NASA Technical Memorandum 102063

Challenges for Future Space Power Systems

(NASA-TM-102063) CHALLENGES FOR FUTURE SPACE POWER SYSTEMS (NASA. Lewis Research Center) 6 p
N89-25506
CSCL 10B
Unclas
G3/44 0210307

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Prepared for the
European Space Power Conference
sponsored by the European Space Agency
Madrid, Spain, October 2-6, 1989

NASA

CHALLENGES FOR FUTURE SPACE POWER SYSTEMS

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E-4820

ABSTRACT

The future appears rich in missions that will extend the frontiers of knowledge, human presence in space, and opportunities for profitable commerce. Key to success of these ventures is the availability of plentiful, cost effective electric power and assured, low cost access to space. While forecasts of space power needs are problematic, an assessment of future needs based on terrestrial experience has been made. These needs fall into three broad categories - survival, self sufficiency and industrialization. The cost of delivering payloads to orbital locations from LEO to Mars has been determined and future launch cost reductions projected. From these factors, then, projections of the performance necessary for future solar and nuclear space power options has been made. These goals are largely dependent upon orbital location and energy storage needs.

Keywords: space power, solar, nuclear, launch costs.

1. INTRODUCTION

One of the most vexing problems inherent in the utilization of space is to accurately forecast the amount of power necessary to perform useful tasks and to meet mission objectives. It seems that nearly every satellite launched is power short. Part of the reason for this is the limitation on the mass that launch vehicles can place in orbit. Figure 1 shows the mass-to-orbit capability of several existing U.S. launch vehicles. (Space Transportation System, Tital IV, III, and II, Atlas/Centaur and Delta.) Major new launch vehicles with capabilities to 100,000 kg to LEO are under advanced development. Similar capability exists in all spacefaring nations so these vehicles will be used as baseline examples. Given the mass-to-orbit contraints imposed by launch vehicles, the next step is to assess the power that might be available to the satellites they launch.

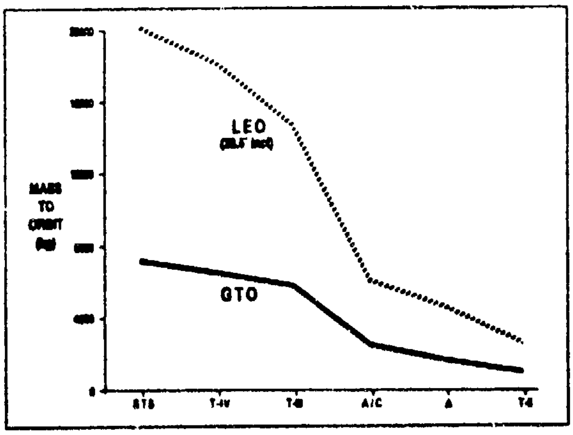
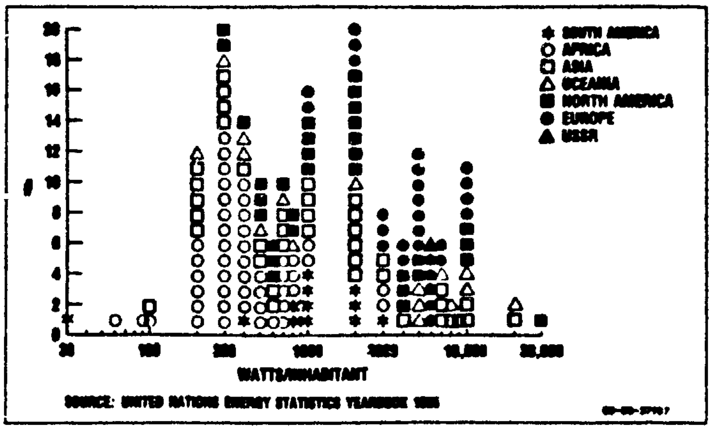


Figure 1 Mass-to-Orbit Capability

While each satellite is different, a general rule-of-thumb that seems to fit most cases is that the power system mass is about 25% of the satellite mass (payload mass fraction is also about 25%). Thus a simple means for estimating power available to a given satellite exists. However what is more complex is the means of estimating on-orbit power requirements.

