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COMPARATIVE ENERGY STORAGE ASSESSMENT ITEM

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INTRODUCTION

Inertial energy storage, or flywheels, emerged as a promising alternative to electrochemical storage methods with the concept of Integrated Power and Attitude Control (IPAC). Energy stored in the flywheel during sunlight portions of the orbit was used to supply spacecraft power during Earth occultation. The flywheel was mounted on double gimbals similar to a control moment gyro (CMG) to permit three-axis control of the spacecraft throughout the orbit. Thus, a single device performed the functions of both power and attitude control. The potential merit of an IPAC concept had been foreseen in the early 1970's and the necessary system application studies and technology demonstrations have since been completed.[1,2] This analysis, a Space Station application study, rediscovered IPAC and found the approach to have lower initial and resupply weight and lower initial and resupply cost than either battery/CMG or regenerative fuel cell/CMG systems. The highly favorable results of this study and companion in-house studies led MSFC to consider IPACS as a strong candidate for the initial Space Station. Technology developments subsequent to the earlier work make flywheels even more attractive for growth Space Stations and free-flying science platforms. These developments include composite rotor material, magnetic suspension and improved charge/discharge electronics. This study found order-of-magnitude advantages over conventional or advanced electrochemical/CMG systems when potential performance improvements were considered.

REFERENCE SPACE STATION

Space Station Concept Definition studies considered a wide range of approaches, including Space Stations and man-tended Space Platforms having power requirements ranging from 20 kW to 140 kW. Orbital altitude and inclination were also variables. The set of requirements assumed for the purpose of this discussion are tabulated in Table 1.

TABLE 1 - MISSION ASSUMPTIONS

Power Source: Photovoltaic, 100 W/m^2 and 50 W/kg
Power Level During Sunlight: 75 kW Nominal
Power Level During Occultation: 75 kW Nominal
Peak Power: 1.5 x Nominal
Minimum Power: Nominal/1.5
Altitude: 463 km
Inclination: 28°
Mission Duration: 15 years
Technology Readiness: 1987

Based on studies performed for a range of mission requirements, study results were considered to be applicable for the spectrum of Space Station concepts.

TRADE STUDIES

Preliminary trade studies were performed comparing Integrated Power and Attitude Control (IPAC) with equivalent independent electrochemical power and control moment gyro (CMG) control approaches. Technologies considered to have adequate status for an initial Space Station were: (1) nickel-cadmium batteries (NiCd batteries), (2) regenerative fuel cells (RFC), (3) Skylab class CMG's, and (4) state-of-the-art IPAC using metal wheels and ball bearing suspension (SOA-IPAC). An advanced IPAC (ADV-IPAC) employing composite rotor material and magnetic suspension was included in the comparisons to illustrate a possible range of performance and cost of inertial systems. The candidates were compared on the basis of initial weight and cost and on the basis of resupply weight and cost for a 15-year mission.

CRITERIA

The differentiating criteria applied to the candidate energy storage options were: (1) integration potential with other subsystems, (2) initial weight and cost, (3) resupply requirements and (4) system efficiency.

The potential for integration with other subsystems was implicit in the IPAC option but more complex for the RFC option. A RFC could be oversized to provide hydrogen and oxygen to the propulsion subsystem and to the Environmental Control/Life Support (ECLS) subsystem. However, the determination of possible cost and weight savings was beyond the scope of this study. There is no integration potential for NiCd batteries.

Resupply cost was based on a 15-year mission because longer missions, such as 30 years, placed unrealistic emphasis on this cost element. Cost discounting was considered to be a more technical method of accounting for resupply cost; however, the option to discount resupply cost by considering a 15-year mission life was adopted for simplicity. The effect was approximately the same as discounting a 30-year resupply cost at an 8 percent rate.

The solar array size required to deliver 75 kW to the user bus is an accurate measure of the charge/discharge efficiency of the energy storage system. Cost penalties relative to a solar array required by flywheel systems were assessed against RFC's and batteries and included: (1) solar array design and development (D&D), (2) solar array recurring, (3) launch, and (4) propellants to compensate for solar array drag.

