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SPACE OPERATIONS CENTER SYSTEMS ANALYSIS
(CONTRACT NAS9-16151, Mod 75)

STUDY OF FLYWHEEL ENERGY STORAGE FOR SPACE STATIONS

D180-27951-1

FINAL REPORT

FEBRUARY 1984

FOR
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

Boeing Aerospace Co.
P. O. Box 3999
Seattle, Washington 98124

FOREWORD

This study was managed by the Lyndon B. Johnson Space Center. Keith Van Tassel was the NASA/JSC Study Technical Manager. This study was conducted by The Boeing Aerospace Company, Large Space Systems Group. The SOC study manager was Gordon W. Woodcock; the technical staff engineering manager was Dr. Richard Olson; the task manager was Sidney W. Silverman; and Sidney Gross was the principal investigator.

Prepared By: Sidney Gross

Sidney Gross

Approved By: Sidney W. Silverman

Sidney W. Silverman

Approved By: Richard L. Olson

Richard Olson

Approved By: Gordon R. Woodcock

Gordon R. Woodcock

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

1.0 INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

Energy storage systems for spacecraft in the past generally have used nickel cadmium (Ni-Cd) batteries for rechargeable systems, or hydrogen-oxygen fuel cells for relatively short duration missions, such as Apollo or Shuttle. Regenerable fuel cells have also been evaluated and found to have good potential for space stations (Ref. 1.1-1). This study evaluates the potential of flywheel systems for space stations using the Space Operations Center (SOC) as a point of reference, and gives comparisons with batteries and regenerative fuel cells.

In the flywheel energy storage concept, energy is stored in the form of rotational kinetic energy using a spinning wheel. Energy is extracted from the flywheel using an attached electrical generator; energy is provided to spin the flywheel by a motor, which operates during sunlight using solar array power. The motor and the generator may or may not be the same device.

Relatively little serious study has been given to the subject of spacecraft energy storage using flywheels. A pioneer study by NASA (Ref. 1.1-2) and Rockwell (Ref. 1.1-3) resulted in studies and demonstration hardware based on the premise that energy storage and momentum management systems would be integrated. A recent study by Hughes Aircraft (Ref. 1.1-4) concluded that flywheel energy storage for spacecraft is not advantageous. Another recent study by NASA Goddard (Ref. 1.1-5) concluded that flywheel energy storage is worthwhile for spacecraft. Most of the flywheel work in past years has been devoted to terrestrial energy storage, where cost was always a desideratum. Department of Energy support of flywheel work has been withdrawn, so, with the exception of Department of Transportation work at AiResearch, government-sponsored flywheel work is now drawing to a close in the U.S.

1.2 SUMMARY

Flywheel energy storage systems have a very good potential for use in space stations. This system can be superior to alkaline secondary batteries and regenerable fuel cells in most of the areas that are important in spacecraft applications. Of special importance relative to batteries, are high energy density (lighter weight), longer cycle and operating life, and high efficiency which minimizes the amount of orbital makeup fuel required. In addition, flywheel systems have a long shelf life, give a precise state of charge indication, have modest thermal control needs, are capable of multiple discharges per orbit, have simple ground handling needs, and have the potential for very high discharge rate.

The major disadvantages of flywheel energy storage systems are that power is not available during the launch phase without special provisions, and in-flight failure of units may force shutdown of good counter-rotating units, amplifying the effects of failure and limiting power distribution system options. Additional disadvantages are: no inherent emergency power capability unless specifically designed for, and a high level of complexity compared with batteries. On net balance, the potential advantages of the flywheel energy storage system far outweigh the disadvantages.

1.3 PROGRAM OBJECTIVES

The general objective of this study is to analyze the potential of flywheels for space station energy storage, and determine if flywheels are worthwhile and competitive with other energy storage systems. Specific tasks are as follows:

Task 1 -- Requirements and Guidelines

Define typical space station requirements and guidelines, both for energy storage and attitude control.

Task 2 -- Electrical Power Systems Study

Define and analyze electrical power systems based on flywheels.

Task 3 -- Integration With Momentum Management System

Determine if it is worthwile to integrate the flywheel energy storage system with the momentum management system.

Task 4 -- Assessment of Benefits and Penalties of Flywheels

Evaluate the benefits and penalties associated with the use of flywheel systems. Make comparisons with batteries and regenerable fuel cells.

Task 5 -- Documentation

Prepare monthly progress reports, a final report, and make an oral presentation to NASA.

1.4 BACKGROUND

The background upon which this study is cast is the Space Operations Center (SOC). Study of the SOC was conducted by Boeing in two parts: a Phase A Systems Analysis and a Phase A Extension. The Phase A study analyzed and defined a manned space station dedicated primarily to operational missions. It developed system design requirements, and design and operational concepts. The Phase A Extension concentrated on development of mission models and analysis of SOC utility. That phase of study considered applications science and technology missions as well as operational missions. The SOC study was managed by the Lyndon B. Johnson Space Center, with Sam Nassiff as the Study Technical Manager. The final report includes five documents:

D180-26785-1	Vol. I	Executive Summary
D180-26785-2	Vol. II	Programmatics
D180-26785-3	Vol. III	Final Briefing
D180-26785-4	Vol. IV	SOC System Analysis Report
D180-26495-2	Rev. A	SOC System Requirements
D180-26495-3	Rev. A	SOC System Definition
	Report	

A separate study was also made to determine the applicability of regenerable fuel cell systems for SOC. That study (Ref. 1.1-1) is documented in Boeing document D180-27160-1, and is titled "Analysis of Regenerative Fuel Cells", dated December 20, 1982.

1.5 ACKNOWLEDGEMENTS

The report is based on a study performed by The Boeing Aerospace Company for the Johnson Space Center, Contract NAS9-16151, Mod. 75. Keith Van Tassel was the technical monitor. Space station momentum management requirements and analyses were performed by Rose Zdybel. Valued consultations with many technologists in this field are gratefully acknowledged, particularly the following:

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2.0 DEFINITION OF REQUIREMENTS AND PENALTIES

The following requirements and penalties are defined for the SOC energy storage system.

<u>Orbital Conditions</u>	
Altitude	370 km (200 NM) to 450 km (243 NM)
Inclination	28.5 degrees
Solar Cycle	Sunlight duration - 55 minutes Occult duration - 37 minutes
<u>Bus Voltage</u>	
Regen. Fuel Cells	200 +2%, -20% dc
Batteries	200 +10%, -30% dc
Flywheels	200 ±2%, Transients ±4%
MIL 1539 (Ref.)	28 +21.4%, -21.4% dc
<u>Equipment Cooling</u>	
Cold Plate Mounting and Cooling (batteries & electronics)	11 percent of equipment weight
Radiator area for batteries (5°C)	14 W/ft^2 radiation surface
Radiator area for electronics (20°C)	19 W/ft^2 radiation surface
Radiator area for flywheel and its electronics (20°C)	19 W/ft^2 radiation surface
Radiator weight	1.27 lb/ft^2 of radiator (2 ft^2 radiation surface/ft^2 radiator in plan view)

Radiator area for fuel cell	Temperature	Watts/ft^2 radiator surface
	60°C	37.2
	70°C	42.9
	80°C	49.0
Design Choice	82.2°C	50.5
	90°C	55.7

Solar Array Incremental Weight Penalty (weight per unit array - generated power)

Half SOC	30.6 lb/kW
Full SOC	30.6 lb/kW
Growth SOC	30.6 lb/kW

Electric Power Requirements

The SOC electric power requirements for loads are 50 kW in sunlight and 39.23 kW during occultation. In addition, the solar array must be sized for the additional power needed for energy storage. Where weight comparisons are made between competitive energy storage systems, an electrical load of 50 kW continuous was used in order to make the results less specific to the initially determined SOC loads, and to permit comparison with the results of Ref. 1.1-1.

In support of studies on integration of energy storage and momentum management systems, solar array sizes ranging from 110 kW to 420 kW of solar array power were analyzed. Spacecraft power levels would be roughly half of these power levels for battery systems. This is discussed in Section 8.0.

Emergency load requirements have not been defined in this study. The reason for this is that the weight of a flywheel system is very sensitive to the emergency requirement, whereas batteries often are not because of their inherent capacity reserve, as shown in Ref. 1.1-1 for postulated SOC emergency requirements. In the analysis given in Section 7.0, emergency requirements are considered as an additional variable.

Attitude Control System Requirements and Guidelines

These are defined in Section 8.0.

3.0 EFFICIENCY CONSIDERATIONS

3.1 THE IMPORTANCE OF HIGH EFFICIENCY

Energy storage efficiency is a key factor in the optimization of any particular energy storage system, and also in the choice between one system and another. Although some missions can be visualized where low weight is paramount, high efficiency designs are compelling for the general purpose solar array-powered space station.

The reasons high efficiency is important are: (1) cost can be lowered by reducing solar array size for a given load, saving both on array cost and on fuel for orbit-makeup propulsion; (2) space station power capability can be effectively increased by permitting more electrical payload for a given size of solar array (alternative to item 1); (3) life of the energy storage system is increased due to the low current density designs needed for high efficiency with electrochemical systems; (4) peak power and failure mode power capabilities are increased due to the low current density electrochemical designs needed for high efficiency; (5) attitude control performance is improved.

3.1.1 Solar Array Size and Cost

An efficient energy storage system reduces the size of the solar array. This is shown parametrically in Figure 3.1-1, and in Figure 3.1-2 for a typical SOC requirement. Costs of solar arrays are expected to be considerably greater than costs of energy storage systems, on the order of six times the cost of batteries. Large solar arrays possibly will also require complex, deployable structures to provide stiffness, and the cost of this would be significant. Efficient energy storage can reduce solar array costs by reduction of solar array size, or alternatively, permit a greater electrical payload for a given solar array size.

3.1.2 Propulsion Resupply Due to Solar Array Drag

Significant quantities of propulsion fuel must be resupplied regularly to offset the effects of solar array drag, and maintain the space station at a selected orbit. Inefficient energy storage systems require larger solar arrays, and hence more propulsion fuel for station keeping. This is shown in Figure 3.1-3 for both hydrazine and hydrogen-oxygen propellants. This penalty can be considerable over the life of the spacecraft.

