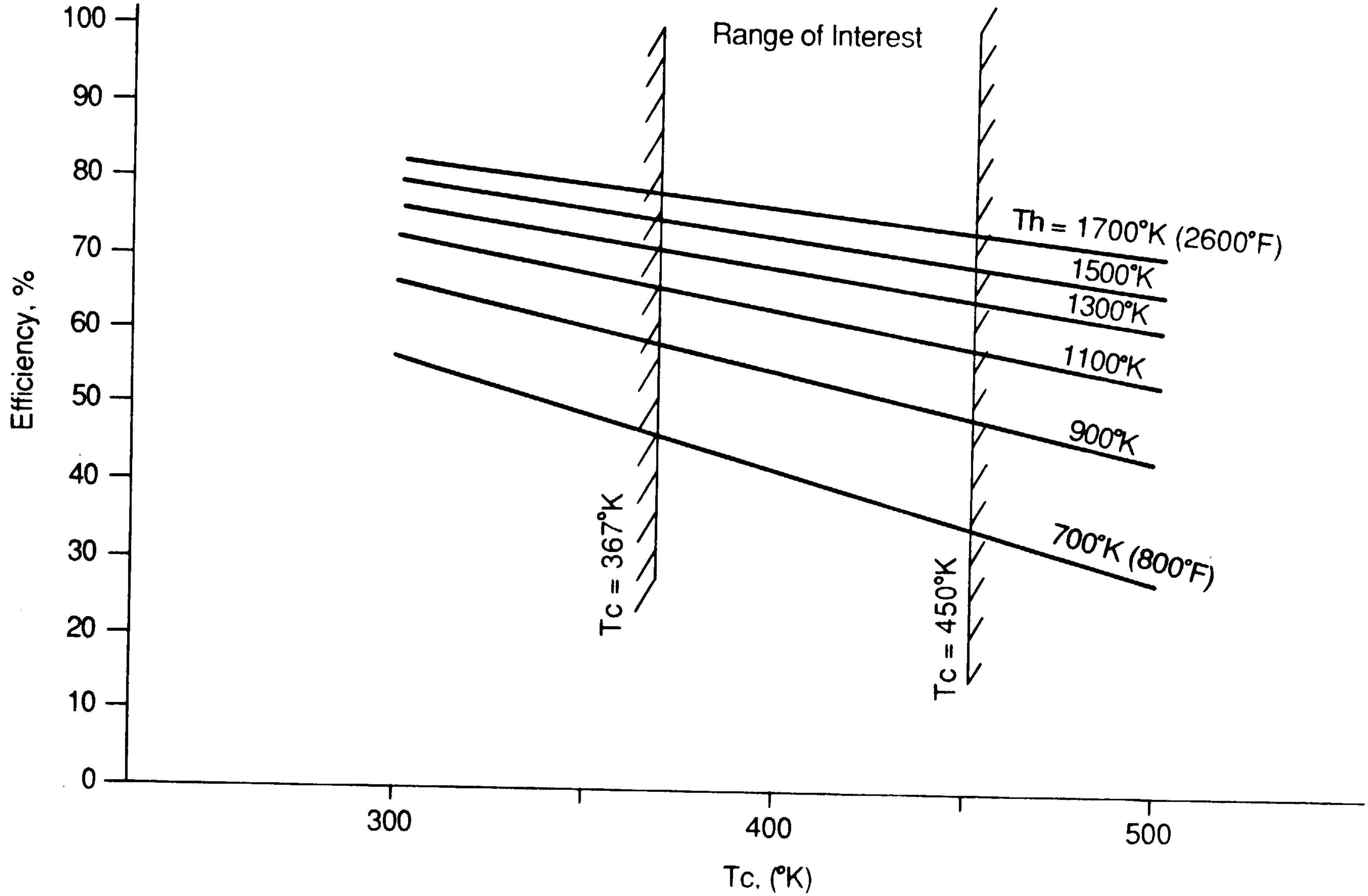
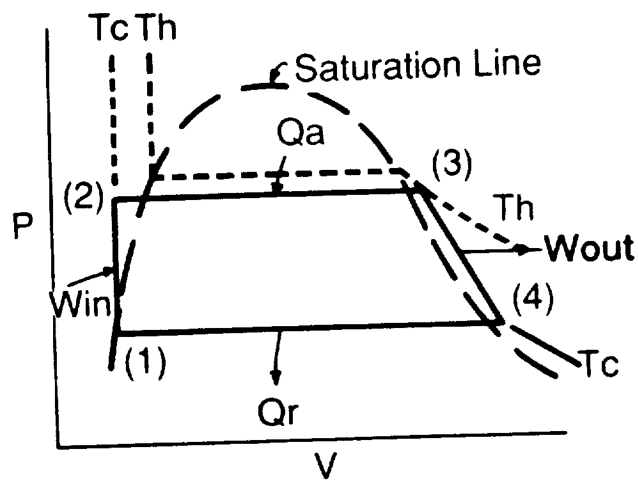