2. POWER REQUIREMENT ESTIMATION

Because no assured methodology exists for forecasting power needs in space, useful insight can likely be drawn from terrestrial experience. From this experience, then, projections to space can be made. As a starting point in this analysis, the average annual per capita power usage was obtained from reference 1, by dividing the average annual per capita energy usage by the number of hours in one year (8760). Power was chosen for comparison as that is a more familiar quantity in space power systems even though energy is the unifying quantity. The energy data in reference 1 include all sources - coal, gas, oil, nuclear, hydro, biomass, solar, etc. Figure 2 shows these data rounded to the nearest interval. Each point represents a single country and the different shaped points represent the seven world geographical divisions. There is virtually no change in these data from 1985 to 1986 or to 1987, except the world average energy usage is increasing at about a 3% annual rate. Interestingly, the demand for electricity by developing countries is increasing about 7% annually. Three broad regions of per capita power usage can be seen. One peaks at about 300 Watts/inhabitant (W/i) and I have chosen to term this value SURVIVAL. Many African countries are typical of this power usage. A second area centers around 2000 W/i (which is also the world average) and that will be termed SELF-SUFFICIENT. Many countries in Europe, North and South America are typical of these levels of power usage. Finally there is a grouping of INDUSTRIALIZED nations clustered around 7000 W/i. Some countries in this category are the United States, USSR, Japan, Australia and West Germany. There are a few small countries with extensive energy resources (e.g. Qatar, Bahrain) that have power usages of 20-30 W/i but these have been ignored in establishing the 7 kW/i value. A variety of interesting sociological implications arise from inspection of these data; however the purpose of this paper is to relate these data to human endeavors in space. The choice of human endeavors was made to emphasize that human expansion into the universe is a primary objective. Obviously, robotic exploration is a necessary precursor and support element but these power needs will not be covered. Figure 3 shows the average terrestrial per capita power usage for the three categories. In order to link these data to space, three different space station satellites were studied.

