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AN ECONOMIC ANALYSIS OF A COMMERCIAL APPROACH TO THE DESIGN AND FABRICATION OF A SPACE POWER SYSTEM

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Abstract

This paper discusses a commercial approach to the design and fabrication of an economical space power system. With the advent of the space shuttle, steps can be taken to back away from the presently used space qualified approach in order to reduce cost of space hardware by incorporating, where possible, commercial design, fabrication, and quality assurance methods. Cost reductions are projected through the conceptual design of a 2kW space power system built with the capability for having serviceability. The approach to system costing that has been used takes into account both the constraints of operation in space and commercial production engineering approaches. The cost of this power system reflects a variety of cost/benefit tradeoffs that would reduce system cost as a function of system reliability requirements, complexity, and the impact of rigid specifications. A breakdown of the system design, documentation, fabrication and reliability and quality assurance cost estimates are detailed.

Introduction

The high cost of future space programs, especially power systems, projected for the mid-1980's and beyond, has been an ongoing concern to NASA planners. The application of present conventional space qualified approaches may limit the size and number of spacecraft that are possible with anticipated budgets. Historically, spacecraft energy costs have ranged from about $300 to as much as $2000 per kW-hr, with an average of about $800 per kW-hr for long duration missions.[1] This is primarily due to the high levels of technology and quality imposed to satisfy mission requirements which are largely mandated by the inability to effect any kind of inflight repairs or modifications. With the advent of the space shuttle it may become possible to back away from such prior high level technical and quality criteria due to the possibility of servicing. In addition, as demand grows for larger space power systems a transition towards standardization, mass-production and modularization of subsystem components will accelerate. With the inception of orbital repairs or replacements, the cost of many areas of system development can become substantially reduced.[1]

The introduction of a commercial approach implies several changes in managing resources and in differentiating between commercial practices and specification for space quaility. Perhaps the one major factor that would differentiate a space qualified from a commercial approach is that the traditional space approach could be viewed as the marketing of a technology whereas a commercial organization is more attuned to marketing a product at competitive prices, having high quality, and in large volume. From an economic viewpoint, reducing product cost enables a greater proportion of the buyer population to obtain the product. Such factors as economy of scale, market diversification, economy of size, automation, standardization and continuous purchasing and production are all fundamental processes that are considered important in achieving the low cost per watt figure that will prove competitive for future applications.

It is important when considering the development of a commercial power system, to recognize that the first level of cost reduction will probably be realized in reduced systems specification. Consideration must be given to insuring that the power system is not overdesigned. Whether space qualified or commercial in approach, the power system must function for a given life cycle. In both approaches similar design effort is employed, with the exception that a commercial product may run a greater risk of malfunction. To mitigate this, the application of warranties and other measures such as service contracts have evolved. Many high technology commercial products exist because the products are designed to be maintained and can be serviced. The traditional space approach requires high reliability for long duration spacecraft missions since servicing in orbit at present is impossible. For this reason much of the effort in developing space qualified hardware has been geared to designing systems which perform without failure for long periods of time. Therefore, to achieve this goal, high reliability design, redundancy, and stringent quality assurance at all levels of design, fabrication and system integration have been the rule. However, this would not be the case in commercial power systems because they have the capability of being serviced.

Scope of Study

The scope of this study includes an estimate of the impact on system cost, by relaxing mission constraints through the concept of repairability and allowing the system to be influenced by the use of terrestrial photovoltaics, avionic batteries, and other commercial equipment. The system and approaches described herein were based on the following system specifications generated for study purposes of future cost comparison.

System Description

Characteristics of the specified space power system which were to be used for this study include:

Launch and orbital characteristics:

- Shuttle launch
- Low earth orbit
- Circular - 200NM
- Inclination - 28.5° incl.

