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Hierarchical Analysis of Options for Lunar-Surface Power

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A decision analysis study was conducted to evaluate potential habitat power concepts for manned lunar-surface operations. The objectives of the study were to rank alternative lunar-surface power systems for the first lunar outpost (FLO). The six alternative power concepts evaluated are the following: photovoltaic with regenerative fuel cell (RFC) storage, solar dynamic with RFC storage, TOPAZ II and SP-100 space reactor systems, dynamic isotope power system (DIPS), and laser-beamed power. The analytical hierarchy decision-making process was used for the decision-making methodology. The process provides a systematic approach to managing complex decisions that involve numerous tradeoffs between alternative concepts and evaluation criteria. Safety, risk, performance, lifetime, supportability, special factors, and versatility were selected as the major evaluation criteria. Based on the available information, DIPS was the power system of choice for a 45-day, 12-kWe FLO mission because of its favorable combination of ranking and cost. When launch costs were not considered, the photovoltaic system with RFC storage ranked first. The results of this study reflect the best judgments of the working group, given the set of requirements, the agreed-on set of selection criteria, and the best available concept information.

Introduction

POWER concepts for the first lunar outpost (FLO) and subsequent lunar and Mars manned surface operations were evaluated by the Lunar-Surface Power Working Group. The working group, consisting of mission planners and power system technology specialists, utilized a formal decision-making process to accomplish the evaluation. The overall objectives of the study of these power concepts are to rank alternative lunar-surface power systems using the analytical hierarchy process (AHP),[1] and to summarize surface power system data. The 10-person working group, listed in Table 1, met for five days to review the mission and power requirements, define feasible power alternatives, develop evaluation metrics, review the status of the alternatives, rank the alternatives, and compare relative cost estimates. This article summarizes the mission requirements, power system information, cost estimates, and evaluations generated by the Lunar-Surface Power Working Group.

Mission Description

The nominal FLO mission will consist of a crew of four on a nominal 45-day stay, lasting 1 lunar night and 2 lunar days. An outfitted habitat will be delivered on a cargo flight followed by a piloted flight approximately six months later. After establishing residence in the habitat, the crew will conduct lunar surface science and exploration activities. Major mission objectives will include the setup of astronomy stations, the conducting of geoscience research, and the extraction of potential resources from the lunar regolith. The crew will deploy remote stations and traverse the lunar surface in a rover. For the first time, humans will face the reality of long-term, isolated operations in the lunar environment. A reliable power supply will be crucial to crew safety and mission success. The requirement for continuous power over the long (354 h) lunar night is a major difference between this mission and previous Apollo missions, during which primary batteries were adequate to meet power needs. Immediately upon landing, the mission crew will need a habitat with the power required to maintain equipment that sustains life, monitors health, controls temperature, and makes communication possible. Details on the FLO mission and its power requirements are given by Cataldo.[2]

First Lunar Outpost Power Requirements

The working group focused on habitat power requirements. The FLO power system could evolve to Mars systems with compatible technologies. The habitat must provide power for the lander, rovers, scientific activities, and in situ resource utilization. The first lunar mission is assumed to occur between 2000–2005, and the first piloted Mars flight in approximately 2016. The following requirements were provided: 1) a crew of four and a 45-Earth-day duty cycle, 2) 12-kWe peak power for the habitat and 2 kWe for housekeeping, 3) 25 kWe for lunar outpost expansion and 40 kWe for the first Mars outpost, 4) 100s kWe for in situ resource utilization, 5) 50-mSv radiation dose limit, 6) 3-yr lifetime, and 7) a mass constraint of 5700 kg and a volume constraint of 31.5 m^3.

These proposed requirements represent the best thinking of NASAs Exploration Office at the Johnson Space Center in November 1992.[2] Requirements must be carefully stated because they can drive the decision on power systems. Since requirements are always subject to change, this study treats the requirements as guidelines. For example, constraints kept power as low as practical to support the FLO mission. However, if minimum power were increased to 30 kWe, some of the systems considered would not be viable.

