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PERSPECTIVES ON ENERGY STORAGE WHEELS
FOR SPACE STATION APPLICATION

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OVERVIEW

The purpose of this paper is to address several of the issues of the workshop from the perspective of a potential Space Station developer and energy wheel user. Systems' considerations are emphasized rather than component technology. The issues of concern are: What is the potential of energy storage wheel (ESW) concepts? What is the current status of the technology base? Does justification exist for advanced technology development? How should such a technology program be defined? etc.

Fig. 1 illustrates the logic flow of the presentation. The study concludes that energy storage in wheels is an attractive concept for immediate technology development and future Space Station application.

- THE IPACS LEGACY

- TECHNOLOGY ADVANCE IN LAST DECADE

- HOW DO ESWs STACK UP FOR SPACE STATION?
 - A SYSTEMS POINT OF VIEW

- TECHNOLOGY ISSUES

- CONCLUSIONS & RECOMMENDATIONS

Figure 1

SUMMARY OF IPACS FEASIBILITY WORK (1970)

The Integrated Power and Attitude Control System (IPACS) work was performed by the NASA Langley Research Center and its contractor, Rockwell International (see refs. 1, 2, and 3). This effort provides a valuable legacy of information for several reasons. In terms of scope, it is the most comprehensive treatment of the application of ESW's to spacecraft at this time despite being approximately 10 years old. It treats systems as well as component-level issues on a rational and consistent basis.

A brief summary of the work and the related conclusions are given in Fig. 2. A much more comprehensive summary is given in ref. 1. In general, the major conclusions of the study are still valid today.

- DESIGN CONCEPTS DEVELOPED FOR A VARIETY OF SPACE APPLICATIONS
 - (MODULAR SPACE STATION, TDRS, EARTH OBSERVATION SPACECRAFT, RESEARCH & APPLICATIONS MODULE, MJS PLANETARY SPACECRAFT, & EXTENDED-DURATION ORBITER)
 - COST & WEIGHT ADVANTAGES FOR MOST MISSIONS
 - TYPICAL ENERGY DENSITIES APPROXIMATELY TWICE THAT OF NiCd BATTERIES
 - ADVANTAGES INCREASE WITH NUMBER OF CHARGE/DISCHARGE CYCLES
 - READILY ADAPTABLE TO GIMBALED & NONGIMBALED APPLICATIONS
 - SUBSTANTIAL PERFORMANCE IMPROVEMENT SHOWN WITH CONSERVATIVE TECHNOLOGY ADVANCES
 - DYNAMIC SIMULATION OF SIMULTANEOUS ENERGY MANAGEMENT & ATTITUDE CONTROL, NO SIGNIFICANT PERFORMANCE OR DYNAMIC INTERACTION PROBLEMS
 - DETAILED DESIGN APPROACH ESTABLISHED
 - ROTATING ASSEMBLY EMPLOYING TITANIUM ROTOR DEVELOPED & SUCCESSFULLY TESTED
 - MODIFIED CONSTANT STRESS ROTOR SHAPE UTILIZED
- TECHNICAL FEASIBILITY, PERFORMANCE & COST ADVANTAGES ESTABLISHED
 - MOST APPLICABLE TO SPACECRAFT WITH LARGER ENERGY & MOMENTUM STORAGE REQUIREMENTS & LONG LIFE

Figure 2

IPACS DESIGN CONCEPT
(EARLY 1970's TECHNOLOGY)

Fig. 3 illustrates the IPACS design concept considered to be state-of-the-art technology in the early 1970's. The laboratory test model employed a high-strength-to-weight titanium alloy rotor and ball bearings with thin-film lubrication for low losses. The rotor design was a modified constant stress shape. Other parameters include:

- Component weight: 173 lb
- Rated angular momentum: 1075 ft-lb-sec
- Rated power delivery: 2.5 kW
- Rated energy storage: 1.1 kWh
- Operating speed range: 17,500 to 35,000 rpm