- Orbital period - 93 minutes
- Time in sun - 57 minutes minimum
- Time in eclipse - 36 minutes maximum

System electrical characteristics:

- Power source - deployable/retractable solar array
- Power level - beginning of life (BOL) 2kW elec. continuous to load
- Distribution voltage - 28VDC unregulated
- Energy storage - batteries
- Battery - depth of discharge (DOD) 25%
- Elect. Mech. system - (1) 2 axis solar array drive
  (2) slip rings

System design life - 4 years

Conceptual Design

Based on these system requirements, a conceptual design was derived. Figure 1 depicts a diagram of the major functional blocks of the power system. Since some subsystems or components are unique to space, the system employs a mixture of commercial and space qualified hardware in several instances. The central aim behind the approach to the design was to offer some insight into the costing factors of a commercial power system. For example, sizing of the arrays was based on a terrestrial photovoltaic cell having a 5cm x 5cm dimension. The rationale for using such a cell size is largely economic in terms of cost/watt in that by increasing cell size the number of fabrication operations is reduced, a greater amount of the original silicon wafer is utilized and a higher packing density can be achieved in the array. The system features depicted in figure 1 (i.e., solar array block), are based on a sizing of the array given worst case thermal conditions, effects of radiation degradation and orbital configuration. This sizing suggested an approximate 9% oversize of the array to compensate for thermal cycling and radiation damage over the four year mission life. The fabrication of these arrays would employ an approach similar to what is presently employed in the development of terrestrial concentrator photovoltaic receivers at Solarex, i.e., glassing of cells and cell to substrate attachment are analogous to space panel fabrications.

Slip ring and deployment assemblies appear to be two technologies less amenable to significant cost reduction because of their lack of having a non-space counterpart that appear acceptable. To reduce cost here we plan to reduce specifications, quality assurance and documentation cost by using or modifying an already proven design. In turn, some additional cost reduction is pos-