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Table 1 Lunar-surface power working group members

Member	Affiliation	Expertise
John Benner	National Renewable Energy Laboratory	Solar systems
John Bozek	NASA/Lewis Research Center	Beamed power/systems
Dave Buden	Idaho National Engineering Laboratory	Nuclear/TOPAZ II
Bob Cataldo	NASA/Lewis Research Center	Missions/systems
Alex Dula	NASA/Johnson Space Flight Center	Missions
Nate Hoffman	Energy Technology Engineering Center	System integration
Ed Mastal	DOE/Nuclear Energy	Isotope power
Paul Nelson	Argonne National Laboratory	Regenerative fuel cells
Lyle Rutger	DOE/Nuclear Energy	Nuclear/SP-100
Mike Schuler	USAF/Phillips Laboratory	Power systems

Decision-Making Process

The AHP was used for the decision-making methodology. The AHP, developed by Saaty,[1] provides a systematic approach to managing complex decisions that involve numerous tradeoffs between criteria and alternatives. The logic permits a group of decision makers to focus on individual parts of a complex problem and to derive global priorities from pairwise comparisons between local components.

The pairwise comparisons accomplished through AHP consisted of three steps. In step 1, we defined the problem and identified feasible alternative solutions. The problem was to evaluate potential habitat power concepts for the FLO and for subsequent manned lunar and Mars surface operations. Six power concepts—photovoltaic (PV) with regenerative fuel cell (RFC) storage (PV/RFC), solar dynamic (SD) with RFC storage (SD/RFC), TOPAZ II and SP-100 (space reactor systems), dynamic isotope power system (DIPS), and laser-beamed power—were identified as feasible alternatives that would satisfy mission power requirements. The goal of this study was to use a set of criteria chosen by the working group in order to select the best of the six alternatives and rank the others. Step 2 was to break down the problem into separate, clearly defined criteria. The major criteria were further divided into subcriteria, thereby developing a hierarchy tree of metrics. After defining the criteria, the working group had to reach a consensus on the relative importance of each one of a pair of criteria. Based on this pairwise comparison, AHP derives numerical values of weights for all criteria on a relative scale. The process determines if the criteria are consistently compared, and the experts can reconsider their evaluations to improve consistency. Step 3 was to conduct pairwise comparisons of the alternative concepts. The working group conducted a one-on-one comparison of each of the alternatives against the weighted criteria and subcriteria. Some criteria, like system mass, had real design data and were quantitatively compared. Others, such as deployability, were more difficult to evaluate because the comparisons had to be based on subjective arguments. The process then synthesized all the information and determined the best alternative and relative ranking of all concepts.

Evaluation Criteria

Safety, risk, performance, lifetime, supportability, special factors, and versatility were selected as the major evaluation criteria. Safety was defined as the potential to reduce impact to health, life, and the environment to a minimally acceptable level. All systems had to meet minimum safety standards to be considered; however, some systems may pose a greater potential risk to the crew. Safety was judged to be worth 25% of the FLO power system decision. Risk, defined as the probability of successfully completing the goals of the program, was judged to be worth 23% of the decision. Performance, the ability of system characteristics to meet requirements, was worth 16% of the decision. Lifetime, the projected and demonstrated system life over full mission requirements, was worth 11%. Supportability, the ability of the system to support mission objectives, was worth 14%. Special factors, issues related to public acceptability, including the potential for spinoff technologies and public perception issues, was given a worth of zero. The working group thought that while special factors could be decisive criteria, they are not technically based and evaluation should be left to others. Versatility, the adaptability of the system to support other missions and requirements, was worth 11% of the decision. Clear definitions of the criteria are required for confidence in the decision analysis. The agreed-on definitions of the criteria are listed in Table 2.

The agreed-on hierarchical decision tree, with subcriteria, is displayed in Fig. 1, where the numbers are the criteria weights based on the pairwise comparison of the criteria. Launch safety was judged to be the single most important criterion because the safety of the crew and the public must be protected above all other requirements. Interestingly, programmatic risk was judged to be the second most important criterion because a power system that jeopardized the future of the program was not worth developing.