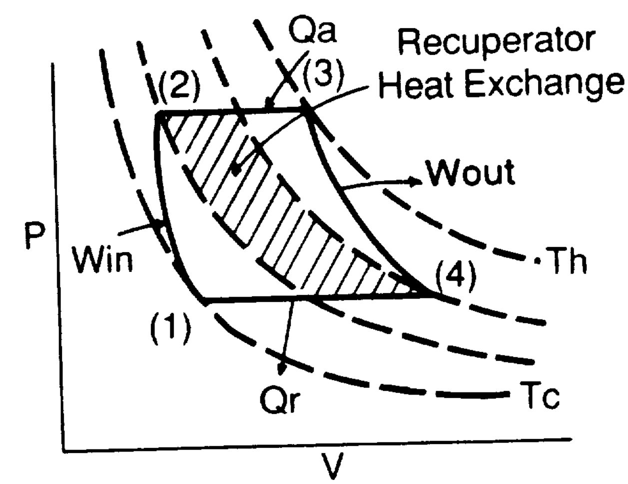
Figure 6

Engine Cycles
Wout = Win + (Qa-Qr)

(a) Rankine
1-2 Liquid Pumping (Win)
2-3 Vaporize / Superheat (Qa)
3-4 Expansion (Wout)
4-1 Condensing (Qr)
Wout ≈ (Qa-Qr)



(b) Brayton
1-2 Compression (Win)
2-3 Heat Added (Qa)
3-4 Expansion (Wout)
4-1 Heat Rejected (Qr)



(c) Stirling
1-2 Isothermal Compression (Win, Qr)
2-3 Constant Volume Heating (Qreg in)
3-4 Isothermal Expansion (Wout, QA)
4-1 Constant Volume Cooling (Qreg out)

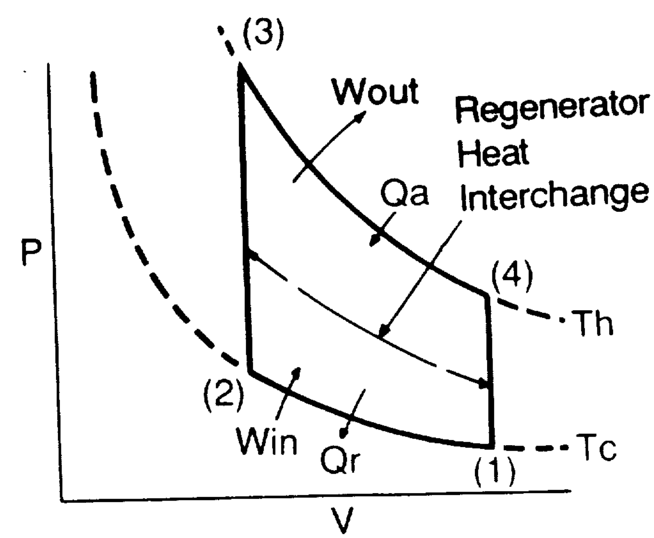


Figure 7

boiler. The efficiency of single stage potassium cycle, as measured by alternator output, would be in the range of 15-20%, operating within the temperature limits for this application. The ORC has some inherent advantages over the liquid metal cycles, which result in higher efficiencies for a given temperature band. The working fluid, however, limits the maximum temperature to about 675°K. With the lunar radiator constraint, the overall or combined cycle efficiency range would be between 22 and 25%.

(b) Brayton: This cycle includes (1-2) polytropic compression, (2-3) heat added at constant pressure, (3-4) polytropic expansion through the turbine, and (4-1) heat rejection at constant pressure. Since the temperature of the fluid exiting the turbine is still greater than the temperature exiting the compressor, heat is exchanged between the high pressure and low pressure gas (recuperator). The net result is a higher cycle efficiency and a reduction in the amount of heat required from the heat source as well as heat rejected to the radiator. The key to high efficiency with the Brayton cycle is the establishment of a high T_h/T_c ratio in order to minimize the effects of compressor work. Within the temperature constraints used in this analysis, the net combined efficiency would be about 25%.

(c) Stirling: This cycle includes (1-2) isothermal compression, (2-3) constant volume fluid transfer from a regenerator where the heat added results in a further pressure rise, (3-4) isothermal expansion, and (4-1) constant volume heat transfer to the regenerator. The key element in this cycle is the regenerator. To be effective, the regenerator must not only retain the heat for a one-half cycle but must be designed to minimize conduction internally in order to assure retention of full effectiveness during the subsequent reheat stroke of the engine. Due to the fact that heat is theoretically added only at constant temperature (T_h) and rejected only at (T_c), the Stirling efficiencies are closely related to Carnot. Actual overall efficiencies are projected to be in the range of 50 to 75% of the corresponding Carnot efficiency (Ref 7). For the temperatures applied in this analysis, the resulting overall efficiency is projected as 34.7%.

3.2.4.2 CYCLE COMPARISONS

Based on the availability of more efficient and simpler cycles, the liquid metal Rankine cycle was deleted from further consideration in this analysis.

The ORC is a reasonably attractive option with efficiencies comparable to the Brayton. The lower receiver temperature allows considerably more flexibility in the construction of the concentrators, since concentration ratios need not be as high as would be required for the higher temperature cycle engines. The main drawback is that the cycle will be more sensitive to the relatively narrow range of operating temperatures available on the lunar surface. The maximum temperature of the working fluid, toluene, is approximately 670°K. When serious effort is considered towards developing a solar dynamic system for this application, the ORC should be revisited but its selection as a basis for this study was considered inappropriate.