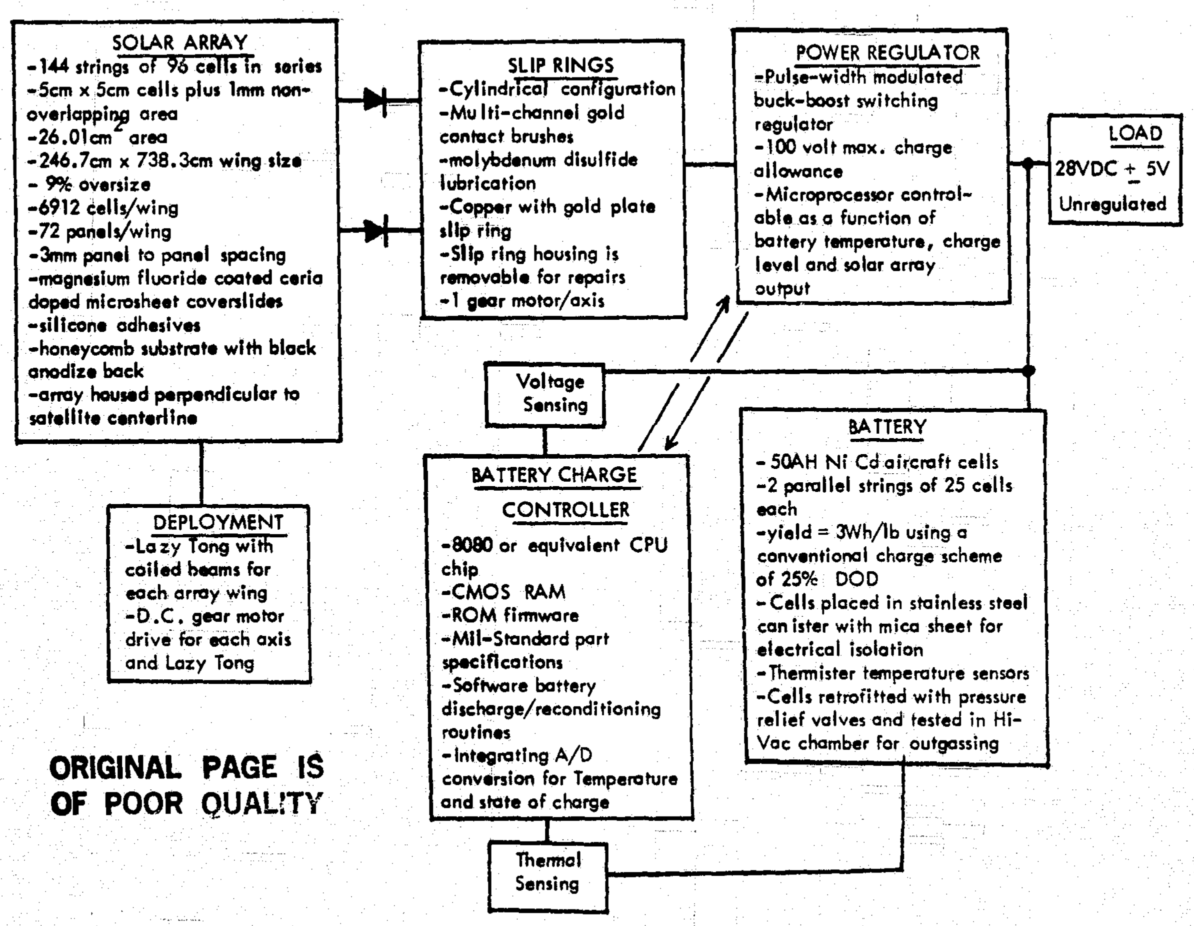

Fig. 1 Conceptual block diagram and description of a proposed commercial space power system.

sible by reducing the space qualified standards in some areas in the development of these two systems.

Several approaches to power regulation, including array detracking and panel disconnection (which are sometimes used in terrestrial photovoltaic system applications) were considered. However, the approach adopted for this study was to use a buck-boost pulse width modulated switching regulator which was felt more amenable to control by a microprocessor charge controller. This concept was also adopted because of its potential advantage in reducing the problem of satellite temperature buildup.

Batteries for this system will consist of two parallel 25 cell strings of 50AHr Ni Cd aircraft cells, using a 25% depth of discharge charge - discharge scheme. Problems associated with aircraft batteries must be addressed. Based on discussions and consultations with cognizant technical personnel it appears that avionic batteries may be useable if precautions are taken to minimize outgassing.[2]

Subsystem Evaluation and Cost Analysis

The study was broken into four major areas of interest from which an economic analysis was performed using the methods and practices that would be used by Solarex Corporation if a production engineering approach were followed to generate space power systems. In this costing exercise many factors associated with system reliability are necessarily traded against cost. The first major factor which impacts system cost is the effect of rigid specification or specifying requirements that generate increased manpower and materials costs.

Solar Array Subsystem. In many respects the solar cell and panel design effort is no less rigorous than what would be anticipated in approaching the problem from the traditional space qualified approach. The Solarex design of terrestrial solar cells requires the same high level of understanding the physical properties of the device, methods of processing and sophisticated metalization, and other techniques characteristic in the semiconductor industries as for conventional space qualified solar cells. The particular cell design used for this system is a square 5cm x 5cm cell, using state-of-the-art terrestrial fabrication methods. We consider a superior design feature the use of the large cell size, multiple contact pads, and a redundant path grid pattern to minimize the effect of mechanical damage. Selection of a large cell is an important economic tradeoff. The imposition of the larger size reduces the number of labor intensive tasks that must be performed during subsequent testing, handling, storage and panel fabrication. Additionally, in the solder joint formation and cell to panel attachment process both time and manpower reductions are realized by designing the solar array with a larger cell size. Secondary to this is the economic impact of the larger cell producing a greater potential for higher packing density. This invokes another important tradeoff; the improvement of packing density allows utilization of a lower cell performance level for the same power output per unit area, and thus, a larger proportion of the cells processed can pass a given performance inspection criteria. By employing this approach the added cost burden associated with high reject rates is minimized. We think also in the design of this panel, cost improvements can be augmented by minimizing specification standards. One example of this would be to relax the inter-cell spacing specification.