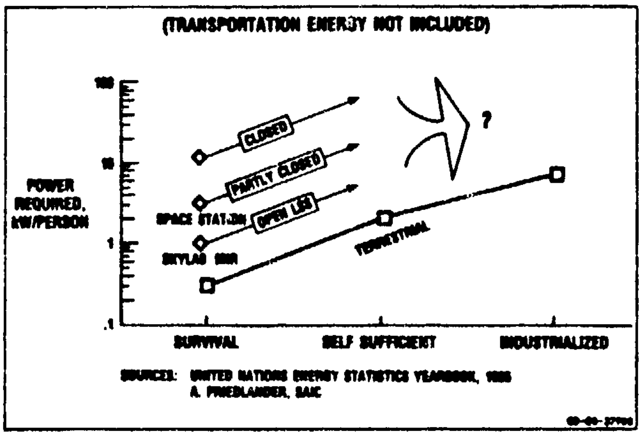


SOURCE: UNITED NATIONS ENERGY STATISTICS YEARBOOK 1985

Figure 2 1985 Average Power Usage Per Capita

The first two, the U.S. Space Station Skylab and the USSR Space Station Mir use open loop life support systems. This means air, food, and water supplies must be replenished and wastes are not recycled. The approximate power required to maintain human life for both these satellites is 1-1.5 kW/i. These satellites are placed in the SURVIVAL category because while some useful work was done, the primary objective was human survival in long duration (up to a year) space flight. The primary power demand associated with human survival comes from the life support infrastructure. Space Station Freedom represents a partially closed life support system with some regeneration and recycling of wastes but resupply is still required. The per capita power requirement jumps to 3.5 kW/i for this case. This point is also placed in the SURVIVAL category for the same reason as above. The third step in ensuring human survival in space is to fully close the life support system. Thus foodstuffs are being produced and consumed, wastes are being recycled and breathable atmosphere is being regenerated. The power demand for this case jumps to 10-12 kW/i (2). It is clear that the demands of simply living in the space environment and doing minimal work requires a substantial increase (almost hundred-fold) in power/energy that is absent on earth for obvious reasons. It is important to also note that the energy used to transport astronauts and their supplies to orbit is not included in these figures. These requirements are substantial. Projection of these data to the SELF SUFFICIENT category suggest that 5-15 kW/i is not unreasonable. Thus, rudimentary lunar base for 6 people with a fully closed life support system would appear to require up to 100 kW just to perform rudimentary work. Full industrialization will likely drive power demands to the megawatt class.

(TRANSPORTATION ENERGY NOT INCLUDED)



SOURCES: UNITED NATIONS ENERGY STATISTICS YEARBOOK, 1985
A. FRIEDLANDER, SAIC

Figure 3 Inhabitant Power Requirements

3. LAUNCH COSTS

Launch costs play a very important role in the utilization of space and strongly affect the commercial viability of space enterprises. It is helpful to examine present U.S. launch costs and their implications for future power systems. Figure 4 depicts the cost in 1988 $ U.S. of delivering 1 kg of mass to various locations in the solar system. Commercial and non-commercial U.S. launch services are shown. The Advanced Launch System (ALS) was not included. These numbers assume that the full launch mass capability of the vehicle is being used. The commercial data points are based on published values and the non-commercial points are a mixture of published costs and projections. The solid line is a reasonable smoothed average and the cross hatch represent an approximate boundary. Typical values are: LEO 7-9 $K/kg, GEO 25-35 $K/kg, Moon 80-100 $K/kg and Mars 500-800 $K/kg. These present costs may place limits on our power needs in space. Projections for the future are made in a later section.

4. POWER SYSTEM TRANSPORTATION COSTS

In order to project the costs of delivering power to orbit, a 100 kW baseline system was chosen. Such a system is believed typical of a fully closed life support system serving 4-6 astronauts with sufficient additional power for scientific enterprise. Light/dark cycles were included in sizing solar based power systems. Figure 5 depicts transportation costs for some representative systems. The SOA photovoltaic system uses 60 W/kg silicon - based flexible substrate solar arrays and 20 Wh/kg IPV nickel-

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hydrogen batteries. The SP-100 Nuclear System is 30 W/kg and the advanced systems line is based on an 80 W/kg SP-100 class nuclear system. The dramatic cost increase in the solar - based lunar power system is caused by the 14-day long night period. This puts extreme demand in the storage system. 100% power availability at night was also assumed. Life support requirements would not decrease during the dark period so full power delivery was felt to be a reasonable assumption. It is seen that launch costs exceed 1 B $ U.S. for power systems on Mars or for solar based power systems on the Moon. These large costs can be ameliorated by two approaches - increase in power system specific power (W/kg) and/or reduction in launch costs.