The Brayton and Stirling cycles are the remaining candidates. Characteristics are listed in Table 6 for systems which would generate and store energy electrochemically to meet a continuous base load of 100 kW. For this comparison, the weight of the electrochemical storage is neglected since it is independent of the engine cycle.

Table 6

Brayton/Stirling Comparisons

Element	Brayton	Stirling
Concentrator Area, m^2	1,302	938
Radiator Area, m^2	2,362	1,650
Weight, kg		
Concentrators	11,070	7,973
Receivers	3,587	2,587
PCUs	10,926	4,396
EM pumps, etc	------	908
Radiators	38,317	24,028
TOTAL	63,900	39,892

In both cases, the system weight is dominated by the radiators. Their weights are about seventy percent of the generation system weight as compared to about 15% in earth orbital applications. The Brayton system would weigh approximately 24,000 kg (52,800 pounds) more than the Stirling system.

The Brayton cycle has been selected by Lewis Research Center for the solar dynamic element of the NASA Space Station. With the implementation of the Station program, the technology base will have been established which would permit the use of this cycle in the lunar base with minimal technical risk. For the purpose of this study, however, the lighter Stirling system was used as the strawman for comparison with the candidate solar static system.

3.2.5 OPERATING MODE SELECTION

For accommodation of the relatively short dark period, it is impractical to consider shutting down and restarting a solar dynamic engine in a low earth orbit mission. The shadowing period is limited to slightly over one-half hour and the engine can remain on-line by storing thermal energy. In the case of the lunar base, the dark period is approximately 400 hours and the amount of energy that must be stored greatly magnifies the problem.

In order to maintain the engine on-line on the dark side, a Phase Change Material (PCM) in the vicinity of 1,100°K is required. Lithium fluoride, with a melting temperature of 1,121°K and a heat of fusion of 1,087 kj/kg (494 BTU/lb) is the most logical selection. Containment of decomposed lithium fluoride will require the PCM containment vessels to weigh about 4 times the weight of the PCM itself. As a result, the net specific energy available from storage of lithium fluoride will be approximately 217 kj/kg (99 BTU/lb).

An alternative to continuous operation would be to oversize the solar generation plant and store energy for night operations electrochemically. The electrochemical trades are already discussed in conjunction with the photovoltaic system, and the storage system would be identical to that required in conjunction with the solar dynamic system. The alternator output energy, however, will need to be converted to DC to be compatible with the RFC.

The energy balance required to maintain continuous generation is illustrated in Figure 8. The solar collectors will be required to intercept 766 kW. Assuming an efficiency of 90% for the concentrators, 401 kW would be transferred to thermal storage and 288 kW