The amount of documentation required in design and fabrication should also be minimized. At Solarex, in the design phase, much of the design and development effort would be conducted through the auspices of a technical manager and a small set of highly trained technicians. Documentation is usually not formalized until processing techniques are completely optimized. At this point specification of materials, process steps and special features in the process are generated. These documents, in Solarex's experience, do not resort to lengthy detailing of operational definitions of process steps. Generally, only major process steps and explanations involved in the cell and panel fabrication effort are documented.

No special cell fabrication technology would be implemented and standard production approaches would be assumed. In the production of a Solarex commercial 5cm x 5cm cell 11 major process/Q.A. steps are used. These are:

1. Incoming silicon and materials Q.A.
2. Etch - Q.A. function is associated with silicon thickness.
3. Diffusion - Q. A. function is on a sample basis to determine quality of the junction formation.
4. Aluminum back field formation - Visual Q.A. for conformity to visual criteria for coloration and texture with occasional samples for electrical resistivity.
5. Back surface metalization - sample pull tests of metalization
6. Photolithography - Q.A. is visual culling of improper photolithographic pattern formation, sampling of cells for microscopic inspection.
7. Front surface metalization - sample microscopic, pull test, other visual inspection.
8. Silver plating - plating bath inspection and plating thickness inspection.
9. Anti-reflective coating - Visual inspection of cells for conformity with a color standard.
10. Edge preparation - Visual inspection.
11. Final Q.A. - Illumination testing and sorting by categories and tab pull testing on sample basis.

Array fabrication would be undertaken at Solarex by the panel development specialty line. The use of the panel development line is appropriate because the total number of panels (N=144) is relatively low and thereby deviates significantly from standard production to warrant utilization of a smaller scale assembly facility. With a production scenario of large volume the required tooling and equipment would be obtained to scale up the fabrication process. Six major process and Q.A. steps are identified for panel assembly:

1. Coversliding - Visual and microscopic inspection on sample basis.
2. Cell tabbing - Visual inspection of solder joints.
3. Cell string attachment to substrate - Visual inspection of intercell gaps, interconnects, and

adhesive.

4. Pumpdown - Outgassing the cell-substrate adhesive interface, no Q.A.

Solar array costing. The following Table 1 is a breakdown of manpower and cost for the solar array subsystem by task area:

Table 1*
Solar Array Manpower and Cost Estimation

	Solar Cells	**	Panels	
	Manhours	Cost	Manhours	Cost
Design	292	5300	595	12100
Documentation	132	3020	165	4300
Fabrication	2264	103869***	450	101900
R&QA	412	13900	390	4500

*The cost reflected in this and all subsequent tables reflect a mix of skill levels and overhead.

**Cost in dollars

***Final cost for 13820 cells to specification @12% AM0

Power Regulation And Battery Charge Control. In selecting a power regulation approach a variety of methods was considered. Such ideas as panel switching, array detracking and other approaches were considered for their potential in simplifying the system. However, these design concepts did not prove amenable to space requirements, even though they are often used in some terrestrial power systems. It was decided that from an overall performance veiwpoint the application of a buck-boost pulse width modulated power regulator would be a superior design approach.[3]

Unlike solar cell production, the design and development of the power processing subsystem employs a somewhat different philosophy. Here Solarex's costing method was based on evaluation of task descriptions generated by consulting hardware design engineers. For both the power regulator and charge controller, the design, testing and Q.A. costs associated with generating the first prototype systems far outweigh the direct assembly labor and hardware costs. The choice of using the buck-boost power regulator was considered best because the components of such systems are typically characterized by high reliability (some off the shelf commercial versions are rated with MTBF 30k hours and more) and are very amenable to digital control.