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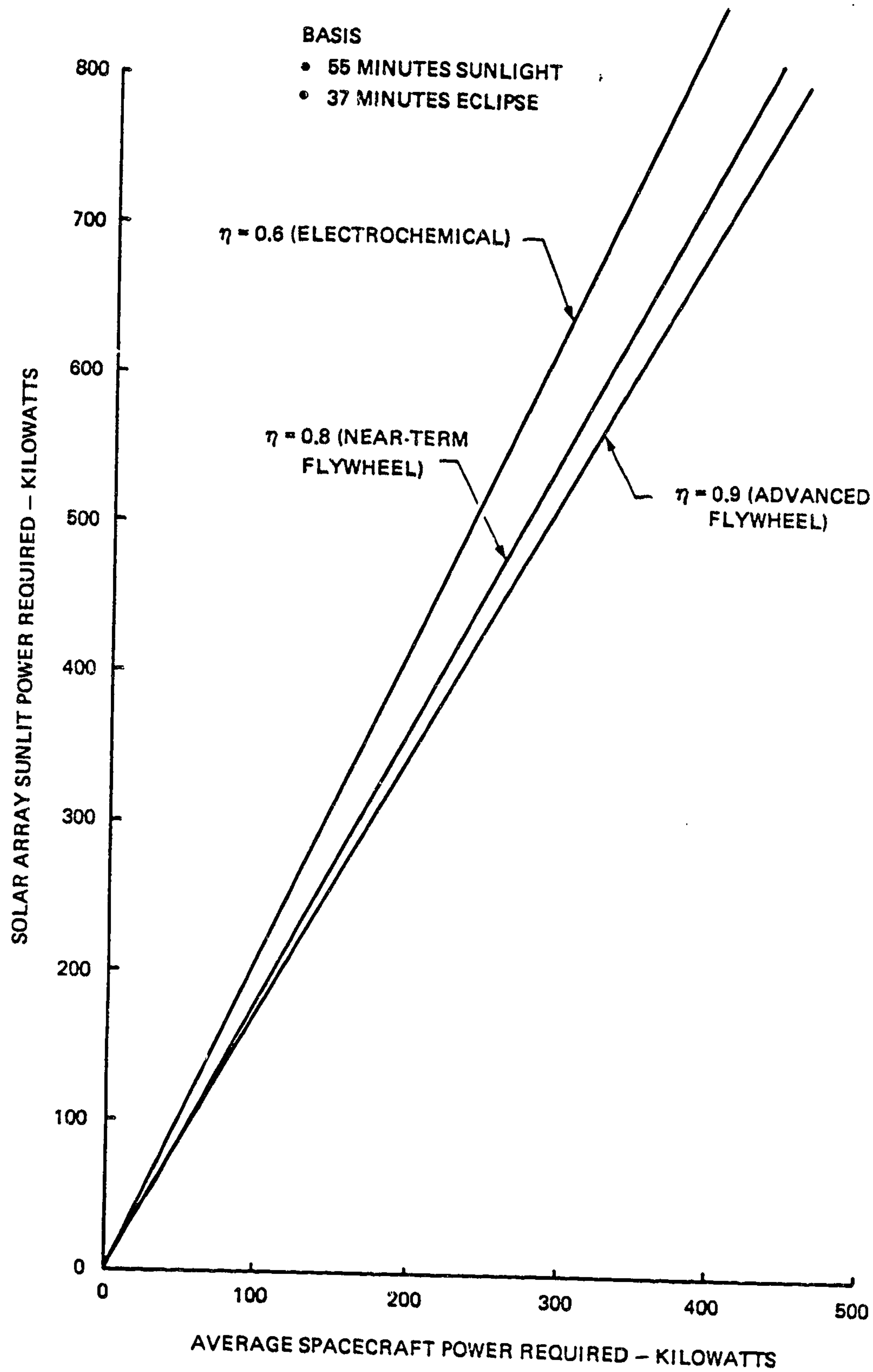


Figure 3.1-1. High Efficiency Energy Storage Systems Result in Smaller Solar Arrays

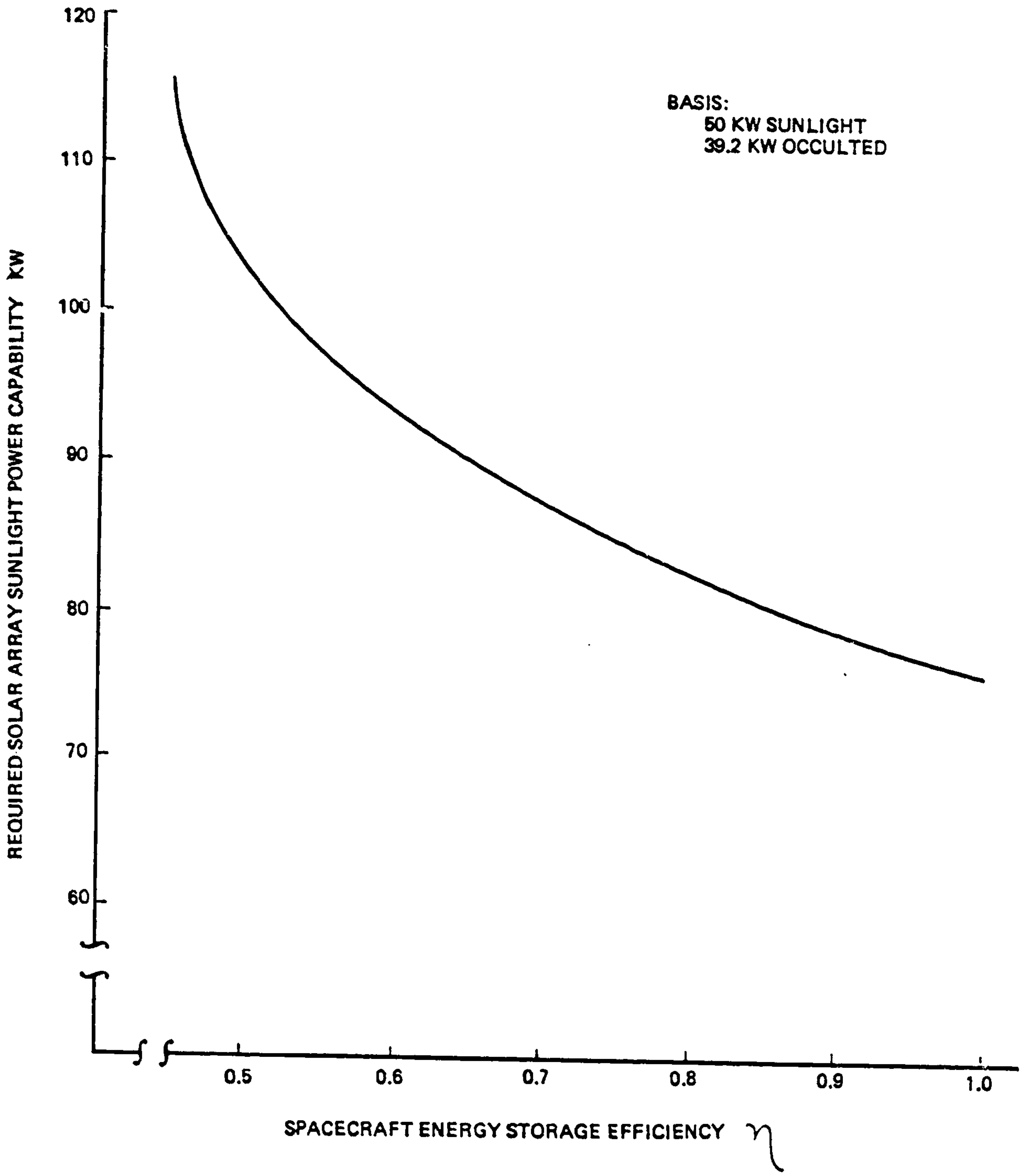


Figure 3.1-2. Effect of Efficiency on Solar Array Size

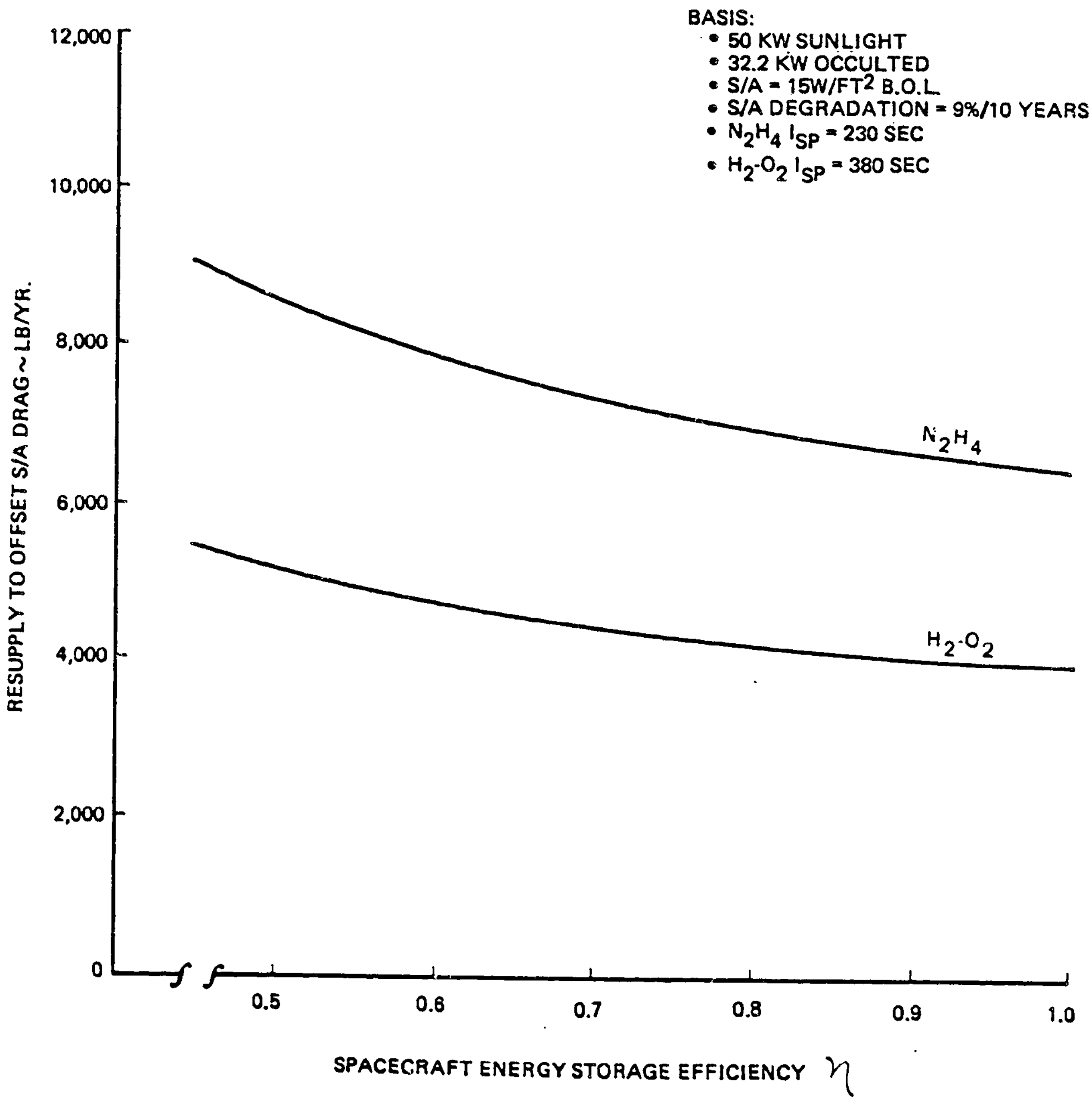


Figure 3.1-3. Propulsion Resupply Due to Solar Array Drag

3.1.3 Attitude Control Effects

Large solar arrays penalize the attitude control system in several ways, as discussed in Section 8.0. Of major concern is the fact that propellant weight consumption rises with array size increase. Attitude control penalties are related to energy storage system efficiency through its effect on solar array size.

3.2 EFFICIENCY OF FLYWHEEL ENERGY STORAGE SYSTEMS

3.2.1 Contributors to Inefficiency

The definition of efficiency commonly used is the energy storage watt-hours out divided by the watt-hours in. This does not account for poor utilization of the solar array, however. Therefore, the definition of efficiency used for this study is the energy storage watt-hours out divided by the watt-hours available from the energy storage section of the solar array. Possible contributors to energy storage system inefficiency with flywheels are: (1) losses from cyclic stress of the flywheel; (2) inefficiency of "charging" during the motor operating phase when the wheel is spinning up; (3) inefficiency of "discharging" during the generator phase when energy is being extracted as the wheel is spinning down; (4) inefficient use of solar array area dedicated to energy storage; (5) power consumption for temperature control; (6) bearing friction or power consumption for magnetic bearings, if used. These items are discussed below.