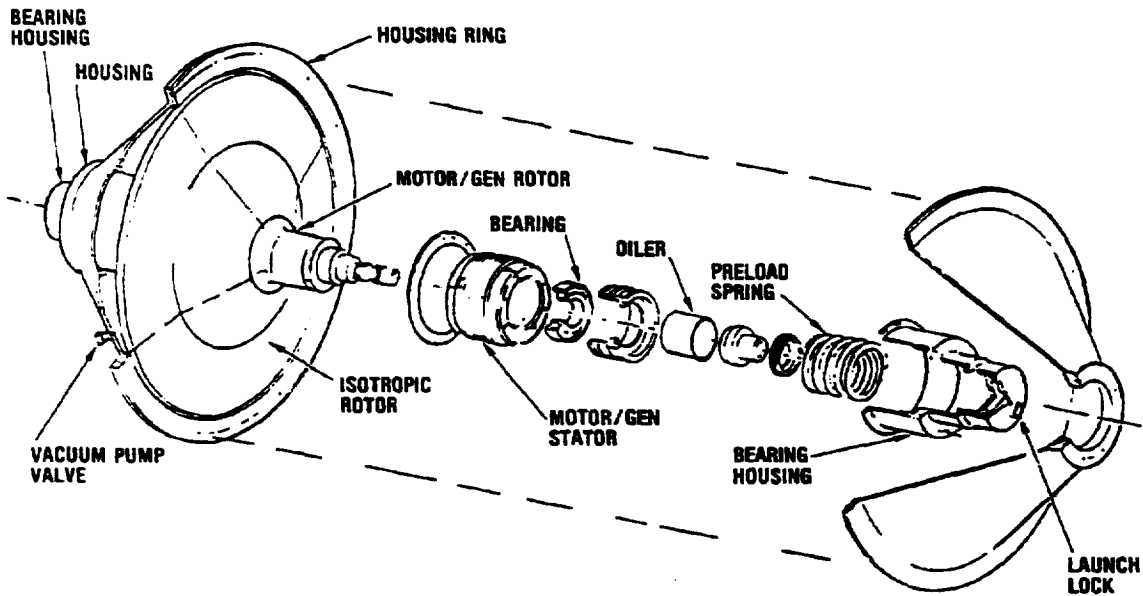


Figure 3

TECHNOLOGY ADVANCES SUPPORTING SPACE APPLICATIONS OF ESW's
(LAST DECADE)

During the last decade, appreciable advances have occurred in the three basic technology areas which form the constituent parts of an advanced ESW System (Fig. 4). Improvements in permanent magnets, design of the magnetic elements, and advancements in power processing and control circuitry have given rise to improved energy recovery efficiencies. These have gone from the 60% range to a potential value over 90% under certain ideal conditions. Ref. 4 presents favorable test data approaching this range.

The magnetic bearing technology has seen many more laboratory and operational system developments and tests. Although the specific magnetic bearing design concept most appropriate to ESW application may not have been selected yet, the general technology is sufficient for incorporation in ESW space applications. The potential merits of very low friction, controlled rotor dynamics, and a maintenance-free, long-life rotor system are sufficient to suggest leap-frogging past the use of ball-bearing technology along with the attendant lifetime and maintenance concerns. The magnetic bearings are the crucial element in achieving a 20-year lifetime without rotor servicing and maintenance. The long-life potential of ESW's may well prove to be their single biggest cost advantage relative to regenerative fuel cell and battery systems which require much more frequent changeout (order of five years) and even more frequent servicing.

The composite rotor technology is the key to achieving higher energy densities, and the recent DOE energy wheel development testing program (see ref. 5) provides a valuable legacy in this area. If historical precedent has meaning, the advances in composite system stress-bearing properties are increasing at a rate that exceeds the energy density improvements seen in secondary battery systems over the last 15 years. Extrapolation suggests that future improvement in composite rotor energy density will advance faster than that of batteries.

There are many agencies and firms beyond those named in figure 4 who have provided strong contributions to the ESW technology base, and the author apologizes for these omissions.

It is concluded that the three basic technology building blocks in figure 4 are adequately developed to support the ESW technology advancement. The next most important technology program step is to define how best to integrate these three areas into a highly efficient ESW System and provide laboratory verification of the performance. Improvements in the three technology areas should also be supported since further advances seem quite feasible.