A possible psychological factor among some electrical power system engineers against the use of rotating machinery may have hindered the acceptance of flywheels in previous studies even though attitude control designers had flown three large CMG's on Skylab and were planning an ever larger system for the Space Station. The principle of rotating machinery would therefore appear to be acceptable despite several design differences; namely, (1) higher rotating speed (8000 RPM for CMG's and 20,000 to 40,000 RPM for flywheels) and (2) rotor configurations.

The significance of the IPAC concept and/or the performance advantages promised by composite rotor material and magnetic suspension is illustrated by the following energy storage trade study results.

ENERGY STORAGE/MOMENTUM EXCHANGE WEIGHT

Weight-to-orbit for a 15-year mission is depicted in bar chart format in Figure 1. The candidates were first compared on the basis of energy storage only (i.e., as they would normally be compared in electrical power subsystem trade studies). Next, the comparison was made for the combined weight of electrical power and attitude control for the purpose of investigating the possible merit of integrating power and attitude control (the IPAC concept). When results appeared favorable to the IPAC concept, special features of flywheel systems were investigated. The effect of high system efficiency is shown in the third representation.

The lifetime of the RFC option was assumed to be either 5 or 7.5 years. The weight differential between one resupply (5-year life) and two (7.5-year life) is indicated in Table 2. Weights and lifetimes for the set of energy storage options investigated are tabulated in Table 2.

TABLE 2 - WEIGHT/LIFETIME SUMMARY

OPTION	INITIAL kg	YEARS
NiCd	8400	7.5
SOA-FW	4600	5
RFC	2600*	5 or 7.5
ADV-FW	1800	15

* Tanks not replaced (311 kg)

The "Power Only" comparison (fig. 1) was considered to favor the selection of RFC's. They offered a significant weight reduction over conventional NiCd batteries and were competitive with the initial weight of advanced flywheels. The absence of resupply weight from the advanced flywheel might easily be overlooked by Space Station study teams that typically place primary emphasis on initial weight. Placing the emphasis on technology development and the flight experience with fuel cells would also favor adoption of RFC's. Selection of regenerative fuel cells might readily be prophesied if this scenario proved correct.

The introduction of the IPAC concept greatly enhanced inertial energy storage options. The effect is illustrated by the second representation in Figure 1 where the mass of CMG's required for attitude control was added to the mass of the electrochemical options. The comparison now strongly favored the advanced IPAC option via the combined effects of high performance, long life and integration of power with attitude control. The Space Station was assumed to require six CMG's based on previous in-house studies. Total CMG weight was 1400 kg and lifetime was 5 years.

State-of-the-art IPAC systems were also shown to be competitive with electrochemical options. Weights were significantly lower than conventional battery systems and competitive with regenerative fuel cell systems. The comparison with regenerative fuel cells was therefore pursued in more detail.

Flywheel systems were found to exhibit a high effective power system efficiency because the controller used for charge/discharge control had the inherent capability to provide regulated voltage to the system without further power processing. An accounting of system efficiency was made by comparing the solar array size required by each of the energy storage options. Solar array weight and the difference in stationkeeping propellants resulting from array sizes relative to the array required by inertial systems are tabulated in Table 3.

TABLE 3 - ENERGY STORAGE SYSTEM PENALITES TO SOLAR ARRAY DESIGN RELATIVE TO 160 kW ARRAY FOR INERTIAL SYSTEMS

ITEM	NiCd BATTERIES	RFC
Power Delta	+ 21 kW	+ 31 kW
Weight	+ 420 kg	+ 620 kg
15-Year Drag	+ 2400 kg	+3600 kg

The third representation shown by Figure 1 includes the addition of initial solar array weight and resupply propellants to compensate for solar array drag. The weight of the state-of-the-art IPAC option was slightly lower than that of the RFC/CMG option.