Stirling Power Plant Energy Balance
Continuous Operation

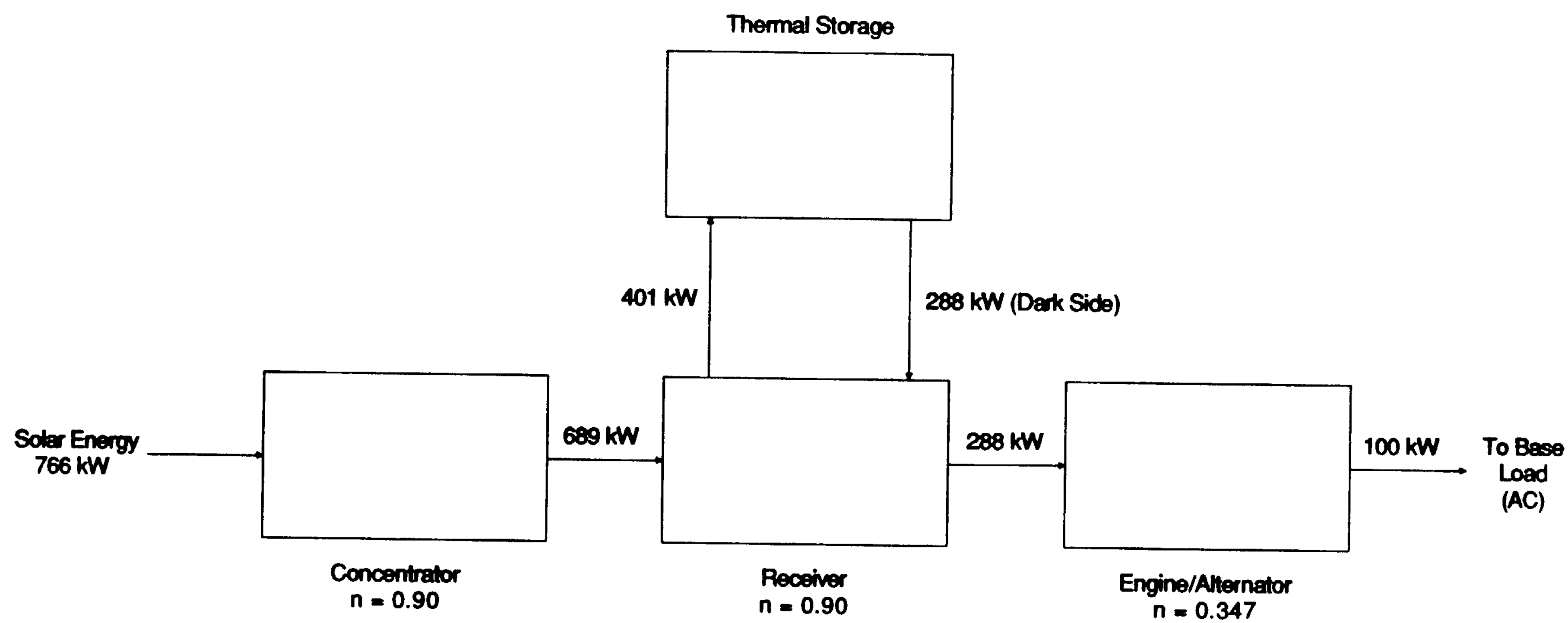


Figure 8

would be transferred to the engine heat exchanger. Assuming a 90% efficiency of retention by the thermal storage devices, 288 kW of thermal energy would be available for engine operation during the 394 hours when direct solar energy is unavailable.

A similar energy balance for intermittent operation is illustrated in Figure 9. In this case, the engines are sized to produce 379 kW during sunlight. After conversion to DC, 322 kW is available of which 222 kW is diverted to the RFC. The RFC, with an operating round-trip efficiency of 56%, supplies buss power during dark-side operation when the engines are shut down.

The resulting weights of the Stirling system in each of these approaches are listed in Table 7.

Table 7

Stirling Operational Mode Comparison

	Continuous, kg	Start/Stop, kg
Concentrators	4,437	7,973
Heat Receivers	1,598	2,587
Thermal Storage	2,100,940	------
Power Generation	1,158	4,396
EM Pump	239	908
Radiators	6,336	24,028
RFC's	------	44,589
TOTAL	2,114,708	84,481