(1) Losses From Cyclic Stress. If one gradually loads a material specimen in tension, then gradually reduces the load, a plot of the stress-strain curves will generally be slightly different for the loading and unloading directions due to hysteresis, which is related to an energy loss. There would be a concern, therefore, whether typical composite materials used for flywheels would exhibit such hysteresis and a concomitant energy loss. At least one series of tests has been conducted that is very encouraging. This was done at Hercules Corp. using test samples of carbon fiber in epoxy layup. The samples were cycled to over 70 percent of ultimate strength, and showed no hysteresis. The samples were loaded in pure tension, with all fibers laid parallel. A more comprehensive series of tests is needed to define behavior under stress conditions typical of flywheel operation, using other matrix materials, and possibly also including weaves and other arrangements with some fibers in the radial direction. Even so, it is expected that hardly any hysteresis will result after an initial internal

deformation. Therefore, no energy loss is attributed at this time to the cyclic stress of flywheels because hysterises-free materials are expected to be used.

(2) Motor Inefficiency. Spinup of the flywheel by the motor results in losses from the motor and its controls. These losses are discussed in Section 5.0. Overall motor and control efficiency for conventional motor/generator technology is determined to be 89.5 percent; for advanced motor technology, the efficiency is expected to be 96.5 percent (Section 5.0).

(3) Generator Inefficiency. Extraction of energy from the wheel during spindown results in losses from the generator and its controls. These losses are discussed in Section 5.0. Overall generator and control efficiency for conventional motor/generator technology is determined to be 91.0 percent; for advanced technology, the efficiency is expected to be 96.5 percent.

(4) Inefficient Use of Solar Array Charging Area. The solar array must have a particular amount of area sized for or dedicated to charging batteries, or with a flywheel system, for powering the motor. If the energy storage system does not make maximum use of all that allocated power, then this becomes a loss chargable to the energy storage system. The motor can be operated at constant power, and thus should obtain very little, if any, inefficiency from this cause.

(5) Power Consumptions For Temperature Control. The use of heat pipes is assumed for temperature control of the motor/generator and its control electronics. Batteries require close temperature control at relatively low temperature, and therefore actively controlled heat pipes are appropriate, which consume some electrical power. The flywheel motor/generator and controls operate at relatively high temperature and can accept a wide temperature range. Therefore, passive heat pipes should be acceptable with no requirement for control power.

(6) Power Consumption For Magnetic Bearings. Electrical power is consumed in the operation of magnetic bearings. This is discussed in Section 6.0. The estimated power consumption for the intermediate objective design (Section 4.0) is 3.9 watts/kilowatt, or 99.61 percent efficiency. The estimated power consumption for the advanced design is 2.8 watts/kilowatt, or 99.72 percent efficiency.

3.2.2 Voltage Range Effects

An inherent characteristic of secondary batteries is a relatively wide bus voltage spread due to the large difference between charge and discharge voltage. A regenerative fuel cell system will have about half the voltage spread of a $Ni-H_2$ battery. A flywheel motor/generator, on the other hand, can operate at a constant input voltage which is the same as the output voltage, and can control output voltages very closely, within approximately two percent. This allows the design of component power supplies to be more efficient. An estimate of the typical improvement in efficiency of these loads is shown in Figure 3.2-1. It is seen that an efficiency improvement of 0.8 percent is possible using the tighter voltage regulation obtainable with a motor/generator. Non-essential loads, such as payloads, could probably take advantage of the potential saving. However, loads essential to the operation of the spacecraft probably would have to be designed to meet the expected wide voltage range of the launch power source and the emergency batteries, and therefore could not take advantage of this. Thus, it is estimated that the solar array could be reduced in size about 0.8 percent due to this efficiency improvement.

3.2.3 Efficiency Comparisons

The calculated efficiency of the flywheel energy storage system is shown in Table 3.2-1. For the intermediate design objective, the overall efficiency is 81.1 percent; for the advanced design objective, the overall efficiency is 92.8 percent. Motor/generator efficiency is the major contributor to losses in both cases.

The efficiency of batteries and regenerative fuel cells was determined in Reference 1.1-1. The battery efficiency determination is reproduced in Table 3.2-2 and shows an overall efficiency in the general range of 55 to 60 percent. The efficiency of regenerative fuel cells can range from 48 percent for a minimum weight design to 67 percent for a high efficiency design. Thus, it is seen that a flywheel energy storage system is superior in overall efficiency to both batteries and regenerative fuel cell systems.

3.2.4 Non-Aerospace Benefits of High Efficiency Technology

The development of high efficiency motor/generators for flywheel systems could have an important spinoff for national energy conservation. It has been determined (Reference 3.2-1) that 58 percent of the electrical power in the U.S. is consumed by electric motors. The potential saving in power and oil imports is extremely large.

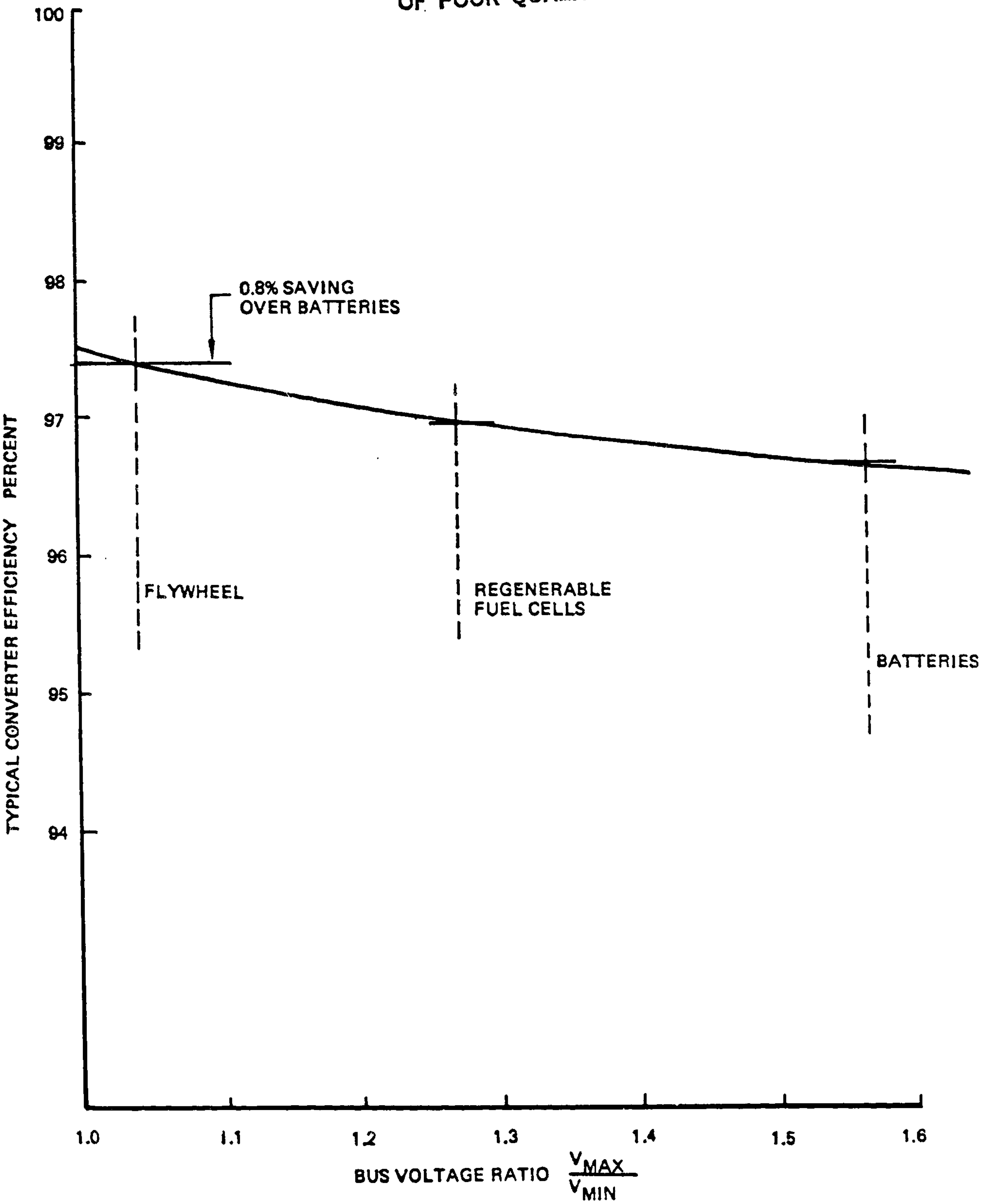


Figure 3.2-1. Effect of Bus Volt Regulation on Power System Efficiency

Table 3.2-1. Energy Storage Efficiency With Flywheels

	EFFICIENCY	
	INTERMEDIATE DESIGN OBJECTIVE	ADVANCED DESIGN OBJECTIVE
LOSSES FROM CYCLIC STRESS	100%	100%
MOTOR EFFICIENCY	89.5%	96.5%
GENERATOR EFFICIENCY	91.0%	96.5%
SOLAR ARRAY CHARGE AREA EFF.	100%	100%
HEAT PIPE POWER	100%	100%
MAGNETIC BEARING POWER	99.61%	99.72%
OVERALL EFFICIENCY	81.1%	92.8%

Table 3.2-2. *Energy Storage Efficiency Determination With $Ni\text{-}H_2$ Batteries*

		TYPICAL END-OF-LIFE PERFORMANCE	TYPICAL DESIGN	DESIGN POTENTIAL
BATTERY RELATED ITEMS	RECHARGE RATIO	1.08	1.09	1.075
	AVE CHARGE VOLTAGE	1.55V	1.57 V	1.53 V
	AVE DISCHARGE VOLTAGE	1.19 V	1.17 V	1.21 V
	FAILED CELL ALLOWANCE	---	---	---
	CELL BYPASS ELECTRONICS	---	---	---
SYSTEM RELATED ITEMS	SOLAR ARRAY CHARGE AREA EFF.	0.90	0.90	0.91
	BATTERY DIODES EFF.	0.995	0.995	0.995
	BATTERY CHARGER EFF.	0.93	0.93	0.93
	BATTERY HEAT PIPE POWER EFF.	0.975	0.970	0.97
	OVERALL EFFICIENCY	0.577	0.552	0.60

SAMPLE CALCULATION FOR DESIGN POTENTIAL:

$$\text{EFFICIENCY} = \left(\frac{1.21}{1.53}\right)\left(\frac{1}{1.075}\right)(0.91)\ (0.995)\ (0.93)\ (0.97) = 0.60$$

3.3 UTILIZATION OF EXCESS SUNRISE POWER

Spacecraft solar arrays become cold during occultation. Upon emergence into the sunlight, there is a higher voltage output, hence a high power output. This increased power condition lasts for about 20 minutes for typical rigid panels, and depends on the time to reach steady sunlit temperature, which is determined mostly by the unit thermal mass of the solar array; for flexible lightweight panels, it lasts only about 5 minutes.