Power System Descriptions

Lunar-surface power system concepts can be divided into three basic categories according to their prime energy source: 1) nuclear power systems, 2) solar power systems, and 3) systems that draw their primary energy from other sources such as chemical reactions. Seventeen surface power system options that potentially could meet the FLO mission power requirements were identified. The concept options are listed in Table 3 according to their prime energy source.

The working group reviewed each of the options available. Two solar concepts, three nuclear concepts, and one power-beaming concept were selected for evaluation. To ensure consistency in mass and cost estimates, we broke each concept down into the following subsystems: energy source, energy conversion, energy storage, thermal management, power management and distribution, instrumentation and controls, deployment, and startup power. The concepts and relevant data are summarized in Table 4.

The nuclear concepts divide into radioisotope systems and reactor systems. DIPS was chosen over thermoelectric because of the higher conversion efficiency and, therefore, lower plutonium inventory. The DIPS surface power system consists of 2.5-kWe modules using encapsulated Pu^{238} heat sources with a closed Brayton cycle power conversion unit. Integrated system designs have been developed for lunar-surface power units.[4] The working group decided to include TOPAZ II[5] and SP-100[6] reactor systems because of their relatively high technology readiness level. TOPAZ II is a 6-kWe, UO_2-fueled, NaK-cooled, ZrH-moderated, thermal spectrum Russian reactor that uses in-core thermionic conversion for electricity production. The system has been ground tested in Russia and is currently being modified for U.S. operation. The SP-100 reactor is a 100-kWe, UN-fueled, Li-cooled, fast-spectrum reactor with a Brayton, Stirling, or thermoelectric conversion system. The SP-100 system has been under development for potential defense and civil missions. Both TOPAZ II and SP-100 include a 2-kWe, PV/RFC system needed for startup prior to deployment. The reactor systems are assumed to be de-

Table 2 Definitions of criteria

Safety: Reduce impact above a minimally acceptable level
Operating safety: Lack of adverse impacts on crew and equipment
Launch safety: Safety from prelaunch through landing on the lunar surface
Environmental safety: Likelihood of contaminating the lunar and/or Earth surface
Risk: Probability of successfully completing the goals of the program
Schedule risk: Likelihood of meeting the schedule
Technical risk: Likelihood of hardware meeting the performance and mission requirements
Program risk: Likelihood of meeting program management objectives
Performance: Hardware characteristics
Reliability: likelihood of meeting performance requirements over the life of the system
Mass: weight of the total power system, support systems, and consumables
Dimensions: deployed footprint
Duty cycle: ability to meet or exceed the power specifications
Robustness: ability to continue to operate despite failures
Lifetime: Projected and demonstrated system life over full mission requirements
Projected: analytical extrapolation of lifetime
Demonstrated: experimental or historical data relating to lifetime
Supportability: Ability to support mission objectives
Produceability: ease of production and manufacturing
Deployability: ease of going from launch configuration to operations configuration
Operational: minimization of crew and ground interaction
Maintainability: ease of maintaining operation
Testability: ease of verifying function prior to launch and on the moon
Resource consumption: materials involved in the use and maintenance of the system
Disposal: removal and/or storage of materials in an acceptable manner
Special factors: Issues related to public acceptability
Spinoff: a positive contribution to industry and stimulate economic growth
Public perception: ability to garner public support
Versatility: Adaptability for support of other requirements
Scalability: expansion within one order of magnitude
Growth: expansion greater than two factors
Mission commonality: ability to support other missions (space station, Mars)
Element commonality: ability to support multiple applications

ployed at a distance from the habitat and shielded in regolith to reduce radiation exposure of the ground crew.

Direct conversion and thermal heat engine conversion were selected as the representative solar power systems. Direct solar conversion utilizes a PV material to produce electricity. Since the PV cells and their array comprised a small portion of the overall system, the panel felt the actual PV material chosen would have little impact on the outcome of the trade study. On the other hand, the energy storage technology would have a significant impact because of large volume and mass. The decision was made to baseline the same solar array technology used on the Space Station. Both battery and mechanical energy storage, no matter how advanced, were deemed too massive to be viable energy storage approaches. Therefore, the system chosen was PV/RFC.