Stirling Power Plant Energy Balance
Stop/Start System

Generating Mode 315 Hours
RFC Supply Mode 394 Hours

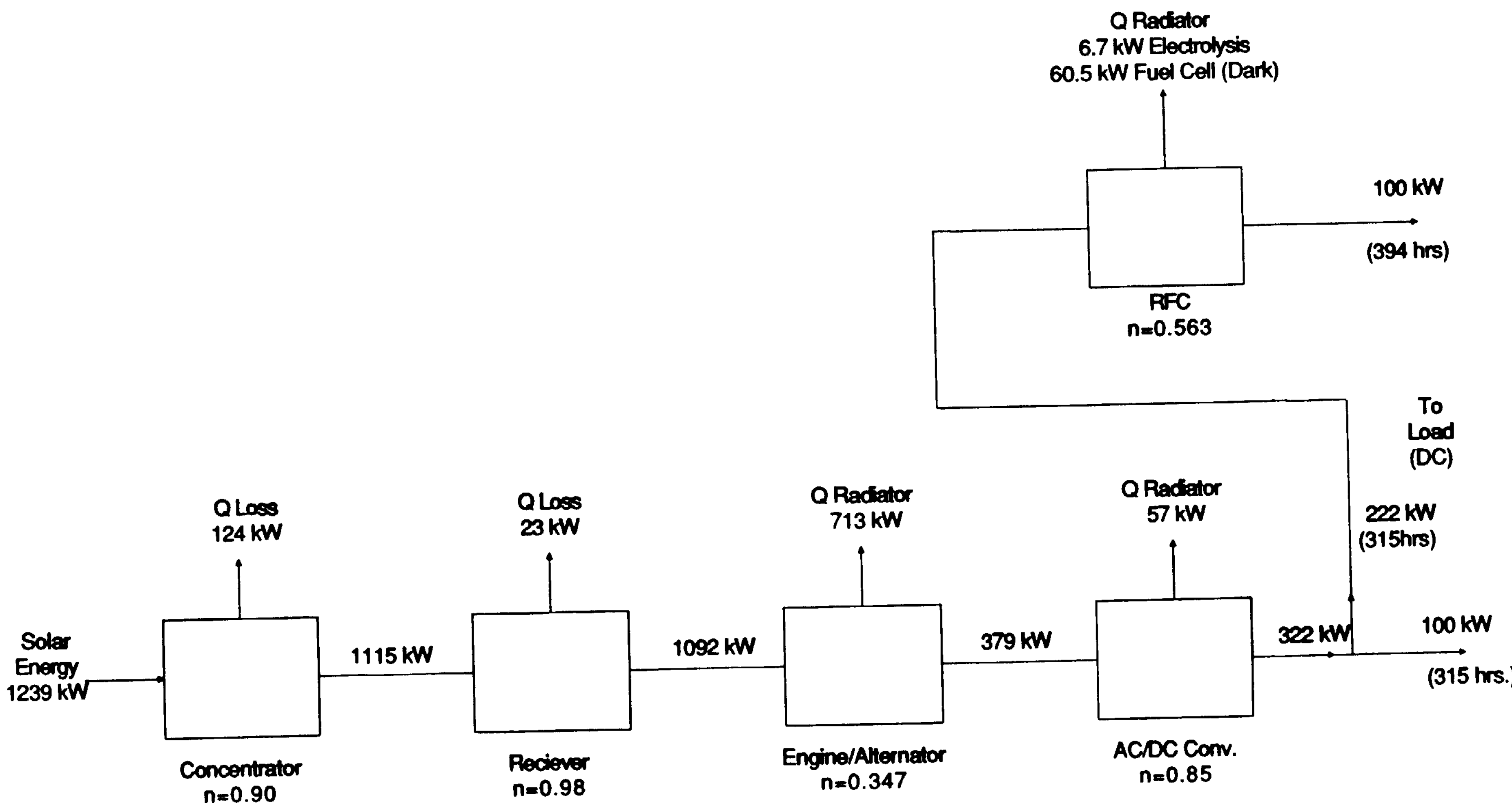


Figure 9

This analysis confirms that thermal storage, using materials that are transported from Earth is illogical. The system weight would be an order of magnitude greater than the intermittent operation of a larger generating and RFC storage system.

Fortunately, the Stirling engine can be started relatively easily if the working cylinder is vented to the crankcase until operating speed is achieved. The starter systems would be similar to the starting system on an automobile engine (Ref 7). The intermittent operation Stirling engine system, coupled with the regenerative fuel cell storage system, was selected as the strawman solar dynamic system.

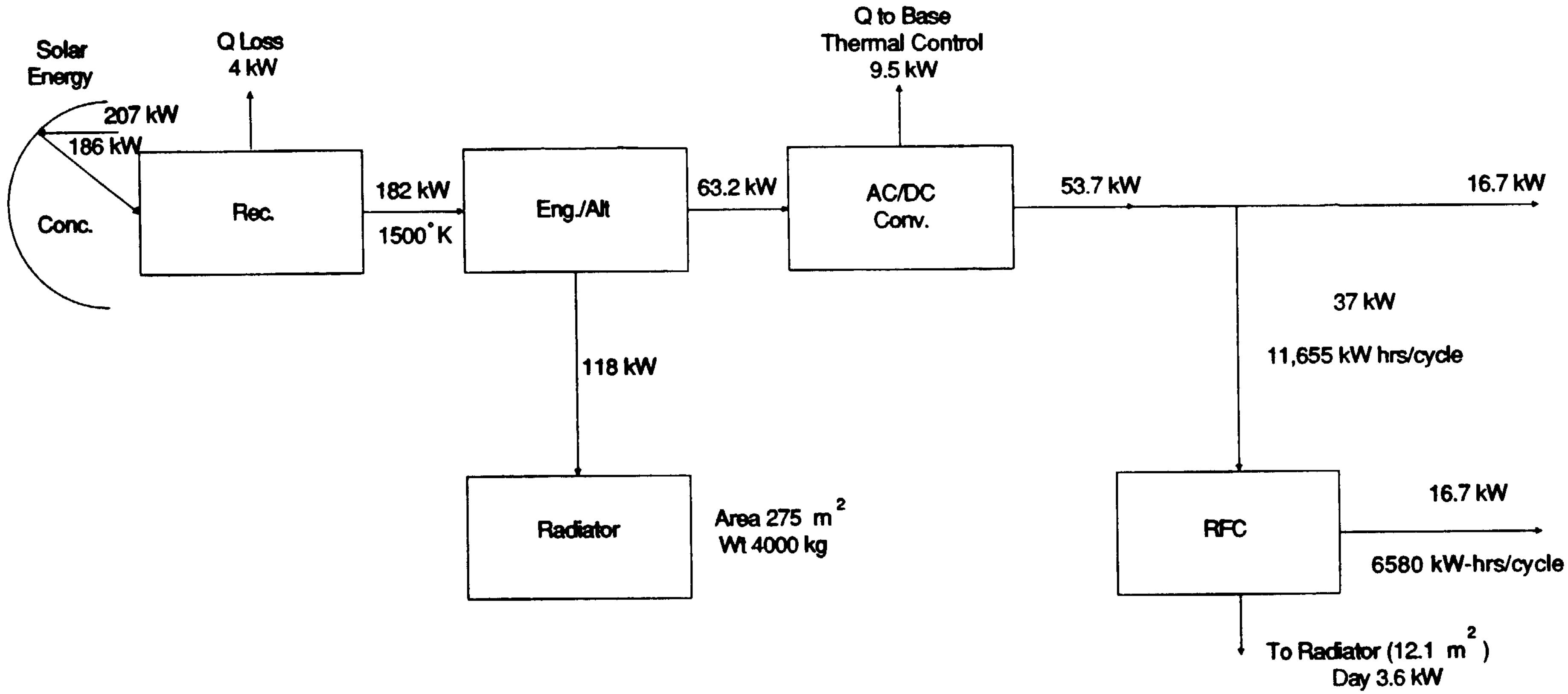
3.2.6 SOLAR DYNAMIC BASELINE

The dynamic power system is sized to generate sufficient energy in sunlight to power the base at 100 kW continuously. Electrochemical storage would use the same regenerative fuel cell technology as incorporated in the solar static system.