This potential for extra power usually is not used. In a shunt regulated power system, the excess voltage is wasted; in the less common series regulated system with pulse-width modulated control, part of the excess power is sometimes used for battery charging, but this can compromise the batteries, which are charge-rate sensitive. Flywheels, within limits, are not charge-rate sensitive, and thus can make use of this additional power. It appears that a shunt regulated system is not amenable to use of this extra power, whereas a series regulated system can make use of it, such as a pulse-width modulated control with peak power tracker. It may be possible to conceive of a modified shunt regulation system which preserves shunting capability and also permits use of most of the excess power.

Typical conventional solar array transient performance in low earth orbit (Ref. 1.1-5) is shown in Figure 3.3-1. The incremental power due to the low temperature transient is an increase in solar array output of approximately seven percent, assuming controller efficiencies do not reduce with this added function. With a lightweight solar array, this would reduce to about two or three percent. The efficiency calculations of Table 3.2-1 assume this excess power is not available as part of the input power. Keeping that same assumption but utilizing the extra seven percent power anyway, the pseudo-efficiency calculated for comparison with efficiencies shown in Tables 3.2-1 and 3.2-2 would be: overall efficiency for the intermediate design objective, increase from 81.1 percent to 86.8 percent; and for the advanced design objective, increase from 92.8 percent to 99.3 percent.

Use of the extra power not only can improve efficiency, but also the size of the shunt heat dissipation system, if used, can be made smaller. Resistive heaters are generally used, and the weight and space they take is proportional to the peak dissipation power. Reduction of that peak dissipation power would therefore produce this additional saving.

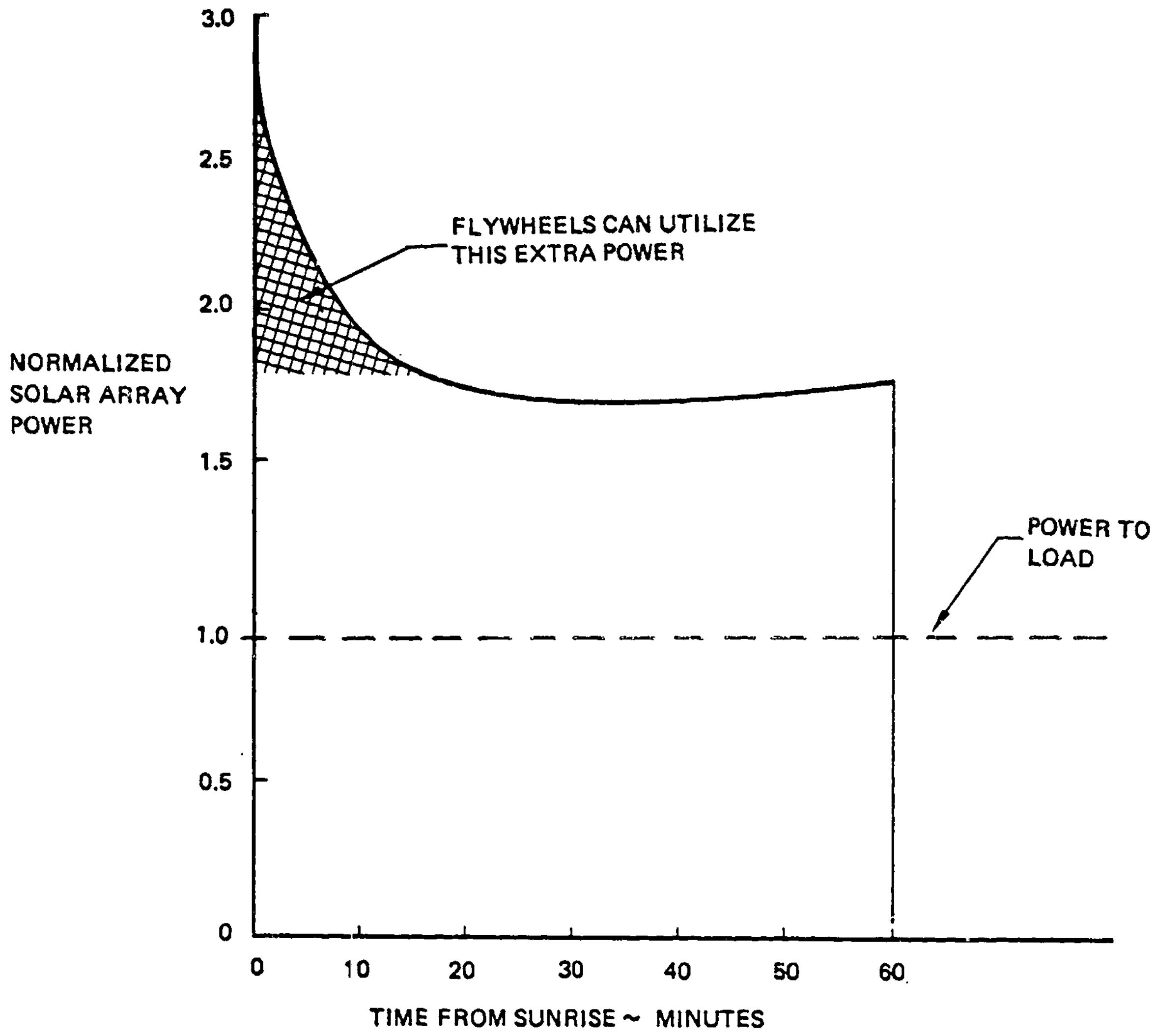


Figure 3.3-1. Typical Sun-Oriented Solar Array Performance in Low Earth Orbit

4.0 FLYWHEEL ROTORS

4.1 GENERAL CONSIDERATIONS

4.1.1 Theoretical Considerations For Energy Storage

Both material properties and geometry are variables in the design of flywheels. The theoretical relationships of flywheel energy storage can be approached by derivation of the stored energy using a simple geometry. If one considers a mathematical thin rim rotating about its axis, a hoop stress is generated as follows:

sigma = (rho)(V^2) EQN (1)

where sigma = tangential stress
rho = material density
V = peripheral speed

Since all points in a mathematically thin rim are at the same speed, the kinetic energy W is:

$W = \frac{1}{2} m V^2$ EQN (2)

Thus, the kinetic energy stored per unit mass is:

W/m = ½ (sigma)/(rho) $= \frac{1}{2}\ \sigma/\rho$ EQN (3)

It can be seen, therefore, that to store a large amount of energy per unit mass, the flywheel material must be able to accept a high stress, and should be of low density. The ratio (sigma)/(rho) is referred to as the specific strength of a material.

Departing from a mathematically thin rim to a rim of finite thickness, a point on the inner side of the rim does not have the same tangential speed as a point on the outer side of the rim. As a result, a radial stress will result. If the material can accept this radial stress, which isotropic materials such as metals can do, then this radial stress can be used to double the amount of theoretical energy stored, resulting in:

W/m = (sigma)/(rho) EQN (4)

Thus, the change from EQN (3) to EQN (4) accounts for the difference between uni-axial and multi-axial stress fields. In order to reach this theoretical limit, it is necessary to design the rotor to a specific optimal shape, referred to as the Stodola geometry, named for its inventor who determined this in 1924. The Stodola shape, applicable to isotropic materials, is a disc which tapers to zero thickness at infinity. All practical rotor designs have lesser capability due to geometry, and this is accounted for by introducing a shape factor K. Thus,

$$W/m = K\ (\text{sigma})/(\text{rho}) \qquad \text{EQN (5)}$$

Some of the simple shapes for which K has been determined theoretically are shown in Figures 4.1-1 and 4.1-2 (Refs. 4.1-2, 4.1-3 and 4.1-4). It is also possible for practical rotors to replace the K in equation (5) by the product K_1K_2 where K_1 is a purely geometric factor, and K_2 accounts for all other effects. An alternative basis is for K_1 to incorporate geometry, material properties, type of fabrication and failure mode, and limit K_2 to time-dependent effects for the specific material. Distinctions can also be made between fiber-controlled strength and transverse tensile strength in the definition of K (Reference 4.1-2).

4.1.2 Theoretical Considerations For Momentum Storage

Different theoretical relationships are involved for storage of angular momentum than for storage of energy in a flywheel. The momentum stored per unit mass (Ref. 4.1-1) in consistant units is:

$$H/m = k\left(2K\frac{\sigma}{\rho}\right)^{0.5} \qquad \text{EQN (6)}$$

where
H = angular momentum
m = mass
k = radius of gyration
K = shape factor

For simple shapes, the radius of gyration can be expressed in terms of the geometry. Note that the energy density, equation (3), is not a function of wheel size, whereas the momentum density, equation (6), does depend on wheel size. Thus, the maximum momentum per unit weight is achieved with large diameter flywheels. For momentum storage, diameter is even more important than materials strength, which has a square

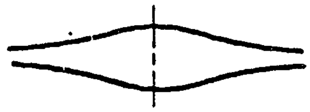
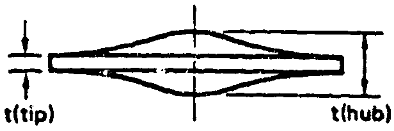
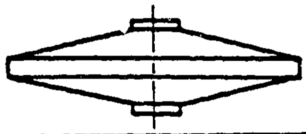
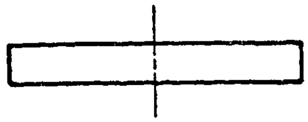
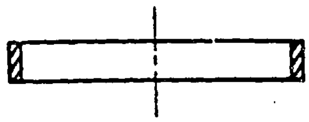
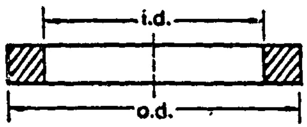
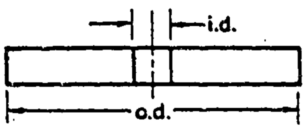
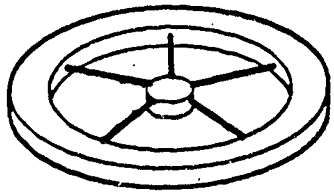
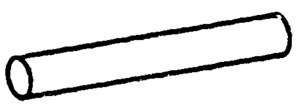
IDEAL EXPONENTIAL DISK		1.0
TRUNCATED EXPONENTIAL DISK		0.807 $\frac{t(HUB)}{t(TIP)} = 5.48$
TRUNCATED CONICAL DISK		0.806
SOLID FLAT DISK		0.606
IDEAL THIN RING		0.500
THICK RIM		0.438 $\frac{i.d.}{o.d.} = 0.1$
PIERCED DISK		0.305 $\frac{i.d.}{o.d.} = 0.1$
WHEEL WITH SPOKES		0.4
THIN BAR		0.333
SHAPED BAR		0.5

Figure 4.1-1. Shape Factors for Some Isotropic Flywheel Roter Designs

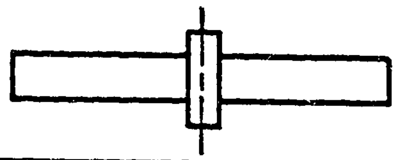
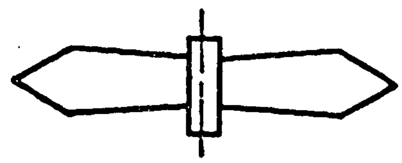
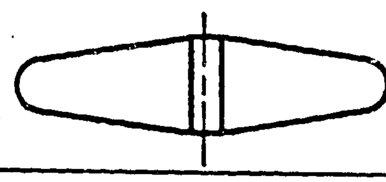
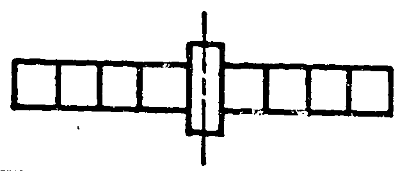
DESCRIPTION		SHAPE FACTOR K
CIRCUMFERENTIALLY WRAPPED FLAT DISK		0.43
CIRCUMFERENTIALLY WRAPPED FLARED DISK		0.47
TAPE OVERWRAP		0.35
MULTI-RIM		0.45

Figure 4.1-2. Shape Factors for Some Composite Material Rotor Designs

root relationship. Therefore, a flywheel which is optimized for energy storage may not be optimized for momentum storage, and visa-versa. Also, stored momentum is linear with rotational speed, whereas stored energy has essentially a squared relationship (Figure 4.1-3). Wheel growth with speed will increase the inertia, and as a result there is a definite though minor departure from the theoretical.