Heat rejection requirements were considered subjectively to benefit flywheel options. Electrochemical systems generated heat primarily during discharge whereas flywheel heat rejection was relatively constant. Determination of possible differentiating criteria, including thermal storage capacitors or relative radiator sizes, and the complexity of relating such factors into equivalent CER's for thermal control systems were beyond the scope of this study.

Results of the weight analysis gave the indication that the SOA-IPAC concept was competitive with regenerative fuel cell/CMG systems, and therefore a preliminary cost analysis was initiated.

ENERGY STORAGE/MOMENTUM EXCHANGE COST

Cost estimating relationships (CER's) for NiCd batteries, regenerative fuel cells, and control moment gyros (CMG's) were based on current projections obtained from the Space Station definition activity. Complexity factors relative to CMG's were used to estimate the cost of inertial systems. Cost estimates used for the comparison are tabulated in Table 4.

TABLE 4 - COST SUMMARY ($\$ \times 10^6$)

ITEM	NiCd	RFC	SOA-IPAC	ADV-IPAC	CMG
D&D	3	30-150	30	45	24
FH	49,5	50	39	44	14
Launch	11.8	3.7	6.5	2.5	2.0
Resupply Flts	1	1 or 2	2	0	2

Results of the cost analysis are shown by the bar charts in Figure 2 and follow the same format that was adopted for the comparison of weight (i.e., power only, power + CMG's and power + CMG's + solar array deltas).

The "Power Only" comparison was considered to favor conventional NiCd batteries by virtue of the very low D&D cost. The disadvantage of weight was largely discounted because launch cost was a small part of total. Many studies ignore the launch weight of particular subsystems and base launch cost solely on utility module volume.

The potential advantage of advanced IPAC systems was indicated only when resupply cost for a 15-year mission was added to the battery option. The low technology status of advanced flywheels and the typical discounting of resupply costs would make NiCd batteries a likely selection for the initial Space Station.

As was the case for the weight comparison, consideration of the IPAC concept greatly altered the relationships. The initial cost of both IPAC options was lower than either of the electrochemical options. Surprisingly, the SOA-IPAC system had the lowest initial cost.

Consideration of relative system efficiencies further benefited the inertial storage options but not to the extent shown in the weight comparison. Solar array cost deltas are tabulated in Table 5.

TABLE 5 - SOLAR ARRAYS RELATIVE TO 160 KW ARRAY FOR INERTIAL SYSTEMS

ITEM	NiCd BATTERIES	RFC
Power Delta	+ 21 kW	+ 31 kW
D&D	+ 1.0	+ 1.4
FH	+ 6.0	+ 8.8
Launch	+ 1.3	+ 2.0
Total Initial	+ $ 8.3 M	+ $ 12.2 M
15-Year Drag	+ $ 3.3 M	+ $ 5.0 M

The objective of the cost analysis was to explore the close weight comparison between RFC's and SOA-IPAC options. Results strongly favored SOA-IPAC. Further, the SOA-IPAC option had lower initial and lower 15-year mission costs than either electrochemical/CMG option, and projected technology improvements offered the technology transparency desired for growth Space Stations.

CONCLUSIONS

The weight comparison found SOA-IPAC competitive with RFC/CMG systems. Both of these systems were much lighter than conventional NiCd battery/CMG systems.

Results from the cost analysis strongly favored SOA-IPAC over RFC/CMG systems and also showed lower costs than NiCd/CMG systems. Thus, SOA-IPAC would appear to be an attractive approach for the initial Space Station and possible technology improvements would further the appeal for the initial and/or growth Space Station.

REFERENCES

(1) Notti, J. E.; Cormack, A,. III; and Schmill, W. C.: Integrated Power/Attitude Control System (IPACS) Study, Volume I - Feasibility Studies. NASA CR-2283, April 1974.

(2) Will, R. W.; Keckler, C. R.; Jacobs, K. L.; Description and Simulation of an Integrated Power and Attitude Control System Concept for Space-Vehicle Application. NASA TN D-7459, April 1974.