If the Brayton system is implemented for the Space Station, the Stirling would constitute a departure from proven technology. However, with continued advancement of the Stirling engine, the risk is not prohibitive and not taking advantage of the higher performance potentially available would unjustly penalize the solar dynamic system in this study.

As illustrated in Figure 10, six modules, each providing a net supply to the buss of 16.7 kW, are baselined for the solar dynamic system.

Stirling 16.7 kW Power Plant



	Concentrator	Receiver	Engine/Alt	AC/DC Conv.	RFC
Effic.	0.90	0.8	0.347	0.85	0.563
Size	Aperture Area 156 m^2		63.2 kW		
Wt (kg)	1390	431	787	108	7438

Figure 10

The concentrator would consist of 19 hexagonal panels with each panel containing 24 triangular reflector facets (Ref. 5). Of the 207 kW of solar energy intercepted by the collector, 10 % or 21 kW would be lost due to misalignment, imperfections, etc.

The receiver would use a heat pipe heat exchanger for transfer of the energy to the engine. Approximately 4.0 kW would be lost due to radiation through the receiver aperture and through the surrounding insulation.

The heat pipe system would transfer 182 kW of thermal power at 1,500°K to the engine. The alternator output would be 63.2 kW with the remaining energy dissipated primarily to the dedicated engine radiator.

The radiator would be mounted adjacent to the engine. As described earlier, the plane of the radiator would be located in the solar plane. In the interest of simplification, no credit was taken for heat rejection from the radiator side towards the equator. The radiator area would be 275 m^2.

The alternator output would be converted to DC with a loss of 9.5 kW. The direct contribution of each engine to the load would be 16.7 kW. The balance of 37 kW would be diverted to the electrolysis unit of the regenerative fuel cell system. For the 315 hour active generation period, the energy diverted to the RFC would be 11,655 kW-hrs. With a 56.3 percent round-trip efficiency, the energy available during the engine shutdown period for each of the six modules would be 6,580 kW or 16.7 kW for 394 hours.

All components of the dynamic system will be required to be protected thermally during the lunar night. This protection, however, is envisioned to be nothing more than an aluminized mylar blanket that can be withdrawn on a frame to expose the power plant. No attempt was made to determine the thermal requirements or weight of this device since it is assumed to be negligible compared to the power plant weight. It was also assumed that the fuel cell waste heat would be used, in part, to maintain reasonable temperatures in the idle power plant.

The module and total weights are summarized in Table 8.

Table 8

Mass Summary, Stirling System

Element	16.7 kW Module, kg	100 kW System, kg
Concentrator	1,329	7,973
Receiver	431	2,587
Engine/Alternator	733	4,396
EM Pumps, etc.	151	908
Radiator	4,005	24,028
AC/DC Convertor	108	648
RFC	7,432	44,589
TOTAL	14,189	85,129

Note that the solar dynamic module was based on a continous power supply of 16.7 kW while the PV module was selected at 25 kW. The size of the solar dynamic module was determined by the prevailing design of the Space Station concentrator. The 6 module system weight would be approximately 85,000 kg. The largest fixed component could be transported in a 4.58 m diameter cargo bay if necessary.

3.3 CONCEPT SELECTION

The system masses of the strawman static and dynamic concepts are summarized in Table 9.

Table 9

Strawman Comparison

Photovoltaic/RFC		Stirling Engines/RFC	
Element,	Kg	Element,	Kg
RFC:		RFC:	
Fuel Cell	860		
Elec. Cell	2,240		
H_2 Tanks	12,144	(Same as for PV/RFC)	
O_2 Tanks	7,260		
H_2O Tanks	2,256		
H_2O	19,708		
Radiator	121		
Subtotal	44,589		44,589
Solar Array	4,056	Solar Concentrators	7,973
		Receivers	2,587
		Engines/Alternators	4,396
		Radiators	24,936
		AC/DC Converters	648
Subtotal	4,056		40,540
TOTAL	48,645		85,129

Both systems use the regenerative fuel cell system, and for the 100 kW load, the RFC weight was determined to be approximately 44,600 kg. The weight discriminator, then, is in the power generation equipment with the dynamic system weighing approximately 35 MT more, or about 8 times that of the photovoltaic array. This is equivalent to approximately 1.3 times the payload mass of the Lunar Lander (25 MT) given in the study guidelines. The 100 kW PV/RFC system can be delivered to the moon in two trips, and the 25 kW modules, a reasonable increment for the power system buildup, would consume only one-half the payload capability, leaving equivalent mass space for other elements of the base.

Other factors considered were ease of deployment, maintenance and repair, and potential failure modes and their effects on the operations. The concentrators will require tight control tolerance in order to maintain accuracy of focus on the heat receiver. A failure in the tracking system will result in the complete loss of output from that module.

While there is a wide latitude for assessing the magnitude of differences between the reliability of static versus dynamic systems, there is no question but that this consideration favors the photovoltaic system.

Based on the weights, flexibility of erection, and simpler operation, the PV/RFC system has been selected as the optimum system to meet the guidelines of this study.

3.4 POWER PLANT DESIGN

The various elements of the power plant were analyzed very specifically as relates to area, power level, weight, etc. For the detailed description, arbitrary rounding of values were utilized where feasible in order to minimize usage of odd dimensions.

