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Key Issues in Space Nuclear Power

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KEY ISSUES IN SPACE NUCLEAR POWER

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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. Finally the cost of present space power systems has been determined and projections made for future systems.

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 hungry. 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, Titan 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 constraints imposed by launch vehicles, the next step is to assess the power that might be available to the satellites they launch.

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. Figure 2 demonstrates the potential power to GEO orbit as a function of system specific mass. It is obvious that substantial additional power can be available on orbit with technology advances. Specific technology examples will be cited later. However what is more complex is the means of estimating on-orbit power requirements.

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 3 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 per inhabitant (W/i) and I have chosen to term this quantity 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 kW/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 4 plots the average terrestrial per capita power usage for the three categories. In order to link these data to space, three different space station vehicles were studied. 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 recyced and breathable atmosphere is being regenerated. The power demand for this case jumps to 10-12 kW/i (2). A terrestrial experiment exploring a closed life support system for 8 people for up to two years is presently underway and it will be interesting to discover whether these power demands will be confirmed. It is clear that the demands of simply living in the space environment and doing minimal work requires a substantial increase (almost a hundred-fold) in energy/power 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 space requirements are substantial. Projection of these data to the SELF-SUFFICIENT category suggest at least a seven-fold increase in power demand for life support alone. Thus, a rudimentary lunar base for 6 people with a fully closed life support system would appear to require almost 100 kW for the astronauts to merely perform rudimentary work. Full industrialization will likely drive power demands to the megawatt class because the crew size will increase and the demands of the work will drive the power needs to roughly 350 kW/i.

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 5 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) or other potential new launch vehicle 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 represents 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. Of course all of these numbers ultimately reduce to the initial mass in low earth orbit (IMLEO) that the booster can provide. It is likely that heavy lift launch vehicles will substantially reduce these costs and projections are made in a later section. These present costs may place limits on our ability to meet our power needs in space.

POWER SYSTEM TRANSPORTATION COSTS

In order to project the costs of delivering power to orbit, a 100 kW baseline system was chosen based on the power projections made in the previous section. The system selected is a fully closed life support system serving about 6 astronauts with sufficient additional power for scientific enterprise. The duration of light and dark cycles were included in sizing solar based power systems. Figure 6 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-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 dynamic power system. The dramatic cost increase in the solar-based lunar power system is caused by the 354 hr. night period. This puts extreme demands on 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. Other studies use a 50% power availability at night. 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 the power system specific power (W/kg) and/or reduce launch costs.

COST REDUCTION STRATEGIES

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 7 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 7 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 indigenous shielding and may be up to one half the cost of a fully 4-pi shielded system, even with advanced dynamic conversion systems.

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 8 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.

COST OF ELECTRICITY

The final factor that limits the widespread use of electric power in space is its cost. It is rather surprising that the cost of electricity is not a fundamental element of spacecraft design. In fact, we are unaware of any published information that details the cost of space electricity. In order to determine the cost of electricity, several major assumptions were made. A typical 3 kW silicon solar cell/NiH_2 battery system was chosen for study. Other assumptions are highlighted in Table 2. The data for recurring hardware costs were confirmed by two independent industrial sources. DDT&E costs were amortized over 5 GEO spacecraft but only one LEO satellite. Table 3 shows the result of these calculations. It is noteworthy that nearly one-half the cost of a GEO satellite comes from launch costs. In neither case is the cost of the flight hardware more than twenty percent of the total cost. The cost of electricity in both cases is surprisingly similar at approximately $800/kWh. This can be compared to $0.10/kWh for most terrestrial electricity sources. Even the emerging solar technologies are projected to cost between $0.125 and $0.25/kWh.