4.1.3 General Material Comparisons

The energy density obtainable from a flywheel rotor is directly proportional to the specific strength of the material used. Where multiple rings are laid up concentrically, using different materials, then the specific modulus, which is a measure of stiffness, also is important, especially the specific modulus of one ring relative to each of the others.

Three general classes of materials can be considered for flywheels. First are the metals, which have seen wide use historically as materials for flywheels. Steel and titanium are the best representative metals. The second class of materials are fibers with a metal matrix. The major fibers that have been used are: carbon (graphite), boron, silicon carbide, alumina, and tungsten; the major metal matrix materials are: aluminum, magnesium, copper, titanium, and the alloy FeCrAlY. The third class of materials is fibers with an organic matrix. The major fibers that have been used are: carbon (graphite), aramid (Kevlar), and glass; the major organic matrix materials are: epoxy, polyimide, polysulfone, and phenolic.

An overall comparison of the three classes of materials is shown in Figure 4.1-4. Theoretical flywheel energy density is proportional to the specific strength parameter (stress divided by density), and theoretical momentum density is proportional to the square root of that parameter. Conventionally, many flywheels have been made of metal, such as the titanium wheel used for IPACS, but it is seen that metals are much inferior to metal matrixes and organic matrixes. The fiber materials with organic matrixes seem to be the strongest, and are obtainable over a wide range of specific modulus. Carbon fiber materials with organic matrixes are of major interest for high energy density spacecraft flywheels.

4.2 FLYWHEEL PERFORMANCE PREDICTIONS

In recognition of the uncertainty of making performance predictions, two separate approaches were taken to predict the energy density of flywheel rotors. These are: 1)

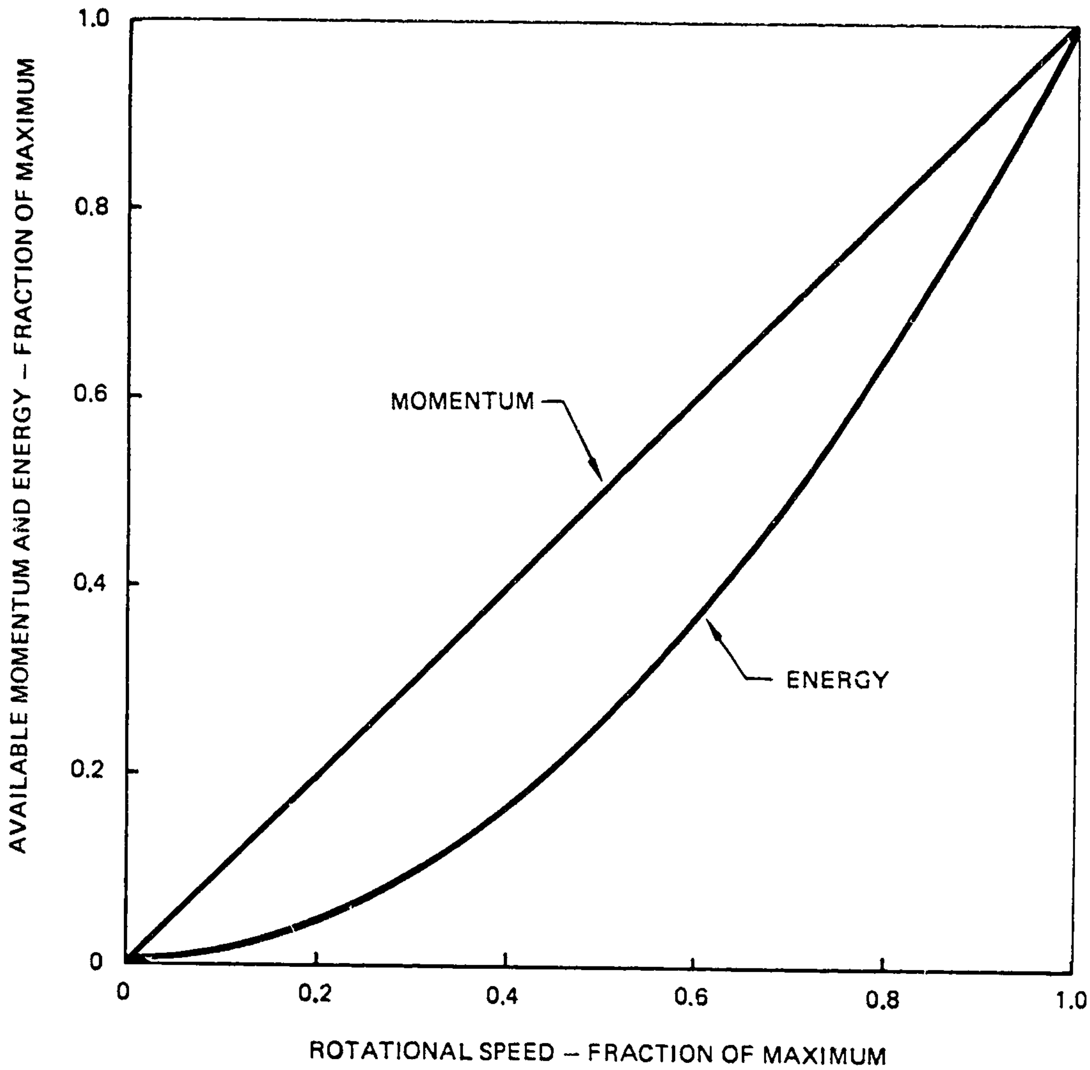


Figure 4.1-3. Available Momentum and Energy in Rotating Wheels

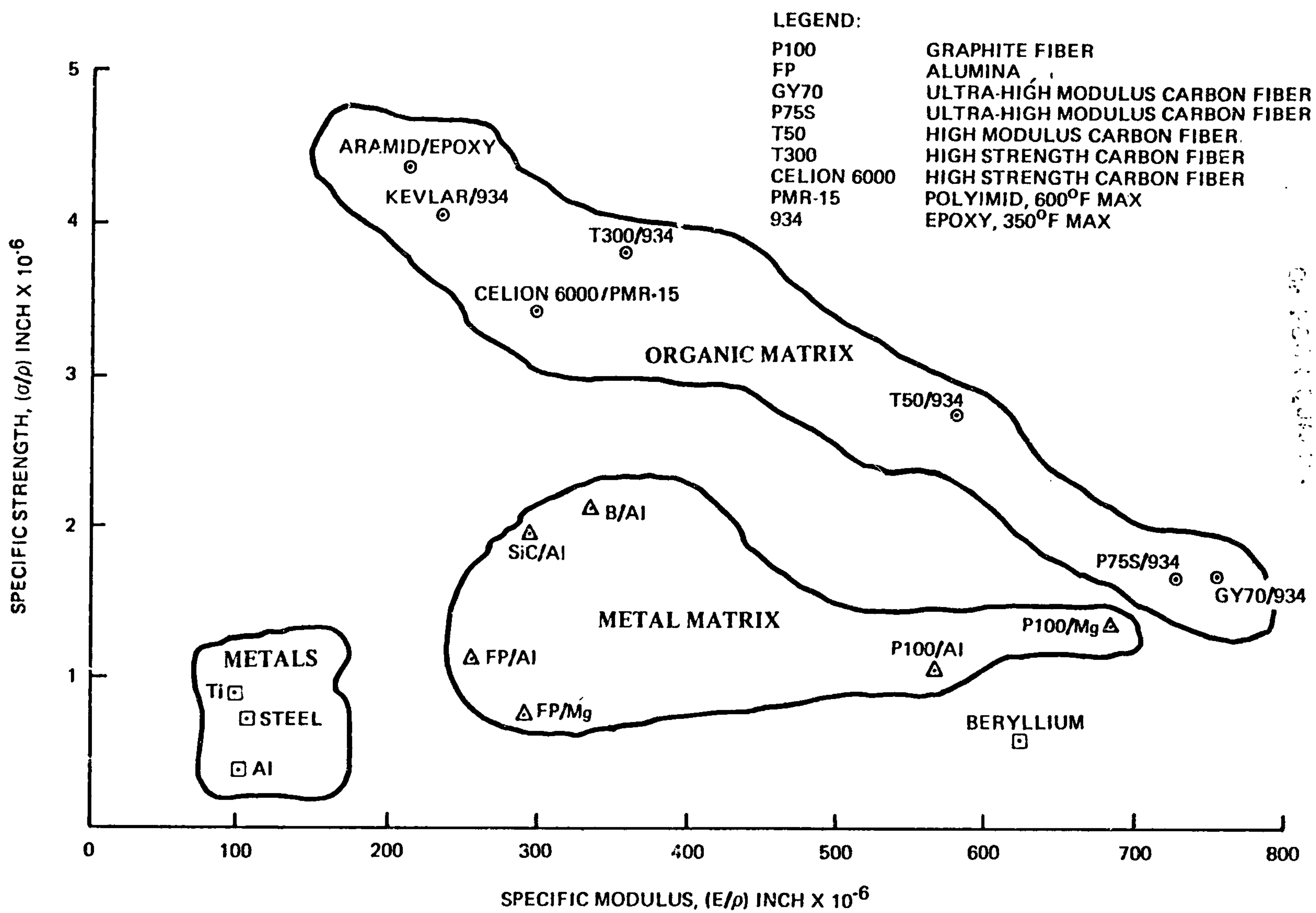


Figure 4.1-4. Strength of Composite Materials

extrapolate from the performance of previously tested wheels, and 2) calculate directly from the expected performance of high performance fiber materials.

4.2.1 Extrapolation of Performance

Tests in recent years of flywheel rotors have resulted in several data points which can be used as a basis for extrapolation to estimate the performance of future high energy density flywheels. One rotor made by AiResearch had a calculated burst energy density of approximately 100 W-Hr/kg, although this performance was not realized in limited tests. Most of the energy in the AiResearch wheels is in the rim. In fact, AiResearch has made a wheel in which about 90 percent of the weight was in the rim, and only about 10 percent was in the hub; this wheel was not successful, however, due to an unsatisfactory test fixture and possibly also the hub design. Rocketdyne has made two-component (graphite/epoxy rim with aluminum hubs) high performance flywheels with a calculated overall burst energy density of 81 W-hr/kg. General Electric has also made high performance, two-component wheels which resulted in an overall burst energy density of 68 W-hr/kg, with a calculated burst energy density for the carbon-epoxy rim of 114 W-hr/kg. Lawrence Livermore National Laboratory developed a graphite-epoxy wheel which had a predicted burst energy density of 121 W-hr/kg. From the above data, it is seen that the carbon fiber-based materials are able to produce burst energy densities today that are in excess of 100 W-hr/kg. By developing flywheel rotors to emphasize this potential and also incorporating even higher strength materials, very high performance rotors should be possible.