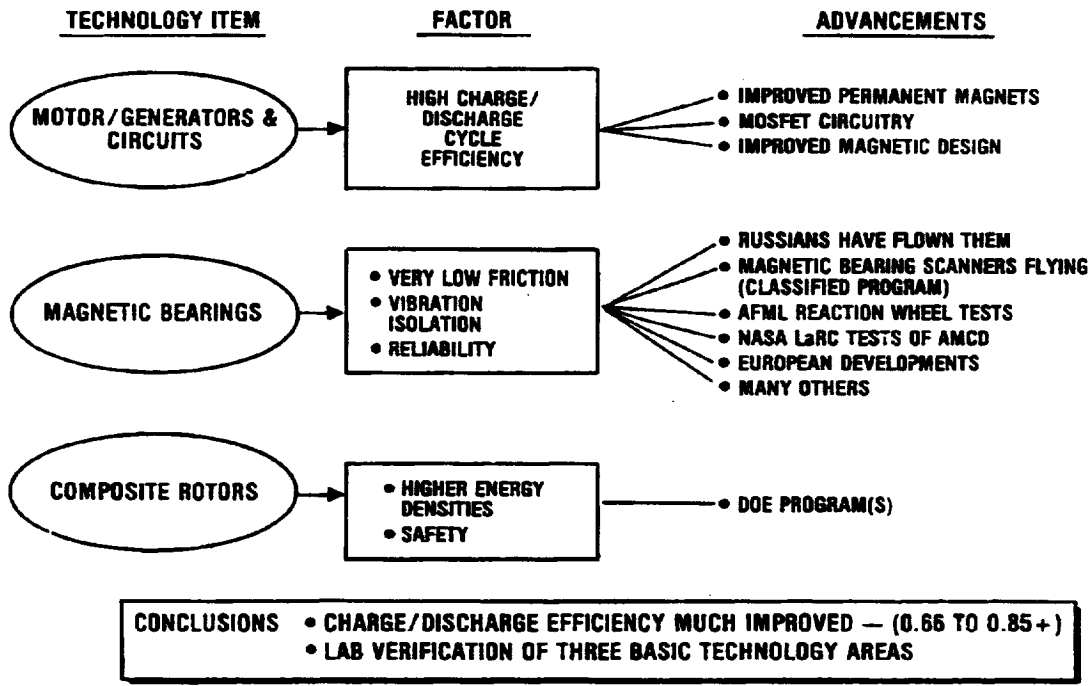


Figure 4

**ELECTRICAL POWER SYSTEM MASS FOR VARIOUS
STORAGE COMPONENT EFFICIENCIES & ENERGY DENSITIES**

The curves and data points shown in Fig. 5 present estimates of the electrical power system (EPS) mass for several parameter variations and for three potential energy storage component types. The data show a distinct advantage for the ESW System. Of course, it is recognized that relatively few test data exist for this type of system, and its predicted performance is more uncertain.

In addition to EPS mass, the storage component energy recovery efficiency has a significant impact on other subsystems, such as the extra thermal control system capacity needed to reject the heat dissipated in the storage element, and propellant required to overcome the drag due to solar array size increases. The ESW System has a clear-cut advantage in these two areas. Of course, the most notable mass saving is in the attitude control system. The control moment gyro mass savings, by integrating the attitude control function with the ESW System, is in excess of 1.8 megagrams for a typical Space Station.

Over the 20-year Space Station life cycle, relatively large mass savings also accrue for the ESW System due to its potential 20-year life. The competing systems typically require changeout at much more frequent intervals as previously noted.

It is concluded that appreciable system mass savings beyond the energy storage element itself can result from its higher energy recovery efficiency. Although formal costing has not been done, these results tend to indicate a possible cost saving.

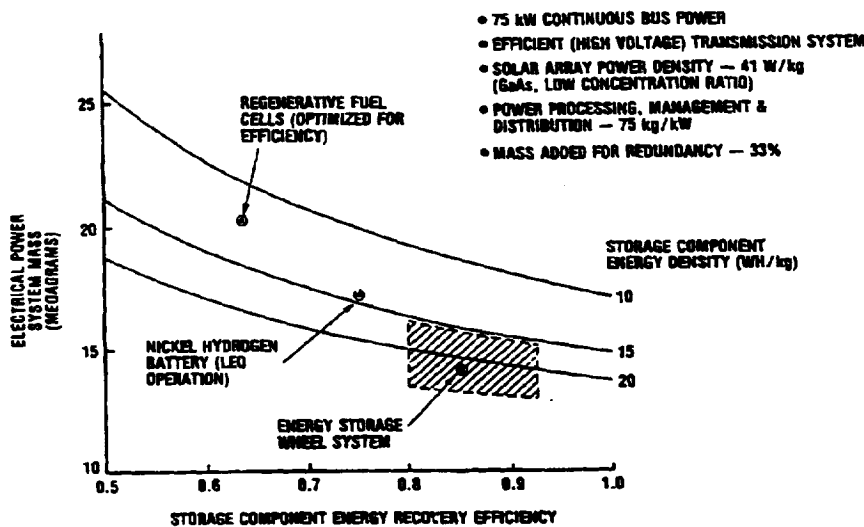


Figure 5

MOMENTUM BUILDUP FROM VARIOUS SOURCES

Fig. 6 provides data for typical sizing of Space Station control moment gyros (CMG's) and for a variety of conditions and situations. Normal CMG sizing of about 20,000 ft-lb-sec (approximately 4000 lb weight) is possible. This is achieved by flying in constrained (low disturbance torque) orientations and by performing the infrequent operations requiring large angular momentum with reaction control thrusters. Use of the Integrated Power and Attitude Control System (IPACS) approach can save most of this CMG weight and cost. In addition, the ESW's produce an excess of angular momentum which will enable more robust operation than is possible with CMG's. Ref. 6 presents additional data and rationale as to why the CMG sizing can become much larger in the absence of prudent attitude constraints, payload operations, and momentum management techniques.