The layout assumes that the entire 100 kW power plant would be installed in 25 kW module increments.

3.4.1 PHOTOVOLTAIC ARRAY

In order to minimize the labor required to begin generating power at the base, a fixed flat plate array configuration was selected to be mounted on minimal structure to effect required surface stand-off dimensions, and utilizing the terrain essentially as found. This assumes that local selectivity of the installation area is an option upon arrival.

For the 100 kW system, 2,200 m^2 of GaAs cells would be required. For a 25 kW segment, 550 m^2 would be installed. The panels would be limited to 3 x 3 m in order to be compatible with the launch vehicle payload dimensions. The rows of panels could be installed in any direction initially, but should be oriented for ease of elevating the South end (or side) of the panels later if it becomes desirable to gain the additional 5% of power associated with the cosine loss at the 18° South latitude. Each segment of panels would provide 123 kW peak power for an effective power level (avg.) of about 78 kW. This would supply 7,875 kWh for daylight operations and 16,695 kWh for energy storage.

Individual cells would be arranged in electrical series and parallel banks as required to produce an output of 440 volts DC. This would impose minimal regulation requirements for use by the electrolysis cells, the largest consumer of the photovoltaic output.

3.4.2 REGENERATIVE FUEL CELLS

The RFC is separated into two discrete units, viz., a fuel cell section and an electrolysis cell section. The location of both units would be side by side and near the power leads from the solar array, in order to minimize line distances and for ease of exchanging waste heat during the respective operating cycles. As the power plant grows, each 25 kW modular RFC and 550 m^2 segment of solar cells would independently increase the available power to the base. In cases of failure in a module or maintenance requirements, the balance of the power plant is not impacted when one unit is removed from the grid.

3.4.3 REACTANT STORAGE SYSTEM

The reactant storage system consists of three tanks approximately 2, 3, and 4 m diameter. These tanks would be buried near the cells in order to minimize thermal cycling and related pressure swings due to the temperature effects on pressurized gas. An additional tank is required to provide a small, high-pressure volume of water for the electrolysis cell. The fuel cell produces H_2O at approximately 400 kpa (~60 psi) and it is stored in the 2-m diameter tank at equivalent pressure. The electrolysis cell operates at approximately 20,000 kpa (~3,000 psi) and must be supplied feed H_2O at equivalent pressure. The feed H_2O tank is pressure-referenced to the O_2 tank in order to maintain proper balance, and a small, pressurizing pump transfers H_2O from the storage tank to the feed tank on a demand basis as signaled by level sensors in the feed tank. The pump and feed tank may or may not be buried but would need to be temperature protected.

3.4.4 RADIATORS

The bulk of heat generation is associated with the fuel cells, which operate during the lunar night when the heat can be utilized. Both the fuel cell and electrolysis cell operate at about 82°C, therefore the temperature of each would ideally be maintained constant as thermal cycling has the greatest impact on operating life. A heat exchanger would be integrated with the common heat transfer fluid of the fuel and electrolysis cell. The exchanger would be integrated with a separate fluid to the radiator, which for the 25 kW module, is 6 m^2. The radiating surface would be parallel with the sun's rays, facing the South pole. No credit was taken for the effect of the North face of the radiator panel.

During the lunar day, the electrolysis cell is operational but the heat load is only about 5.4 kW.

Figure 11 illustrates the Lunar Solar Power Plant.

3.4.5 INITIAL DEPLOYMENT

The logistics guidelines given were the HLLV's would be either 4.56 m (15 ft) or 9.15 m (30 ft) diameter, and that the maximum lunar lander payload would be 25 MT (55,000 lbs). While it seems likely that the larger vehicle would be available at the turn of the century, the smaller version was selected for sizing of the various pieces to be delivered to the moon. The solar panels, the most difficult volume driver, were therefore limited