Upon consideration of the above data, the General Electric data point of 114 W-hr/kg was used as the basis for the upward extrapolation. This data point was taken with a rim whose diameter ratio (i.d./o.d.) was 0.8. A wheel with a lower diameter ratio, about 0.3 to 0.5, is believed to be essential for the hubless wheel (motor/generator concentric with flywheel), and preferred for the hubbed wheel. Therefore, appropriate ratio factors were needed to extrapolate to lower diameter ratios.

When a wheel is made with a low diameter ratio (i.d./o.d. = 0.3) there is a theoretical loss in flywheel energy storage efficiency. This is shown in Figure 4.2-1 for isotropic, constant-thickness disc wheels, and for isotropic wheels the theoretical loss is a function of geometry only. For anisotropic materials, such as composite materials, the radial stress developed is an additional factor to be considered. This results from the fact that the outer strata want to grow outward, relative to the inner strata which

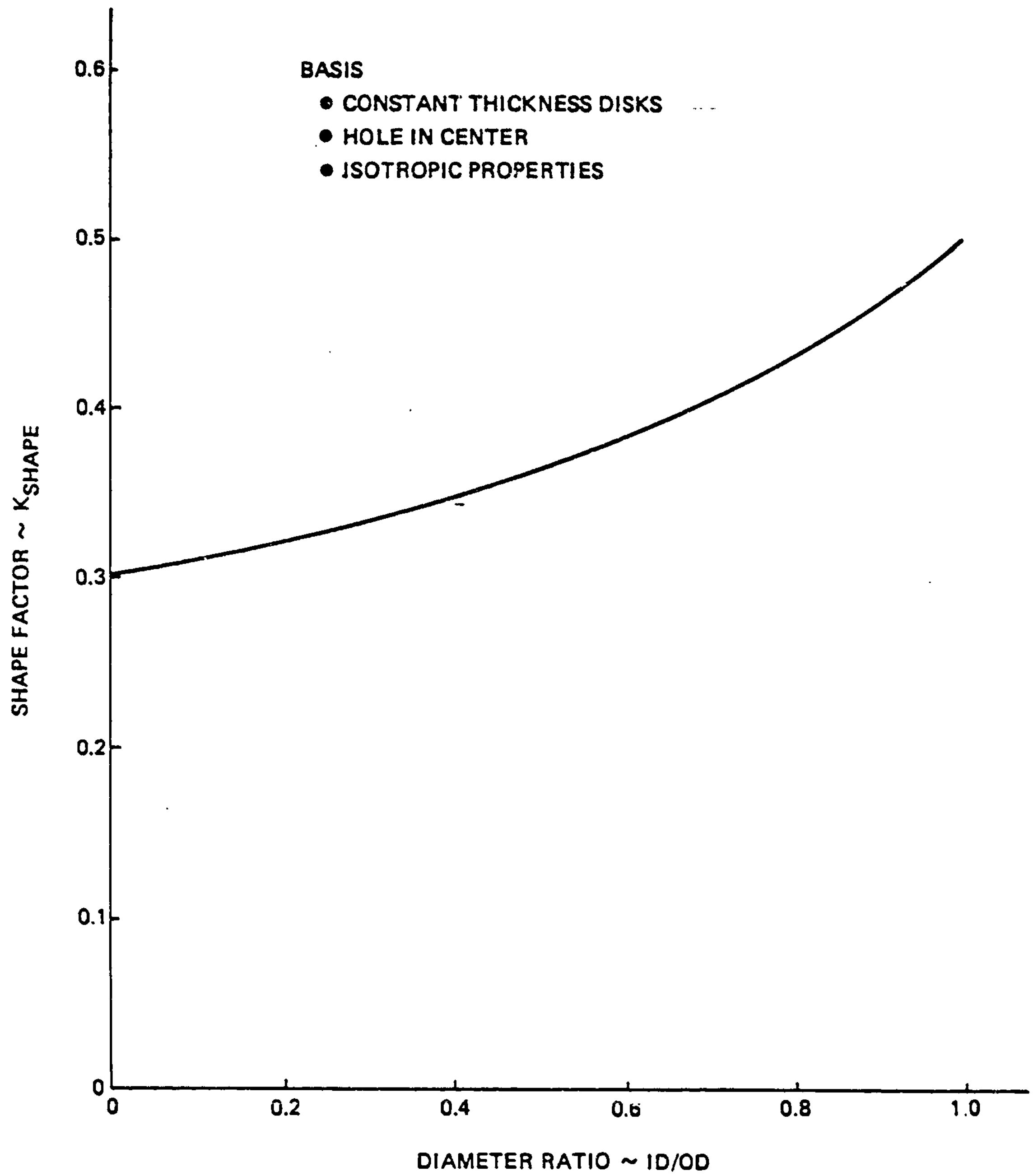


Figure 4.2-1. Shape Factor for Isotropic Disks

are pulling away, creating a delaminating effect. This is a problem only with thick rings, and to solve this it is necessary to rely on the matrix properties plus the development of suitable manufacturing methods to prevent delamination. Some approaches to this are: (1) build up a radially thick rotor out of thin hoops which are discontinuous and thus strain-relieved at their interfaces. These hoops should be manufactured with an interference fit, which presents some manufacturing difficulties; (2) buildup a radially thick rotor out of thin layers in which a different material (modules) and/or a different pretension is used for each layer. Rocketdyne has successfully built and tested flywheels with as many as 17 layers. (3) weave the fibers in different directions so that strength is obtained in both radial and axial directions. AVCO has developed a two-dimensional weave to hold the different layers together, loading the hoops on the inside by transfer of the load; calculations show this performs well, with fairly uniform stress. G.E. has used special weaves for nose cones, which may also be applicable; (4) use a matrix material which is more flexible than epoxy. There are limitations in the extent to which radial strength should be increased, for as radial strength is increased, you tend to lose tangential strength.

Adequate theoretical shape factor data are lacking for composite materials, which have complex behavior. Therefore, theoretical geometric shape factors for isotropic materials were used in a limited way, by ratioing, in order to predict energy density obtainable with low diameter-ratio wheels and high strength fibers. To this was applied an additional factor for radial stress, which was estimated to be in the range of 0.8 to 0.9. This radial stress factor is generally included as part of the knockdown factor which lumps the effects of geometry, material orthotrophic properties, type of fabrication, and failure mode. Separation of radial stress effects was done to facilitate use of existing test data in making future performance estimates. A radial stress factor of 0.8 hypothesizes fair success in solving the fabrication problems, and a factor of 0.9 denotes good success with that problem. This prediction is shown in Figure 4.2-2 for composites with carbon fibers up to 1000 KSI strength. Assuming an orderly development of high-energy flywheels, three sequential objectives, near-term, intermediate-term, long-term, are identified with increasingly improved performance.

It is expected that wheels of high diameter ratio, such as the postulated near-term objective, are not well suited to use with a motor/generator because of the more severe hub problem. Thus, no total energy storage system weights are presented with

DIAMETER RATIO ~ ID/OD	K_{SHAPE}	$K_{RADIAL\ STRESS}$ (ESTIMATED)
0.8	0.438	1.0
0.5	0.376	0.9
0.3	0.338	0.9
0.3	0.338	0.8

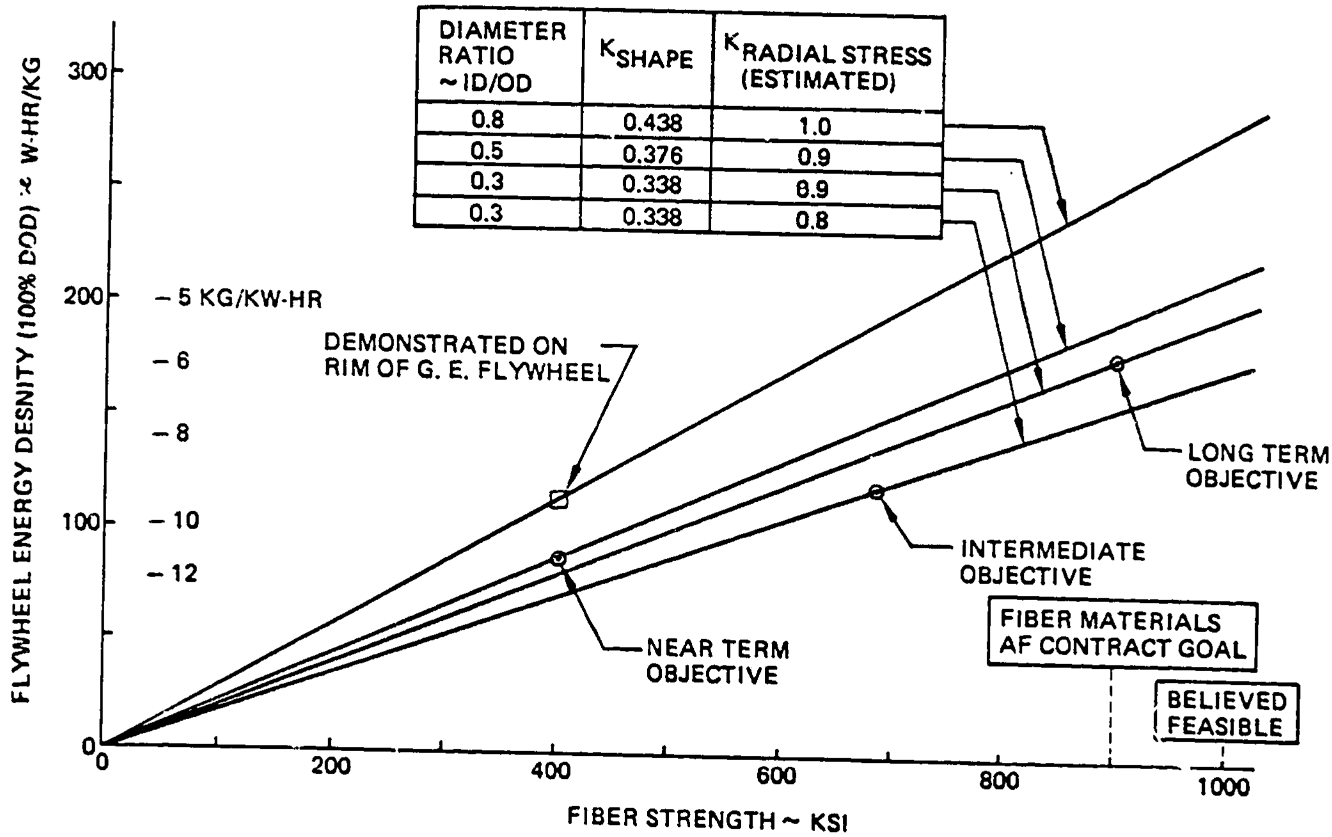


Figure 4.2-2. Estimated Burst Energy Density of Flywheels

the postulated near-term flywheel rotor, but only with the intermediate and long-term advanced design system.