Oxygen/hydrogen fuel cells with either high-pressure or cryogenic reactant storage were selected as the RFC technology. During the lunar day, PV energy is used to support normal base operations and to electrolyze water. During the lunar night, the stored reactant gases are used in the fuel cell to generate electric power. The system evaluated included a fuel cell, regenerator, and reactant storage components. The panel felt that the major difficulty would be reactant storage since this occupies over 95% of the system volume and greater than 60% of the system mass. Three options were discussed: 1) using separate high-pressure storage tanks, 2) using two of the descent propellant tanks modified to handle high-pressure storage, or 3) using cryogenic reactant storage in the two propellant tanks. Option 2 was used as the baseline.

The SD system uses optics to focus solar energy on a thermal receiver, which in turn transfers heat to the heat engine that converts the thermal energy to electricity. The SD concepts the panel considered varied only in the dynamic conversion system used. The panel felt that the specific choice of dynamic conversion technology would not significantly impact the trade study; a Brayton cycle conversion system was baselined. Passive heat engines were discussed but not chosen because of the early need date anticipated for FLO and the potentially rough environment, launch, and landing the FLO power system must endure. Significant interest was shown in an SD power system that utilized in situ thermal energy storage; however, thermal storage was rejected because of the lack of system definition and design.

Two other concepts were considered: 1) a hydrogen/oxygen primary fuel cell with either high-pressure or cryogenic reactant storage and 2) Earth-based laser power transmission (laser beam power). The primary fuel cell was not chosen because of its high system mass in the stored reactants and tankage. Power beaming[7] was discussed at length, and the working group decided to include it as the representative advanced system. The system consisted of multiple Earth-based sites employing 0.8-μm-wavelength, high-power lasers and adaptive optics for transmitting power to a tuned monochromatic PV receiver on the lunar surface. An emergency keep-alive energy source was included in order to accommodate single-transmitter site outage or unavailability. Although a highly speculative system, power beaming provided the least-mass system and the one with the greatest versatility and potential for growth.

Table 3 Potential FLO surface power system concepts

Nuclear	Solar	Other
Reactor	Photovoltaic	Primary fuel cell
SP-100 with thermoelectric	Regenerative fuel cells	High-pressure storage
SP-100 with Brayton cycle	Batteries	Cryogenic storage
SP-100 with Stirling cycle	Flywheels	
In-core thermionics		Energy Transmission
TOPAZ II	Dynamic	Laser power beaming
Radioisotope	Brayton cycle and RFC	
	Stirling cycle and RFC	
Thermoelectrics	Rankine cycle and RFC	
Brayton cycle		
	Thermal	
	Dynamic conversion and in situ thermal storage	

Table 4 Surface power system concepts selected for evaluation

Concept description	Launched mass, kg	Launched volume, m^3	Projected lifetime, yr	TRL[a]
PV/RFC	4749	25	5	4
SD (Brayton cycle)	4495	39	5	3
Dynamic isotope (Brayton cycle)	1480[b]	19	5	6
SP-100 dynamic (Brayton cycle)	2588	14	7	5
Thermionic TOPAZ II	4087[c]	14	15	6
Laser power beaming	469	1	10	1

[a]Technology readiness level[5]. [b]Four 2.5-kWe units. [c]Two 6-kWe units.

Table 5 Lunar-surface power system cost ($M)[a] and mass estimates

	PV/RFC	SD/RFC	DIPS	SP-100	TOPAZ II	Beamed power
Nuclear material			221			
Facilities				53	5	176
Development	223	443	89	155	200	402
Safety			12	32	10	
Production	212	108	171	89	50	21
Startup				60	60	
Operations						202
Management	61	77	55	83	40	18
Subtotal (cost)	496	628	548	451	360	819
Mass (kg)	4749	4495	1480	2588	4078	469
Launch (cost)	418	396	130	228	359	41
Total (cost)	$914	$1024	$678	$679	$719	$860

[a]Cost in millions.