Figure 9 gives some rather gross estimates for future trends in space electricity costs. There is presently no substantial basis for projection of these costs, however, some logic can assist the process. As the power level rises, as evidenced by Space Station Freedom, some reduction in cost (on the order of 25%) is expected due to economy of scale. However, the cost of human-rating the system may obliterate this reduction. The solar dynamic growth option for the space station has recurring costs that are about one-half that of a photovoltaic system, and a similar reduction in electricity cost could be expected as shown. Next, the cost of the SP-100 nuclear system may be below $100M, leading to costs about one-fifth that of the solar option. The dynamic conversion option for the SP-100 boosts its power substantially, with a concomitant reduction in cost of electricity to below $100/kWh. Key factors in achieving substantial cost reductions in space-generated electricity are straightforward. First, use more electricity - more is cheaper as seen by the impact of dynamic power conversion options on SP-100. Next, advanced technologies are important: mass reductions to reduce the transportation costs, alternative technologies that reduce recurring costs. For solar-based technologies these include solar dynamic systems and concentrator-based photovoltaic systems such as SUPER. Of course, the nuclear-based power systems offer substantial cost advantages, just as on earth. One additional part of the power system that must also be improved is the power management and distribution element. Finally, the costs of delivery of payloads to orbit must be reduced by a substantial margin, hopefully by about five-fold.

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. These conditions imply that power needs for commercial viability of endeavors on the Moon may exceed 1 MWe. While launch costs play a preponderant role at the present time, 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 is 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 humankind's expansion into the solar system. It is hoped that the cost of electricity in space will drop from its present level near \$800/kwh to about \$80/kWh. This will begin the process that permits humankind to move from survival to self sufficiency and thence to industrialization of the final frontier. In space as it has been on earth, power remains the critical element that must be provided at a cost effective price in order to unleash human potential.

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2. A. Friedlander, SAIC, private communication