In evaluating the design approach to battery charge control the assumption was to avoid developing any custom circuits. Moreover, it was viewed that using a microprocessor based controller having a multiplexed A/D converter to measure battery temperature and voltage through the charge-discharge cycle and determine discharge and reconditioning when battery performance begins to diminish below a given set point was deemed an efficient design approach. Firmware for such applications can be commercially obtained at relatively low cost. Such systems have had wide application throughout industry having been proven many times over.

The power regulator and battery charge control systems are viewed as having a somewhat larger dependence on documentation than that associated with the other systems, largely because of the complexity and detailing of PC boards, wiring diagrams and component listing and materials requirements. It is envisioned that a commercial fabricator of these two subsystems would produce these items.

As a buyer of a commercially fabricated subsystem the approach to fabrication and Q.A. would be identified and specified by Solarex Corporation. The vendor would be required to demonstrate compliance to scheduling by supplying either Gantt or PERT charts on the procedures they would use to fabricate the systems. A full accounting of subsystem performance, certificates of compliance for both environmental tests, and system operation would be mandatory. Table 2 gives a breakdown of cost for these two systems

Table 2
Power Regulator and Charge Controller
Manpower and Cost Breakdown

	Power Regulator		Charge Controller	
	Manhours	Cost	Manhours	Cost
Design	744	12700	2277	46200*
Documentation	610	9800	329	7800
Fabrication	---	3500**	---	6000
R&QA	360	13500	1120	24100

*Design items reflect the manpower and reliability analysis effort associated with fabricating a limited number of copies, plus software development and special testing.

**Fabrication cost reflect estimated component hardware and specialty item (i.e., PC board layout, etc)

Batteries. The design efforts associated with development of a battery system are largely tied to the generation of the test and Q.A. specifications. Solarex proposes to examine the data effectiveness of the vendor of the cells, determine the charging characteristics, and define the canister enclosure, sensor placements, type of intercell connectors, electrolyte levels, in addition to the design and documentation of the testing procedure of the cells procured from a vendor.

In this approach the substantial cost savings obtained by using aircraft Ni Cd cells commonly used in starting jet turbines appear to be well within the performance standards needed for this system. Much of the design issues of cell containment for the low pressure environment and deriving a charge methodology that would minimize the outgassing and pressure buildup within the cells would have to be evaluated. At this time it appears feasible to use avionic batteries because the constraints imposed by the space environment can be remedied.

An approach to producing a battery system ready for application at a reduced cost would employ reducing the requirements previously associated with testing and performance appraisal of a set of cells obtained from a battery vendor. After the lot (N=100) is obtained the cells would be submitted to an abbreviated acceptance testing and matching program. Briefly, these cells would be charged to approximately 95% nameplate capacity, temperature soaked (i.e., for a duration long enough to insure thorough temperature stabilization) at the maximum predicted temperature inside the spacecraft and discharged at a one-hour rate and continuously monitored for voltage and polarity deviations. A minimum allowable cut off voltage for each cell, temperature, and discharge rate will be established as the acceptance criteria. Following this, the same procedure would be replicated for the lowest predicted temperature the cells would be operating in.[2] From these data the remaining sample of cells are then matched and fitted with high pressure relief caps, and inserted into a rigid stainless steel canister. Subsequently, these batteries would be submitted to vibration and vacuum testing to verify performance and compliance. Table 3 gives a breakdown of the estimated manpower and cost of this subsystem.

Table 3

Battery Subsystem Manpower and Cost Breakdown

	Manhours	Cost
Design	720	15300
Documentation	280	8600
Fabrication	---	10000*
R&QA	668	12300**

*Cost of 100 avionic Ni Cd cells.