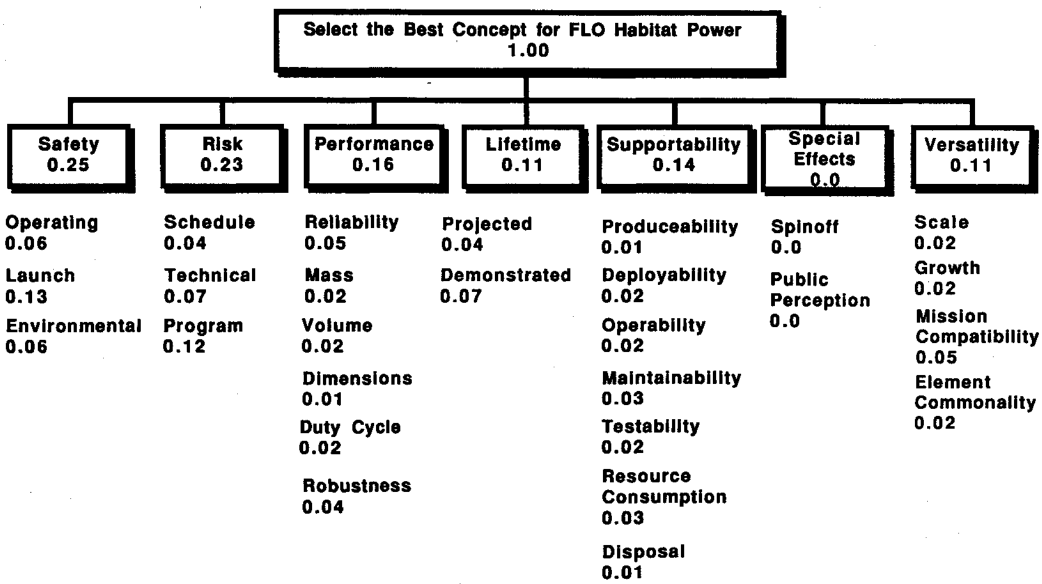

Fig. 1 Hierarchical criteria tree with first and second tier criteria; the numbers represent the value of the criteria weights.

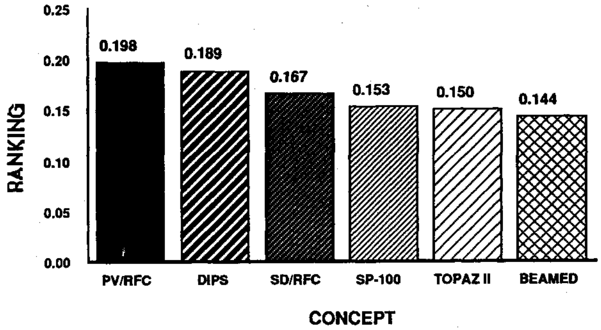

Fig. 2 Summary of pairwise comparison results.

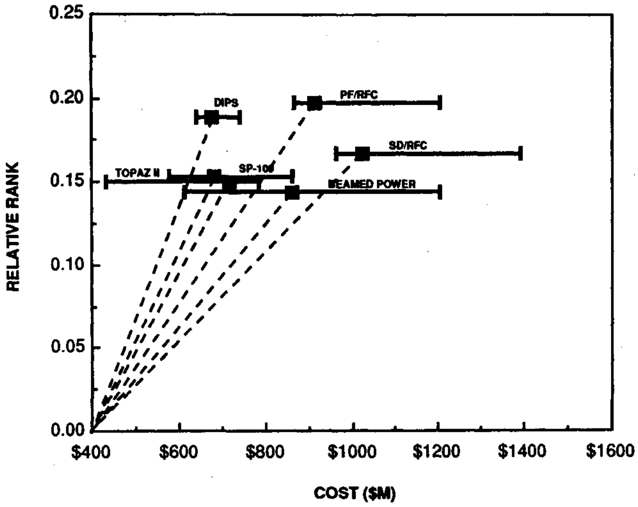

Fig. 3 Concept relative ranking as a function of cost.