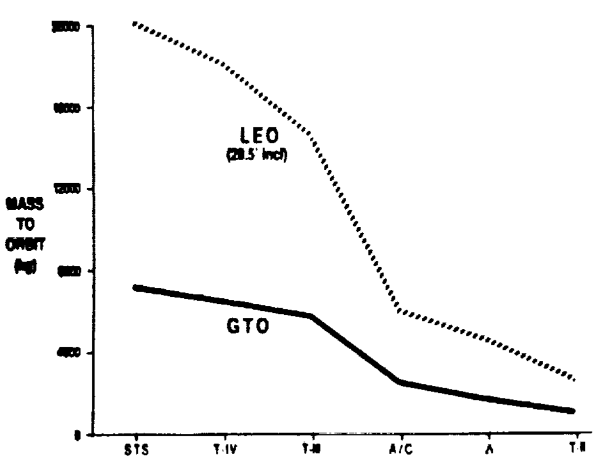

FIGURE 1. Mass-to-Orbit

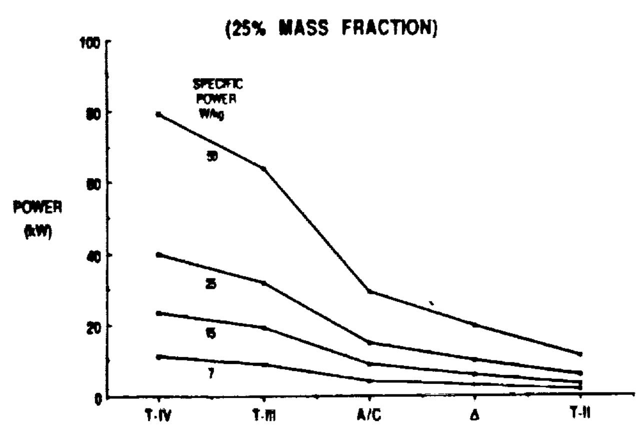

FIGURE 2. Impact of Power System Specific Mass on GEO Orbit Power

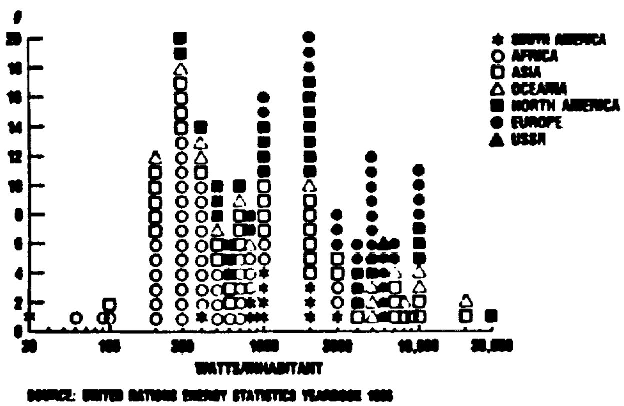

FIGURE 3. 1985 Average Power Usage Per Capita

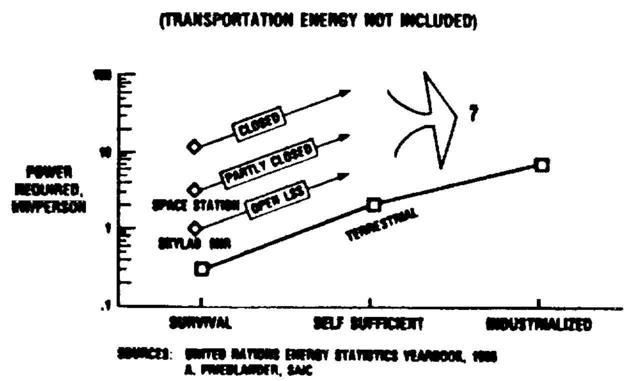

FIGURE 4. Inhabitant Power Requirements

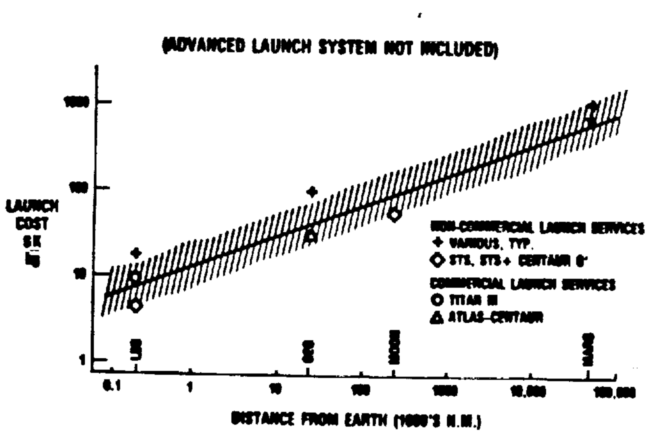

FIGURE 5. 1988 Cost of Delivering 1 kg Payload to Orbit

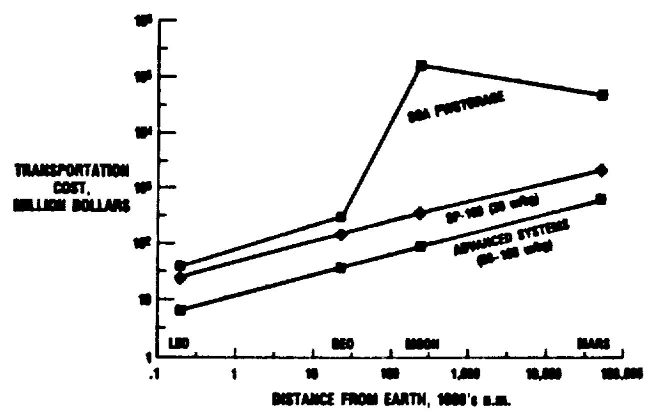

FIGURE 6. Cost of Delivering 100 kWe of Usable Power

	SOA	NEAR TERM	ADVANCED
PHOTOVOLTAICS	50 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