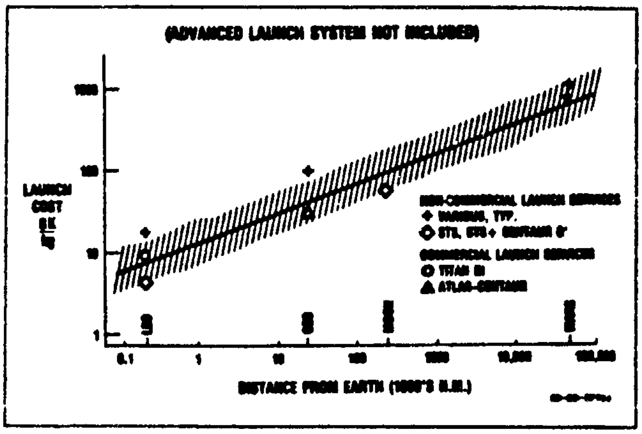

Figure 4 1988 Cost of Delivering 1 kg Payload to Orbit

5. COST REDUCTION STRATEGIES

5.1 Technology Improvements

There can be major improvements in power system specific power (W/kg) through advanced technology. Table 1 lists advanced technologies that are reasonable candidates for future missions. Using the 1988 launch costs shown previously, Figure 6 depicts the impact that advanced technologies can have on lunar and Martian missions at the 100 kW level. Regenerative fuel cells at 1000 Wh/kg with lightweight solar arrays make a dramatic thirty-fold reduction in launch costs for lunar missions. However their cost remains about ten times greater than nuclear-based systems that use lunar mass for shielding (as assumed here). Were a full 4-pi shield to be used for the nuclear system, transportation costs for the solar would still be a factor of about 3 greater. Nuclear systems will have preponderant mass advantage over solar based systems where long periods of darkness are present. On Mars, the night is about 12 hours duration. Figure 6 also shows that advanced photovoltaics with regenerative fuel cell storage offer a ten-fold decrease in launch costs over SOA PV and NiH_2 batteries. The launch cost for this system is about 50% greater than for the SP-100 with native shielding and may be up to one half the cost of a fully 4-pi shielded system, even with advanced dynamic conversion systems.

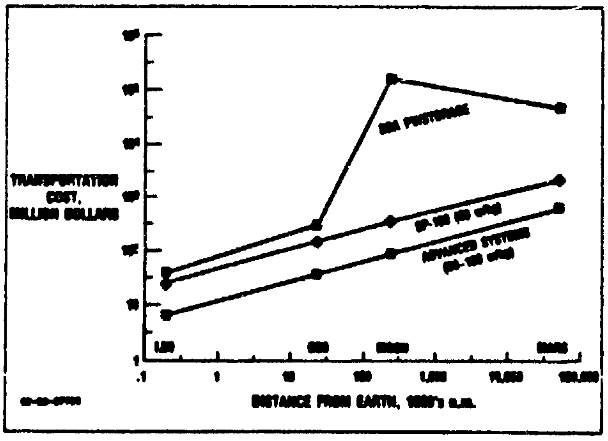

Figure 5 Cost of Delivering 100 kWe of Usable Power

5.2 Launch Cost Reductions

While it is difficult to assess what the future cost of launching payloads to orbit will be, reasonable first-order extrapolations can be made. Five general factors impact launch costs - vehicle size, launch rate, production volume, quality and operations. A sixth factor - advanced technology also has an impact but is more difficult to quantify because it is system specific. With these considerations, Figure 7 represents the trend in LEO launch costs. It can be seen that the STS derivative "Shuttle C" with payloads exceeding 50,000 kg could reduce launch costs to about one half present values. Boosting launch rate to 6 or 8 per year with commensurate production volume and high quality can reduce the costs another factor of two. A new launch system such as the Advanced Launch System (ALS) with payload approaching 100,000 kg will likely include new technologies that could effect another two fold reduction. While all these factors may not be achieved, it is reasonable to expect a five fold reduction in launch costs by the year 2000.

6. CONCLUSIONS

The cost of launching mass to orbit is an important factor that impacts the availability of abundant, cost effective power on orbit. With human expansion into the solar system, significant increases in power consumption will take place. Terrestrial power usage can be grouped into three general categories - SURVIVAL, SELF SUFFICIENCY and INDUSTRIALIZATION. Comparison of these categories to space needs indicates that sustained human presence at the survival level will require per capita power needs at least 40 times larger than on earth. This presumes a fully closed human life support system. Implications of this suggest power needs for commercial viability of endeavors on the Moon may exceed 1 MWe. While launch costs play a preponderant role presently, advanced power system technologies have been identified which can effect a 100-1000 fold reduction in launch costs on the Moon and a 10-30 fold reduction on Mars. Nuclear based systems have a strong advantage where nights are long (Moon). On Mars with a 12 hour night this advantage largely disappears. The use of indigenous planetary material for reactor shielding highly advantageous. Finally, a drop in launch costs by about a factor of 5 is expected over the next decade through increased vehicle size, launch rate, production volume, quality, improved operations and new launch vehicle technologies. Overall it appears that cost of power system transportation will drop by a factor of at least 100-1000 over the next decade. This coupled with another 10 fold decrease in cost of space power systems through advanced technologies will ensure an abundance of cost effective energy for humankinds' expansion into the solar system. This will begin the process that permits humankind to move from survival to self sufficiency and ultimately industrialization of the final frontier. As it has on earth, power remains the critical element that must be provided to unleash human potential.