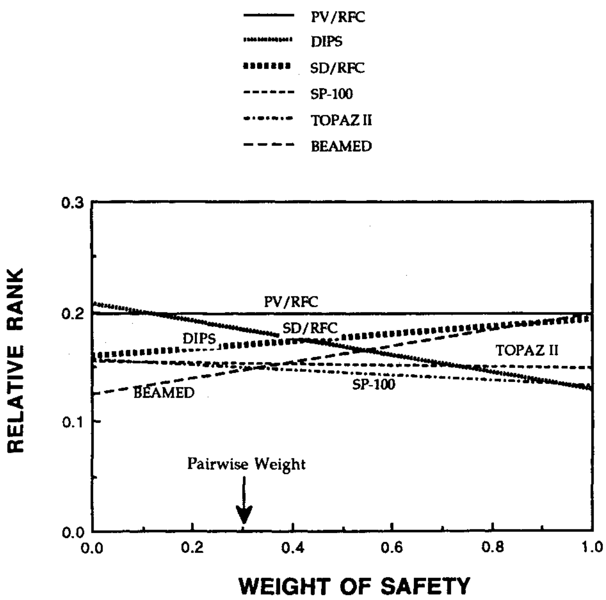

Fig. 4 Gradient sensitivity of surface power concepts with respect to safety.

Cost Comparisons

Concept costs included estimates for materials, facilities, technology development, safety, unit production, management, launch, and operations for a 3-yr mission. Accuracy of the cost estimates might be challenged because of the lack of detail in concept descriptions and the inconsistency of estimating techniques. Research, development, testing, and procurement costs should be separated to permit more careful comparisons. The system descriptions also need to be expanded, and parallel sources of funding for similar systems also need to be identified before an adequate cost can be established. In addition, cost estimates were not supplied at the same level of detail. For example, TOPAZ II costs included a flight validation estimate; no other system included a test flight.

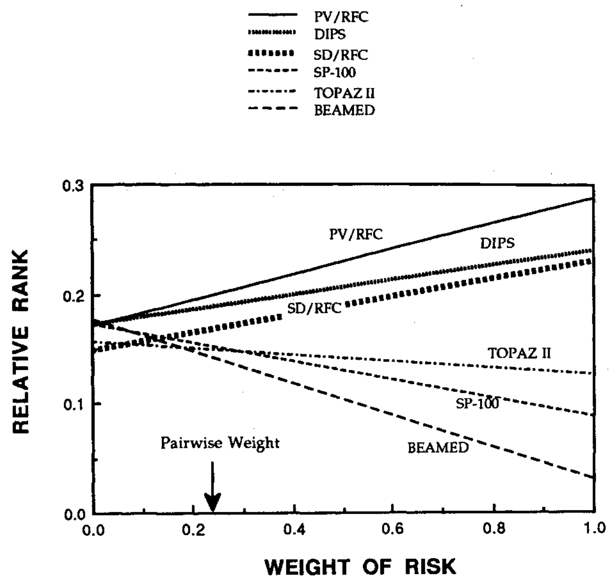

Fig. 5 Gradient sensitivity of surface power concepts with respect to risk.

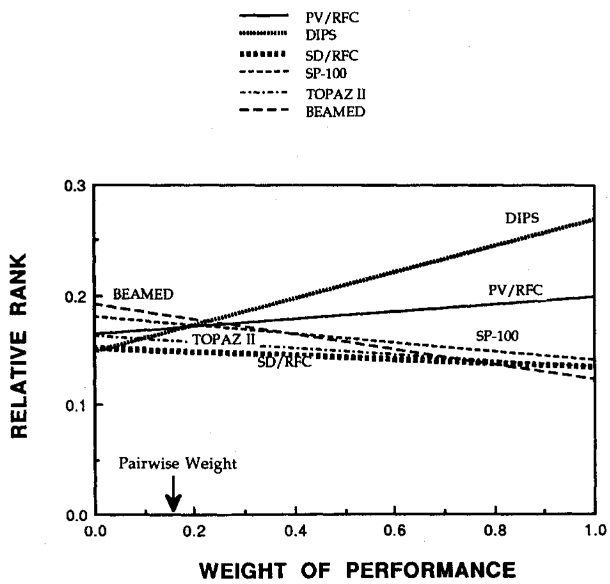

Fig. 6 Gradient sensitivity of surface power concepts with respect to performance.

Unfortunately, time did not permit a detailed evaluation of the fidelity of the cost estimates; only after a more detailed look at costs should cost data be applied to a final decision process. Nevertheless, relative cost comparisons, based on the best available information, were considered valid for this exercise. Launch costs, assumed to be $88,000/kg, were a major component of total costs; therefore, system mass proved to be a principal cost driver.