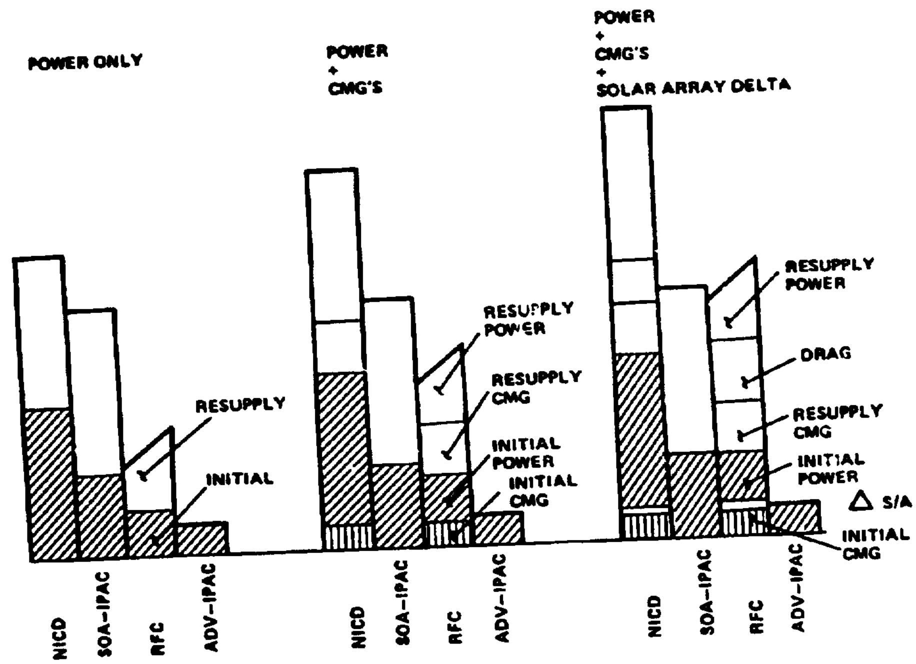

Figure 1.- Weight comparison.

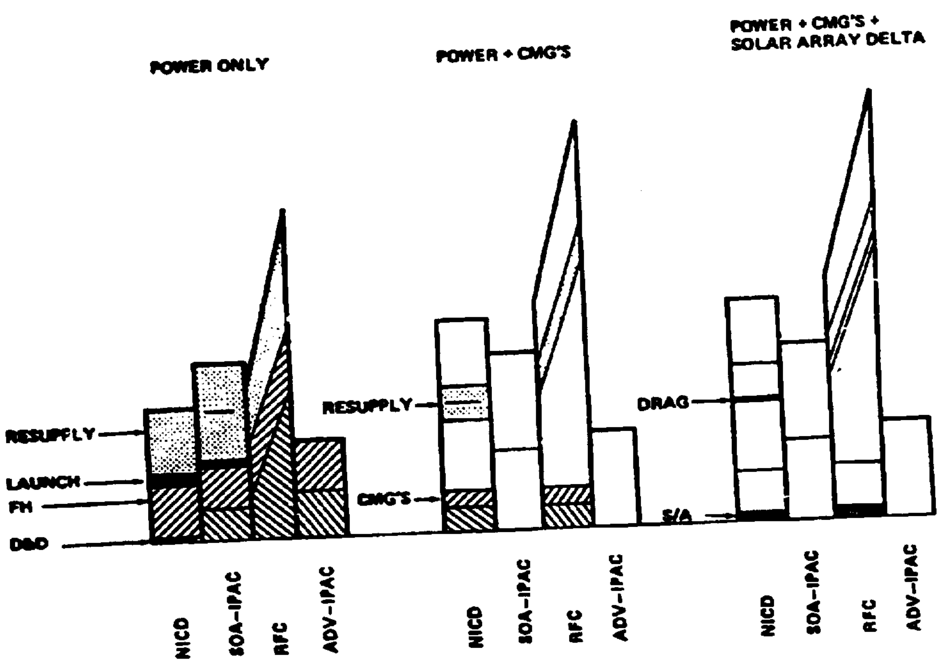

Figure 2.- Cost comparison.