TABLE 1. Power System Technology Options

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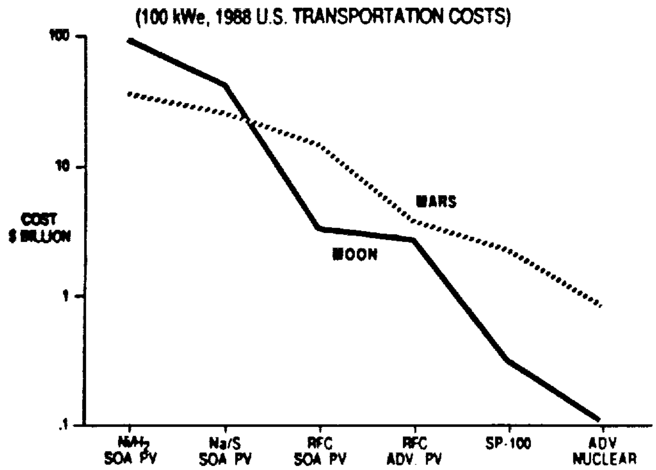

FIGURE 7. Impact of Power Technology Advances on Transportation Costs

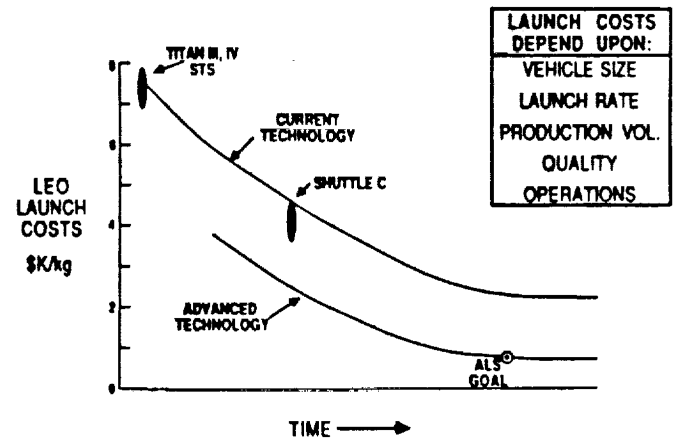

FIGURE 8. LEO Launch Cost Trends

3 kW PV / BATTERY SYSTEM

ELEMENT	LEO	GEO	COMMENT
RECURRING HARDWARE COSTS:	$ 7 M	4.8 M	(SUN / SHADOW CYCLE DOMINATED)
CAPACITY FACTOR:	80 %	50 %	(AMOUNT OF AVAILABLE ENERGY USED)
TIME PERIODS:	DOT & E 5 YRS. SERVICE LIFE 7 YRS.	5 YRS. 10 YRS.	(1 S/C LEO, 5 S/C GEO)
INSURANCE COSTS:	10 %	10 %	
LAUNCH COSTS:	$ 8 K / kg	$ 32 K / kg	(± 25 %)

TABLE 2. Cost of Electricity in Space - Assumptions

3 kW PV / BATTERY SYSTEM

	LEO	GEO
DELIVERY TO ORBIT	$ 6 M	$ 16 M
DEVELOPMENT AND TEST	$ 25 M	$ 5 M
HARDWARE COSTS	$ 7 M	$ 4.8 M
INSURANCE	$ 3.9 M	$ 2.6 M
OPERATIONS	$ 0.1 M / YR	$ 0.1 M / YR
APPROXIMATE TOTAL COSTS	$ 38.5 M	$ 33.8 M
COST OF ENERGY	$ 785 / kWh	$ 770 / kWh

TABLE 3. 1989 Cost of Electricity in Space

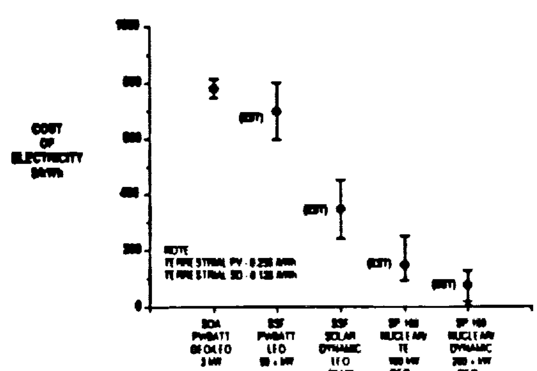

FIGURE 9. Projected Costs of Electricity in Space

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16. Abstract

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