Table 5 summarizes the cost estimates in constant fiscal year 1993 dollars. The subtotal gives the estimated cumulative costs up to the delivery of the system for launch. The total cost approximates life-cycle costs through 3 yr of operation. This total cost was the most likely forecast based on input data for high and low life-cycle cost estimates.

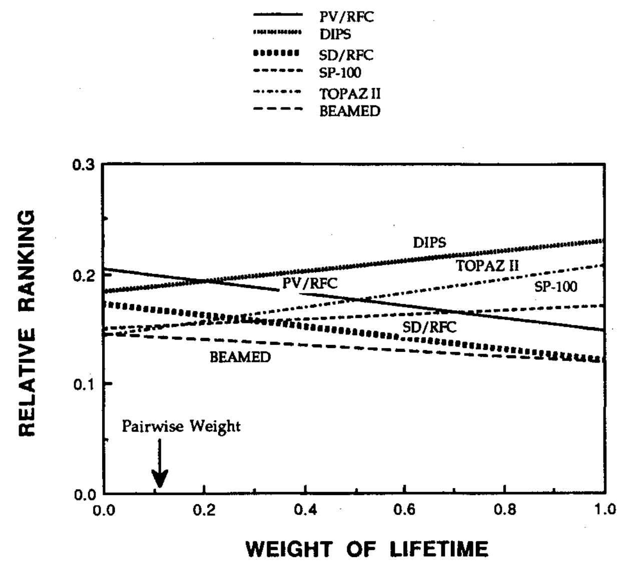

Fig. 7 Gradient sensitivity of surface power concepts with respect to lifetime.

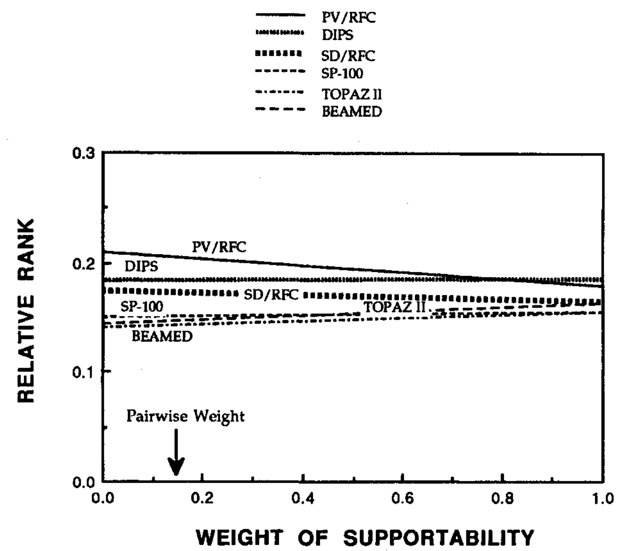

Fig. 8 Gradient sensitivity of surface power concepts with respect to supportability.

Ranking Concept Alternatives

Each of the concepts was evaluated against the criteria through the use of the AHP pairwise comparison method; Fig. 2 summarizes the results of the pairwise comparison of the alternatives. The most significant insight from the rating proved to be an understanding of the relative differences between concepts. Some general trends became apparent after the information was reviewed.

The solar power systems analyzed are large and bulky because of the amount of high-pressure, gaseous oxygen and hydrogen required for the regenerative fuel cell reactants. PV arrays may have problems, especially in a dusty environment. However, solar power systems are attractive for the initial habitat because of availability, low risk, and safety considerations.

Isotope power systems have limited power growth potential and are subject to the uncertainty of Pu^{238} availability. The DIPS system has a mass and lifetime advantage over the other concepts. Isotope systems may also be used for remote power, transportation, and habitat backup.