4.2.2 Direct Calculation of Performance

This performance prediction method consists of determining the energy density obtainable from high strength fibers and applying suitable knockdown factors which relate maximum fiber performance to wheel performance. The maximum theoretical kinetic energy obtainable from fibers, in terms of energy per unit mass, is the ratio of the tangential stress to the density per equation (4), that is, W/m = sigma/rho.

Fiber strength is a key factor in obtaining high energy density. Quality fibers available in recent years have been about 400,000 psi yield. Review of this technology has disclosed that the strength of experimental fibers is well beyond this value, and that the prospects are excellent for continued improvement. The manufacturing methods being used are proprietary; in one case, however, very high strength, in excess of 700,000 psi, has been obtained by the use of a combination of very thin fibers, special fiber drawing technique, and fiber coatings using boron (Ref. 4.2-1). This work is proceeding under an Air Force contract with the objective of obtaining 900,000 psi fibers. Hercules has obtained 800,000 psi in experimental bundles of carbon fibers, with a strength of 1,000,000 psi in individual fibers. Tests on carbon fibers (94 percent carbon) extrapolated to zero flaws results in strength predictions of 1.5 to 2.0 million psi. The theoretical strength of pure carbon is approximately 5 million psi.

Progress anticipated by manufacturers on fiber strengths, assuming adequate development programs, is given in Table 4.2-1. Using that data, calculations have been made, using equation (4), of the projected energy density from these carbon fibers. These calculations are tabulated in Table 4.2-1 and plotted in Figure 4.2-3. For comparison, the calculated fiber energy density of some other materials are:

4340 steel	53.7 W-hr/kg	(24.4 W-hr/lb)
S-glass/epoxy	262.6	(119.1)
Kevlar/epoxy	372.6	(169.0)

For further comparison, it may be noted that the theoretical energy densities of some battery systems are:

Table 4.2-1. Expected Development of High Strength Carbon Fibers

		EXPECTED AVAILABILITY (APPROXIMATE)	FIBER STRENGTH	FIBER SPECIFIC GRAVITY	FIBER ENERGY DENSITY	
					W-HR/LB	W-HR/kg
HERCULES	AS4	1983	550 KPSI	1.52	314.0	692.4
HERCULES	AS6	1983	610	1.52	348.6	768.7
HERCULES	IM6	1983	630	1.52	360.0	793.8
HERCULES	—	1985	680	1.52	388.6	856.9
HERCULES	—	1989	950	1.52	542.9	1197.1
HERCULES	—	2003	1500	1.52	857.2	1890.1
FIBER MATERIALS	0 – 61	1983	710	1.74	354.4	781.5
FIBER MATERIALS	—	1986	900	1.74	449.3	990.7
FIBER MATERIALS	—	1988	1,000	1.74	499.2	1100.7

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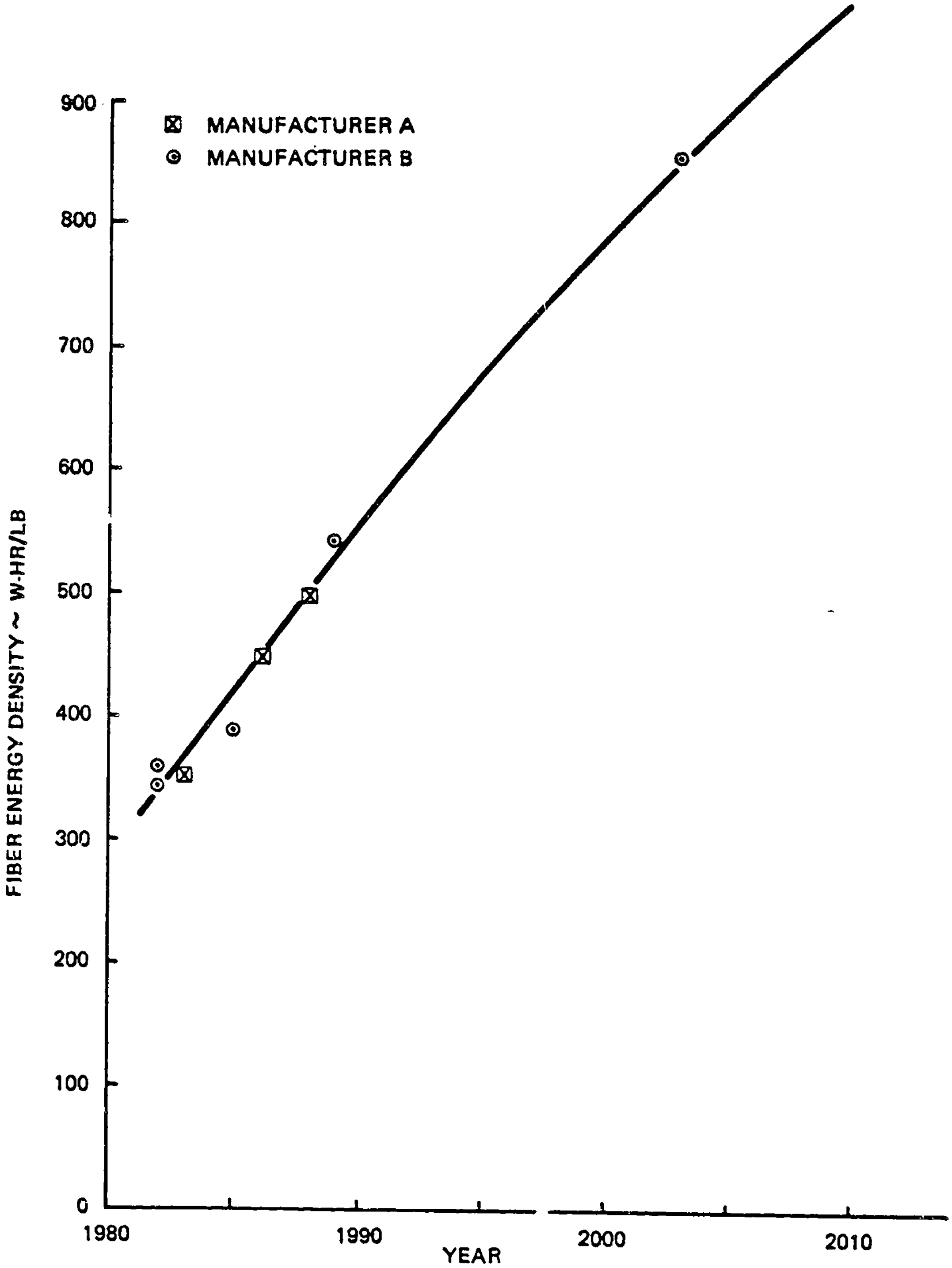

Figure 4.2-3. Energy Density from Projected Development of High Strength Carbon Fibers

sodium/sulfur	758 W-hr/kg	(343.8 W-hr/lb)
lithium/iron sulfide	458	(207.7)
nickel/hydrogen	378	(171.4)

Using the fiber energy density data of Figure 4.2-3, calculations were made of the energy density available from flywheels, by applying suitable knockdown factors to the theoretical energy density from fibers. Factors used were: (1) a 60 percent factor to allow for use of an organic matrix with the carbon fibers (typically, the fibers comprise 55 to 65 percent of the composite, with the larger amount of fiber used for the highest strength applications); (2) a 45 percent knockdown factor as reported by Kulkarni (Ref. 4.1-2) for well-designed composite discs (this compares with the theoretical limit for discs of 0.5); and (3) an additional knockdown factor of 70 percent to allow for design and manufacturing compromises that may be needed.

Results of this analysis by the direct calculation method yields the theoretical burst energy density of composite disc flywheels, given in Table 4.2-2. For 700,000 psi fibers, expected to be available in 1985, an energy density of 179 w-hr/kg is calculated; for 900,000 psi fibers, expected to be available in 1989, an energy density of 208 w-hr/kg is calculated. These correspond to the intermediate and long term objective cases postulated in Figure 4.2-2. Yet another case was analyzed, referred to as the penultimate case, which projects the energy density for the year 2000. This calculated energy density was 331 w-hr/kg.

These estimates, done by the direct calculation method, are shown in Table 4.2-3 in comparison with values from the extrapolation method; it can be seen that these predictions are reasonably close to the Oak Ridge National Laboratories expectation of 150 W-hr/kg (Reference 4.2-2). The direct calculation method is the more optimistic of the two, suggesting the possibility that additional energy density gains can be made in the manufacture of flywheels by developing ways to more fully utilize fiber strength. These additional improvements might not be achievable, so the lower energy density values obtained by extrapolation were used for system weight estimates.

4.2.3 Useful Energy Density Of Flywheels

The useful energy density of flywheels will be appreciably less than the burst energy density. Allowance must be made for factor of safety, containment, fatigue and long

Table 4.2-2. Direct Calculation of Energy Density

Basis—

- Geometry factor = 0.45 as reported by Kulkarni for discs
- 60% fiber loading, fiber-dominated strength
- 70% factor for efficiency

	Year Fibers Available	Stress	Fiber Burst Energy Density W-hr/lb	Wheel Energy Density - - 0.45 geometry factor 0.60 loading factor, 0.7 eff factor	
				W-hr/lb	W-hr/Kg
Intermediate Objective	1985½	700 ksi	430	81.27	179.20
Long-Term Objective	1989	900 ksi	500	94.50	208.37
Penultimate	2000	1430 ksi	795	150.26	331.31

Table 4.2-3. Useful Energy Density of Flywheels

	BURST ENERGY DENSITY ~W-HR/KG HUBLESS FLYWHEEL			INVERSE ENERGY DENSITY ~Kg/KW-HR HUBLESS FLYWHEEL			INVERSE ENERGY DENSITY ~Kg/KW-HR FLYWHEEL WITH HUB	
	EXTRAPOLATION METHOD	DIRECT CALCULATION METHOD	SELECTED VALUE	BURST	70% FATIGUE FACTOR, 100% DOD, AND 25% WT FOR CONTAINMENT	70% FATIGUE FACTOR, 75% DOD, AND 25% WT FOR CONTAINMENT	70% FATIGUE FACTOR, 100% DOD, 25% WT FOR CONTAINMENT AND 14% WT FOR HUB	70% FATIGUE FACTOR, 75% DOD, 25% WT FOR CONTAINMENT AND 14% WT FOR HUB
NEAR TERM OBJECTIVE	88.0	–	88.0	11.36	20.29	27.05	23.13	30.84
INTERMEDIATE OBJECTIVE	121.0	179.2	121.0	10.20	14.75	19.67	16.83	22.44
LONG TERM OBJECTIVE	178.0	208.4	178.0	6.93	10.03	13.37	11.44	15.26
PENULTIMATE	283.0	331.3	283.0	3.53	6.31	8.41	7.19	9.59

term creep, depth of discharge, and, if used, the weight of a hub which is able to handle the required charge/discharge torques. The following factors were applied:

- o A weight increase of 25 percent is used for containment and bearings.

- o A factor of 0.7 is used to allow for fatigue and long-term creep (see section 7.2).

- o A factor of 0.75 is used for depth of discharge, based on a two-to-one speed ratio.

- o A weight increase of 14 percent is used for a flywheel hub for the category in which hubs are used. Hubs can be designed to be either flexible or rigid.

A factor of safety must be used in determining useful energy density, with the safety margin either combined with other factors or broken out separately. The size of the safety margin depends on the predictability and repeatability of performance, sensitivity to fatigue, and the consequences of failure. In this analysis, no separate factor of safety is identified, it being combined in part with the knockdown factors and the fatigue factor. Design maturity with good repeatability is assumed, and it is also postulated that flywheel design approaches which would permit a total rotor burst are unacceptable. Even so, it could be argued that an additional margin of safety should be used. Further work of this subject is needed.