Lunar Power Plant

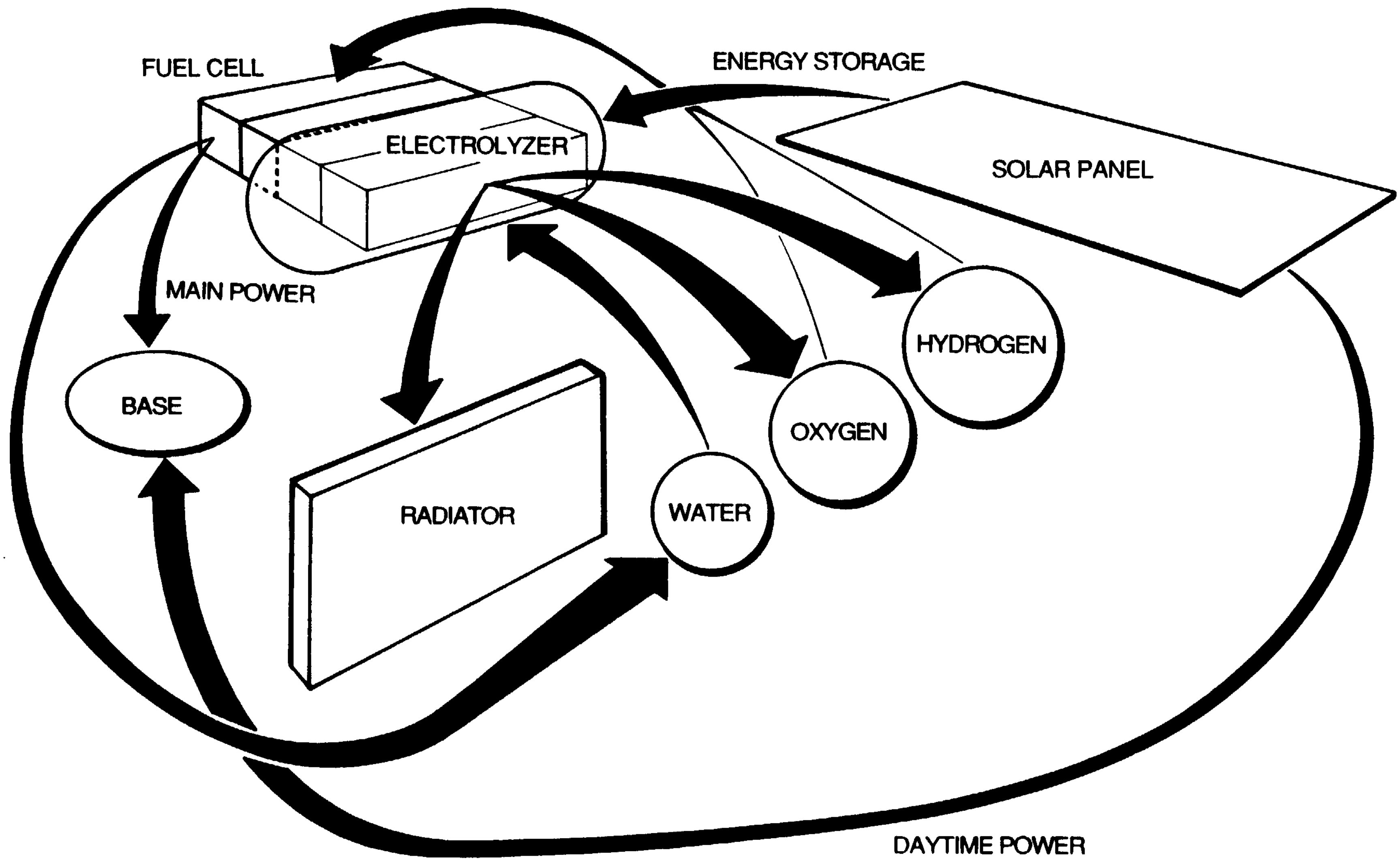


Figure 11

in size to 3 x 3 m in a foldup configuration. The diameter of the largest tank (H_2) is 3.81 m, the smallest, 2.07 m. The weights are: 2,898 kg H_2; 1,739 kg O_2; 5,657 kg H_2O. These dimensions dictate regolith-moving equipment and a forklift and/or a crane for equipment handling. It is assumed that such equipment will have been delivered and basic preparations made before arrival of the first PV/RFC module.

Assuming that the first module is landed near lunar dawn, the first priority will be to deploy the solar array to furnish support power. The RFC would then be installed and placed on the line. A more intensive study of base buildup is required to determine if the first lunar night power demand can be supported solely from reactants generated on the lunar surface after the solar array of the power plant is activated. It may be necessary to reduce the amount of water transported, and carry an equivalent amount of gaseous H_2 and O_2 in order to meet these requirements.

At approximately 50 MT total weight for the 100 kW system (Table 5), the 25 kW module weight is exactly 1/4, therefore, a module is completely transportable in one trip at 12.5 MT. Thus, equivalent payload mass capability is available for other elements of the base.

3.5 CONCLUSIONS AND RECOMMENDATIONS

The best available concepts for a 100 kW Solar Lunar Power Plant based upon static and dynamic conversion concepts have been examined. The two concepts which emerged for direct comparison yielded a difference in delivered mass of 35 MT, the mass equivalent of 1.4 lander payloads, in favor of the static concept.

The technologies considered for the various elements are either state-of-the-art or near-term, therefore, significant technology advancements are not required to implement the system, but certain advancements should be considered in order to capture potential pay-off's for the use of other options.

For example, two photovoltaic cell concepts should receive high priority for development; viz., the amorphous silicon and the indium phosphide cells. The amorphous silicon, because it can be made so light weight and rugged; and the indium phosphide, because it shows very high efficiency potential and is reportedly not degraded by radiation. Also the amorphous silicon cells may be mounted on flexible backing that may be rolled up much like a carpet for compact storage, delivery, and ease of deployment at the base.

The fuel cell and electrolysis cell technology is quite well along for the lunar base applications, and because both the Shuttle and the forthcoming Space Station incorporate these devices, the "status quo" will at least be maintained. However, due to the long, uninterrupted operational life requirement imposed by the lunar base, early development of emerging improvements should be implemented so that essential life verification test programs can be commenced. In devices of this sort, no way has been discovered that will short circuit the one-for-one life test requirement, and a factor of two or three in life demonstration over mission requirement is desirable, especially if safety is involved.

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