Nuclear reactor systems must be deployed at a distance from the habitat in order to provide the exclusion area needed

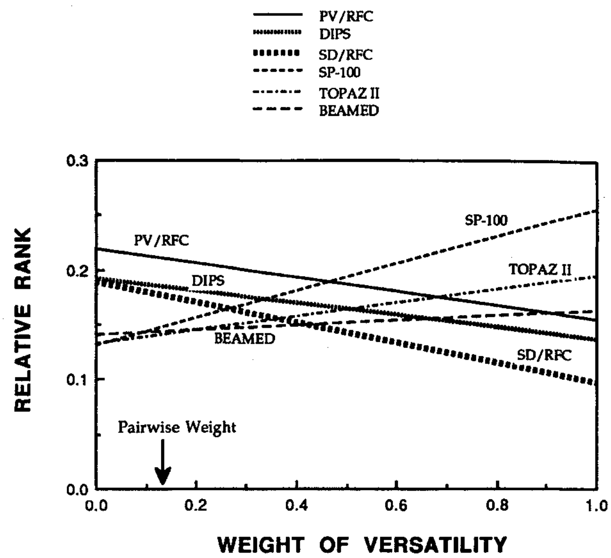

Fig. 9 Gradient sensitivity of surface power concepts with respect to versatility.

for avoiding radiation effects. Both SP-100 and TOPAZ II systems offer low mass and excellent growth potential. Reactor systems would probably not be selected for a circa 2002 FLO mission because of potential programmatic risks but will be favored for extended lunar outposts and Mars missions.

Power beaming concepts have availability and performance uncertainties. While it appears premature to consider this technology for FLO, power beaming could become viable for permanent lunar outposts because growth potential is high and launch mass will be relatively small. In addition, beamed power has the potential benefit that most maintenance will be limited to terrestrial components.

The relative concept rankings are plotted as a function of estimated life-cycle cost in Fig. 3. Based on the available information, DIPS, with its favorable combination of ranking and cost, would be the power system of choice for 12-kWe FLO requirements. Public perception issues and Pu^{238} availability could reverse this conclusion. When launch costs were not considered, the PV/RFC system ranked first because it has the highest ranking with low development and production costs.

Sensitivity Analysis

The AHP permits sensitivity analyses to determine the effect of changing criteria worth on the ranking of the concepts. The effects of changes in criteria assumptions are summarized in the sensitivity analysis plot in Figs. 4–9. The weight derived from the pairwise comparisons is indicated on each figure. The sensitivity plots enable a decision maker to understand the implication of overriding the judgments made by the group of experts. Increasing the worth of safety favors nonnuclear systems because of radioactivity release concerns (Fig. 4). Increasing the worth of risk favors the established technologies (isotope and solar) because of the increased potential for success (Fig. 5). DIPS becomes a stronger candidate when the worth of performance is increased because of favorable mass and reliability characteristics (Fig. 6). Increasing the worth of lifetime favors TOPAZ II and DIPS because their lifetimes have been demonstrated (Fig. 7). None of the systems were particularly sensitive to increases in the worth of supportability because of the lack of real data on using lunar-surface power systems (Fig. 8). Because of their power growth potential, nuclear reactor power systems become stronger candidates when the worth of versatility is increased (Fig. 9).

Conclusions and Recommendations

The AHP for decision-making is a valuable decision-making tool for focusing discussion on system options because it leaves a traceable record of the evaluation process, permits evaluation with incomplete data, allows relative comparisons, and clearly identifies areas of weakness. The methodology is best for forcing decision makers to think about all of the important factors influencing a decision. The process should be used for evaluation of technology options as missions, concepts, and costs become better defined. Although the AHP provides a structured means for evaluating decisions and choosing among alternatives, there are some cautions for the use of this method.

The apparent accuracy of the ratings is not matched with design details; therefore, one should be careful about placing too much credence in the precise nature of the AHP results. Changes in assumptions can dramatically alter the results, and the FLO mission is still in the early stages of definition, a time when requirements can change dramatically. Therefore, conclusions represent only a preliminary evaluation. Nevertheless, the trade study yielded the following conclusions:

1) DIPS would be the system of choice for the FLO because of its low mass and advanced state of development.

2) Solar PV/RFC would be the system of choice if the system mass and subsequent launch costs were not so high.

3) Because of their ability to grow in power, nuclear reactor systems would be chosen if the Mars mission were the prime goal.

Acknowledgments

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