ITEM	BASIS	MOMENTUM BUILDUP* (ft-lb-sec)	
		WITH ORBITER	WITHOUT ORBITER
GRAV GRAD TORQUE:			
• LVLH ATTITUDE	PRINCIPAL AXES $\pm 10^\circ$ FROM LVLH	8,470	2,250
• LVLH ATTITUDE	BODY AXES ALIGNED TO LVLH	200,000	12,000
• LVLH ATTITUDE	WORST CASE PRINCIPAL AXES ORIENTATION	243,000	64,500
• INERTIAL ATTITUDE	PRINCIPAL AXIS $\pm 10^\circ$ FROM POP	18,800	5,120
AERODYNAMIC TORQUE	90-day ORBIT DECAY, CP-CG = 10 ft	—	10,700
DYNAMIC PAYLOAD OPERATIONS	LARGE PAYLOAD MOVED WITHIN 1 ORBIT PERIOD	2,000	2,000
ATTITUDE MANEUVERING	MINIMUM SLEW RATE = $40^\circ/\text{min}$ (90° IN QUARTER ORBIT)	64,900	22,600
CREW DISTURBANCE	200 lb PUSHOFF IN WORST LOCATION	6,000	4,000
DOCKING DISTURBANCE	CLOSURE VELOCITY = 0.5 ft/sec	81,110	—

*MOMENTUM STORAGE CAPACITY REQUIRED IF CONTROLLED WITH MOMENTUM STORAGE DEVICES, SECULAR COMPONENTS BASED ON BUILDUP OVER ONE ORBIT

Figure 6

SOME ENERGY STORAGE WHEEL (ESW) SYSTEM DESIGN ISSUES

Fig. 7 presents a series of design issues related to the Space Station application and should be given consideration in ESW technology development programs. Many of the earlier design concepts from previous studies and other ESW applications may no longer be appropriate due to the unique requirements of Space Station and due to the availability of new design concepts. A methodical search for the best design approaches and rigorous engineering is necessary to avoid time-consuming and costly correction of design problems. It is concluded that the cost-effective development of the ESW technology and systems presents an achievable design challenge.

SYSTEM LEVEL

- ENERGY STORAGE ONLY vs INTEGRATED WITH ATTITUDE CONTROL?
- BEST WHEEL ARRAY CONFIGURATION?
 - GIMBALED vs NONGIMBALED?
 - COUNTER-ROTATING PAIRS vs SKEWED ARRAYS, etc.?
- REDUNDANCY & RELIABILITY?
- THERMAL CONTROL?
- ACCOMMODATION OF STATION GROWTH?
 - TECHNOLOGY UPGRADING

ELEMENT LEVEL

- BEARINGS — BALL vs MAGNETIC?
- MAGNETIC BEARING DESIGN APPROACH?
- BEST ROTOR SHAPE?, HOOP vs HUB, etc.?
- MOTOR/GENERATOR TYPE & DESIGN?
- CIRCUITRY?
- COMPOSITE ROTOR DESIGN?
- SAFETY APPROACH?

DESIGN OF ESW SYSTEMS FOR SPACE STATION REPRESENTS A FORMIDABLE, BUT ACHIEVABLE, DESIGN CHALLENGE

Figure 7

CONCLUSIONS AND RECOMMENDATIONS

Many supporting conclusions are drawn in the text, and the major ones are summarized in Fig. 8. The ESW concept is found to be a very attractive option for Space Station (as it was a decade ago). The prompt initiation of a well-conceived technology development program, including laboratory testing, is necessary in order to meet a technology readiness need date that is consistent with the Space Station development goals established by the President. The destiny of such a technology development program may well rest on the action of this workshop.

- **THE THREE BASIC TECHNOLOGY BUILDING BLOCKS (MOTOR/GENERATOR/CIRCUITRY, COMPOSITE ROTORS, & MAGNETIC BEARINGS) ARE ADEQUATELY DEVELOPED TO PROCEED WITH ESW TECHNOLOGY DEVELOPMENT**

- **THE MOST IMMEDIATE TECHNOLOGY NEED IS DEFINING HOW TO INTEGRATE THESE BUILDING BLOCKS INTO A WELL ENGINEERED ESW SYSTEM & VALIDATING ITS PERFORMANCE. LABORATORY PERFORMANCE VERIFICATION IS MANDATORY**

- **ADVANCES IN THE THREE BASIC TECHNOLOGY AREAS ARE DESIRABLE & WILL FURTHER ENHANCE THE APPLICABILITY OF THE CONCEPT**

- **DEVELOPMENT OF THE ESW TECHNOLOGY & SYSTEMS FOR SPACE STATION PRESENTS AN ACHIEVABLE, ENGINEERING CHALLENGE**

Figure 8

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