**Reflects cost of development of acceptance tests and containment system.

Deployment And Slip Ring Assembly. In considering these two assemblies it has been found that comparable commercial systems are virtually nonexistent. Therefore, an aerospace vendor with proven experience in fabricating these systems would necessarily be employed. Initially the deployment system would be based on a Lazy Tong - Coiled beam configuration, largely because it is a deployment approach that has had proven use.[4] In the case of slip rings, a favored appraoch would be to limit the design effort of the system such that the slip rings are identical in each axis and are fabricated from copper stock with gold plate.[5] This would be less expensive than using pure silver, gold or other exotic composites. Such a materials selection and engineering approach would prove acceptable choices given limited rotational speed, even though lubricants would be used. Array axis drives would employ torque motors with gear reduction, with the facility for quick disconnect of the motors for inflight repairs. Similarly, the slip ring housing could have faceplates through which repairs could also be effected in the event of vacuum welding or arcing of the brushes and the rings.

Since the majority of the cost of the slip ring assembly and deployment systems are reflected in life testing, design specification and reliability analysis, the approach in design and development and fabrication would be to duplicate or modify an already proven configuration. Cost and manpower breakdowns showing the estimated cost of these two subsystems is given in Table 4.

Table 4

Mechanical Subsystem Manpower And Cost Breakdown

	Slip Ring & Drive Assembly		Deployment Subsystem Assembly	
	Manhours	Cost	Manhours	Cost
Design	630	16000	728	21000
Documentation	180	2500	270	3300
Fabrication	---	14000	---	45000*
R&QA	---	8000*	---	10000*

*Cost estimates may vary widely, vendors contacted did not give useful input to derive accurate values.

System Integration And Qualification Testing. The overall approach to system integration is to conduct bench testing on the system after a detailed system inspection and configuration checkout during the process of assembling all the subsystem parts. This process would require either purchase or rental of needed equipment in order to test and qualify all assembly of the subsystem parts. After this phase of the system assembly the components, including connectors, wiring harnesses, and PC board brackets, are assembled and performance tests conducted to determine whether or not the system is fully operational. With appropriate testing measures, the system would be prepared for a full system qualification checkout in a large simulation chamber. Because the system manufacturer is a commercial venture, a large aerospace firm would have to be contracted to conduct the appropriate full system tests under simulated environmental conditions. Such testing could economically be grouped into one test setting in order to minimize the overall cost of final qualification testing.

A cost breakdown of final integration and qualification testing indicates that the final testing would contribute the majority of the expense associated with the system checkout cost. Table 5 depicts manpower cost estimates and vendor cost estimates.

Table 5

System Integration And Qualification Testing

Task Area	Cost
Documentation of testing regime for bench testing and system qualification testing, documentation of test procedures	2000
Test equipment purchases and rentals estimate	20000 and above
System integration inspection	5000
System integration operation test	2000
Vendor supplied qualification testing	80000

Discussion And Conclusion

This paper has traced a set of ideas, approaches and cost considerations examining the development from design to production of a space power system which could potentially be produced by a commercial approach. The major overriding emphasis presented here has been one of deriving a space power system in which the burden of stringent traditional space qualification has been relinquished. Throughout the entire subsystem cost estimating process the approach has been one that assumes its development would be predicated on the basis of servicability throughout the extent of its mission, and that it conforms to a less rigorous set of specification criteria than would be experienced in the traditional space approach. This system, while expected to achieve a high level of system availability, does not assume a comparable reliability figure as one would expect from a traditional space power system.

In Table 6 a finalized cost breakout is presented comparing an equivalent traditional space qualified system with the commercial power system. As shown, a relatively uniform diminution in cost across all the major subsystems evaluated is indicated. While the unforseen risks implicit in engaging in such a venture are legion, the potential for savings to future space missions cost is substantial enough to warrant a further study and possible implementation of such an approach.

On the basis of this analysis it is estimated that a reduction of about 74% in cost from a comparable space qualified system is indicated.

Table 6
Finalized Cost Breakdown

Category	Space Qualified[6]	Commercial
Solar Array	$1,500K	$249K
Batteries	180K	46K
Power Processing	360K	124K
Mechanical Systems	225K	120K
System Integration & Qualification	400K	109K
	2,665K	648K

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