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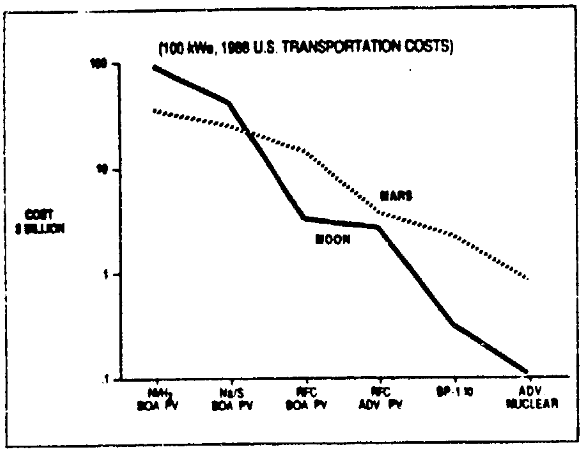

Figure 6 Impact of Power Technology Advances on Transporation Costs

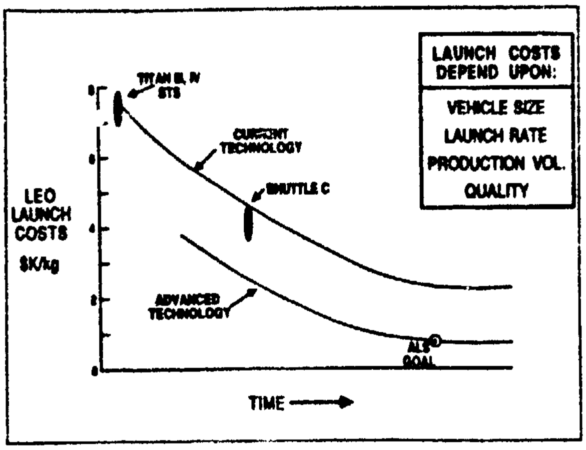

Figure 7 LEO Launch Cost Trends

TABLE 1 - POWER SYSTEM TECHNOLOGY OPTIONS

	SOA	NEAR TERM	ADVANCED
PHOTOVOLTAICS	80 W/kg Si	125 W/kg Si/GaAs	300 W/kg THIN FILM
STORAGE	40 Wh/kg IPV Ni/H_2	80 Wh/kg Na/S, IPV Ni/H_2	300-1000 Wh/kg H_2/O_2 RFC
NUCLEAR	30 W/kg SP-100	—	80 W/kg DYNAMIC SP-100

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National Aeronautics and
Space Administration

Report Documentation Page

1. Report No.
NASA TM-102063

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Challenges for Future Space Power Systems

5. Report Date

6. Performing Organization Code

7. Author(s)
Henry W. Brandhorst, Jr.

8. Performing Organization Report No.
E-4820

10. Work Unit No.
506-41-41

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared for the European Space Power Conference sponsored by the European Space Agency, Madrid, Spain, October 2-6, 1989.

16. Abstract

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17. Key Words (Suggested by Author(s))
Space power; Launch costs; Solar cells; Energy storage; Nuclear; Energy needs

18. Distribution Statement
Unclassified – Unlimited
Subject Category 44

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No of pages
5

22. Price*
A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161