A summary of the expected useful weights of flywheels is given in Table 4.2-3. The hubless design postulates that the flywheel rotor is concentric with the motor/generator, avoiding the need for a hub attachment, and possibly a drive shaft, which would be required in a non-concentric design. It should be noted that the energy densities reported are the energies stored by the flywheels. In sizing a wheel, allowance must be made for the motor/generator loss in extracting this energy and delivering it as electrical power.

Comparison of the data in Table 4.2-3 with flywheel test results shows that the energy densities attained are not far distant from the near term objective, given as 23.13 Kg/KW-Hr for 100 percent DOD. For example, Rocketdyne has built and tested a composite flywheel consisting of a ring composed of seventeen graphite/epoxy layers using aluminum hubs and gearing adapters. The calculated burst speed is 32,500 RPM.

At the selected operational speed of 24,000 RPM, the wheel stores 2.0 kW-hrs of energy and has an inverse energy density of 25 Kg/KW-Hr (40 W-hr/Kg). Calculating the Rocketdyne wheel performance the same way as in Table 4.2-3, using a 25 percent factor for containment and applying a 70 percent factor to the energy obtainable at 32,500 RPM, the resulting inverse energy density is 25.67 Kg/KW-Hr, which is very close to the near term objective of 23.13 Kg/KW-Hr.

4.3 FLYWHEEL ROTOR CONTAINMENT

A containment housing is required around the flywheel to perform five functions: (1) Provide a pressure shell to permit near-vacuum operation for prelaunch checkout; (2) protect the wheel against abusive handling and against meteoroid damage; (3) contain wheel fragments from causing external damage during a wheel failure; (4) manage debris developed and angular momentum exchange during wheel failure; (5) transfer angular momentum during wheel failure.

Flywheels cannot operate in a pressurized environment because the aerodynamic friction will quickly destroy a high speed flywheel. Batteries for space stations often have been planned for location in unpressurized areas. Similarly, flywheel energy storage systems could be located in unpressurized areas. Thus, it may be possible to design the pressure shell for removal prior to launch, especially when it is recognized that spin-up of the wheel probably must be deferred until after the launch phase to avoid damage during the harsh launch vibration environment.

Spacecraft damage from meteoroids has not proven to be as severe a hazard as was projected in the early years of space technology. However, carbon fiber composite flywheels are impact sensitive (Figure 4.3-1), so protection against any impact damage, including meteoroids, must be a consideration in their design (Reference 4.3-1).

Containment of composite wheels to prevent external damage is an important aspect of flywheel energy storage system design. Containment studies and experiments first were done with metal wheels, and several workable concepts were developed. These include approaches where the wheel rim would detach by breaking in a predetermined way. This was found to be a workable method for metal wheels, as demonstrated in tests by Rocketdyne; this feature has been incorporated in their flywheels, such as the 6 kW flywheel power system for a coal mining shuttle car. For composite rotors, the

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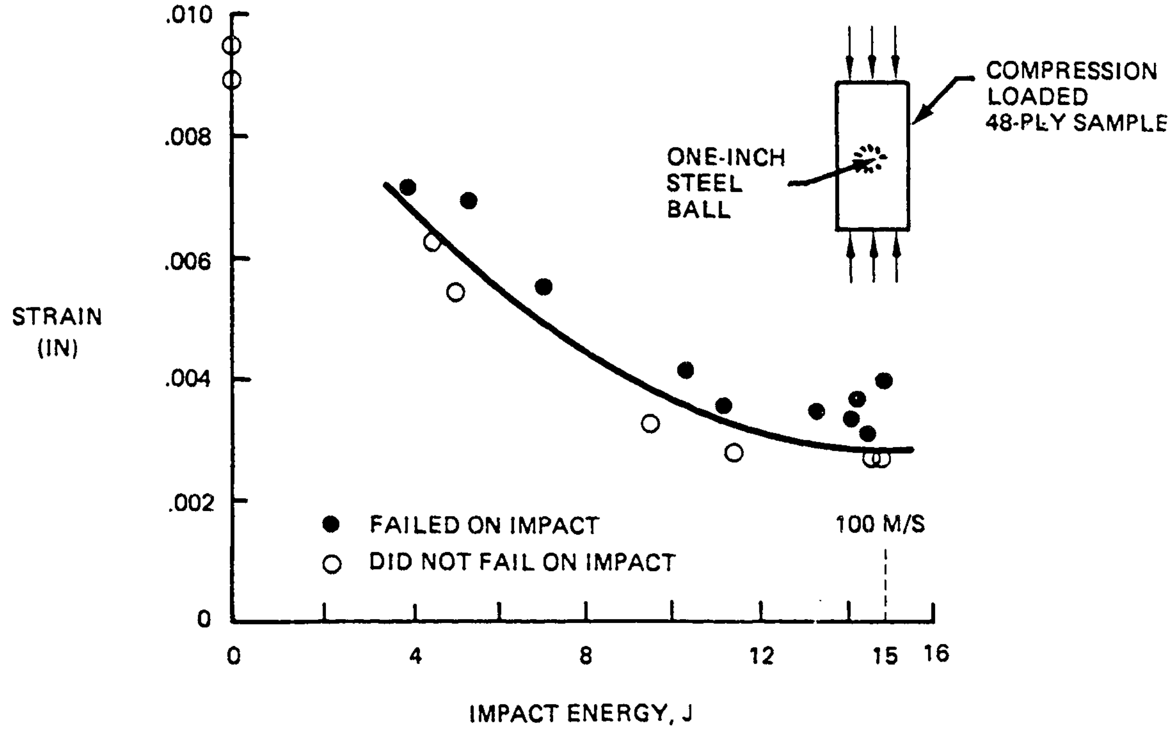

Figure 4.3-1. Sensitivity of Carbon Fiber Composites to Impact

initial concept planned for was to contain a complete rotor burst within a strong housing. This was a brute force approach, with the containment structure approaching the weight of the rotor. Recently, the burst processes of composite rotors have been analyzed and tested, which has improved the understanding of this subject (Reference 4.3-2). It should be noted, however, that only one containment test has ever been conducted on a high energy composite wheel within a realistic, vehicular-type containment housing; considerably more analytical and experimental work is required to develop safe, lightweight approaches to containment.

Composite flywheels have less severe containment needs than do metallic rotors. Benign failure modes can be designed in with composite flywheels. This has been demonstrated several times, as with the Garrett sub-circular rim flywheel test, which failured due to dynamic instability related to rim circularity. Thick-ring tests by Hercules and Union Carbide also showed benign failures, producing cracking with minor balance changes; such failures give good promise that warnings can be obtained early enough to prevent catastrophic failure.

A second reason that containment requirements on composite flywheels are less severe than for metallic wheels is that the failure of composites produces either stringy masses or crushable fragments. This stems from the low transverse strength of composites.

The philosophy proposed for spacecraft applications is that design approaches which permit a total rotor burst are unacceptable. Analyses by A. Coppa (Ref. 4.3-2) show that a good containment approach would be to design the rotor to fail either (a) in transverse radial tension in which case no fragmentation is released, or (b) in circumferential rupture of the outermost fibers in which case relatively minor fragmentation is released. In either case, failure could be detected easily and the wheel could then be shut down, with minimum damage and energy release. For failure mode (b), for example, rather than having to contain large chunks of the wheel, the need would be to contain a fibrous mass. By contrast, a failure which begins in the interior of the wheel could rapidly progress and culminate in a full burst of the wheel.

Although heavy structure is not needed to contain the fibrous mass with this approach, it is possible that the amount of debris generated during a failure could be voluminous.

Debris handling therefore is expected to be an important detail in the containment design, for which at this time there are no dependable answers.

One of the merits of magnetic bearing systems is that the information obtainable from the bearing sensors provides full knowledge of all rotation characteristics, such as speed, bearing loads, position of the rotation axis, eccentricity, out-of-balance, and disturbance frequency. This information can be used to detect incipient failure and shut down the wheel.

For unmanned, highly weight-sensitive spacecraft, it may be an acceptable risk to eliminate the containment. If the wheel is located such that the wheel fragments will not damage the spacecraft equipment, then a wheel failure may not be catastrophic to the spacecraft.

One of the functions of the housing, which is associated with the containment, is to provide a low pressure environment for the wheel. Otherwise, the air drag would cause a large energy loss and even destroy the wheel. The low pressure housing is needed for ground testing, but is not needed in space. Therefore, it may be possible to remove all or part of it prior to launch; this will depend on design limitations, the amount of weight involved, and testing needs.

4.4 FLYWHEEL OUT-OF-BALANCE CONSIDERATIONS

It is important that flywheels or inertial wheels be closely balanced for operation at high rotational speeds. With metal wheels, it has been found that even if the wheel initially is well balanced, repeated cycling causes irreversible changes in the metal structure which creates out-of-balance. To minimize this, momentum wheels are sometimes designed to operate at relatively low maximum stress, referred to as the precision elastic limit.

Out of balance due to structural changes with cycling can also occur with flywheels made of composite materials. Fibers can shift their position slightly within the matrix, as well as small structural changes within the fibers themselves. Information is not available on the extent to which carbon fiber composite wheels will become out-of-balanced during repetitive cycling, though it is known this can occur. Critical speeds are generally not a problem, typically appearing at low speeds (below 2000

RPM), when the flywheel shifts its center of rotation from the geometric center to the mass center.

The past concern for out-of-balance with momentum control systems has been to have an invariant control law, one which would not have to be altered as the wheel properties changed. Vibration has not been the major problem. This is not regarded as a major concern with today's advanced data processing technology, however. For flywheel energy storage systems, the principal concern is the vibration that may result, reflecting itself as jitter in the adjacent structure.

To help understand the problem of jitter resulting from an out-of-balance wheel, an analysis was made based on a metal reaction wheel used in a typical momentum control system with metal bearings. The wheel analyzed was a Sperry P80-2 with an angular momentum of 34.5 ft-lb-sec, weighing 26.5 lbs, and was operated at a speed of 3000 RPM. The allowable axial, radial, and torque vibration spectra for the wheel were used, and an unbalance was postulated, based on prior wheel tests. The analysis assumed the wheel to be incorporated into a momentum control system which senses the out-of-balance torque and attempts to compensate for it. Figure 4.4-1 shows the out-of-balance torque generated by the wheel in the X and Y axes, and the lagging torque commanded to the system to compensate for the torque produced by the out-of-balance. The resulting perturbation on the stiff vehicle structure near the wheel is given in Figure 4.4-2, shown as an angular rate of change. This is an example of a low level of perturbation resulting when there is good compensation by the momentum control system, which requires sensing and feedback. Not yet analyzed is: (a) the more severe condition in which there is no compensation, and (b) the condition in which magnetic bearings are used, both with and without attempted correction of out-of-balance by adjustment of the nominal bearing position. Until such analyses are conducted, it is not known to what degree there may or may not be a concern with the effects flywheel out-of-balance may have on spacecraft.

Limited data are available on long-term dimensional changes in composite flywheel rotors following fatigue testing. Tests on a General Electric disk/ring hybrid design after 10,000 cycles showed a dimensional change of less than 0.02 percent. Data on flywheel diameter in inches as a function of angular position are as follows:

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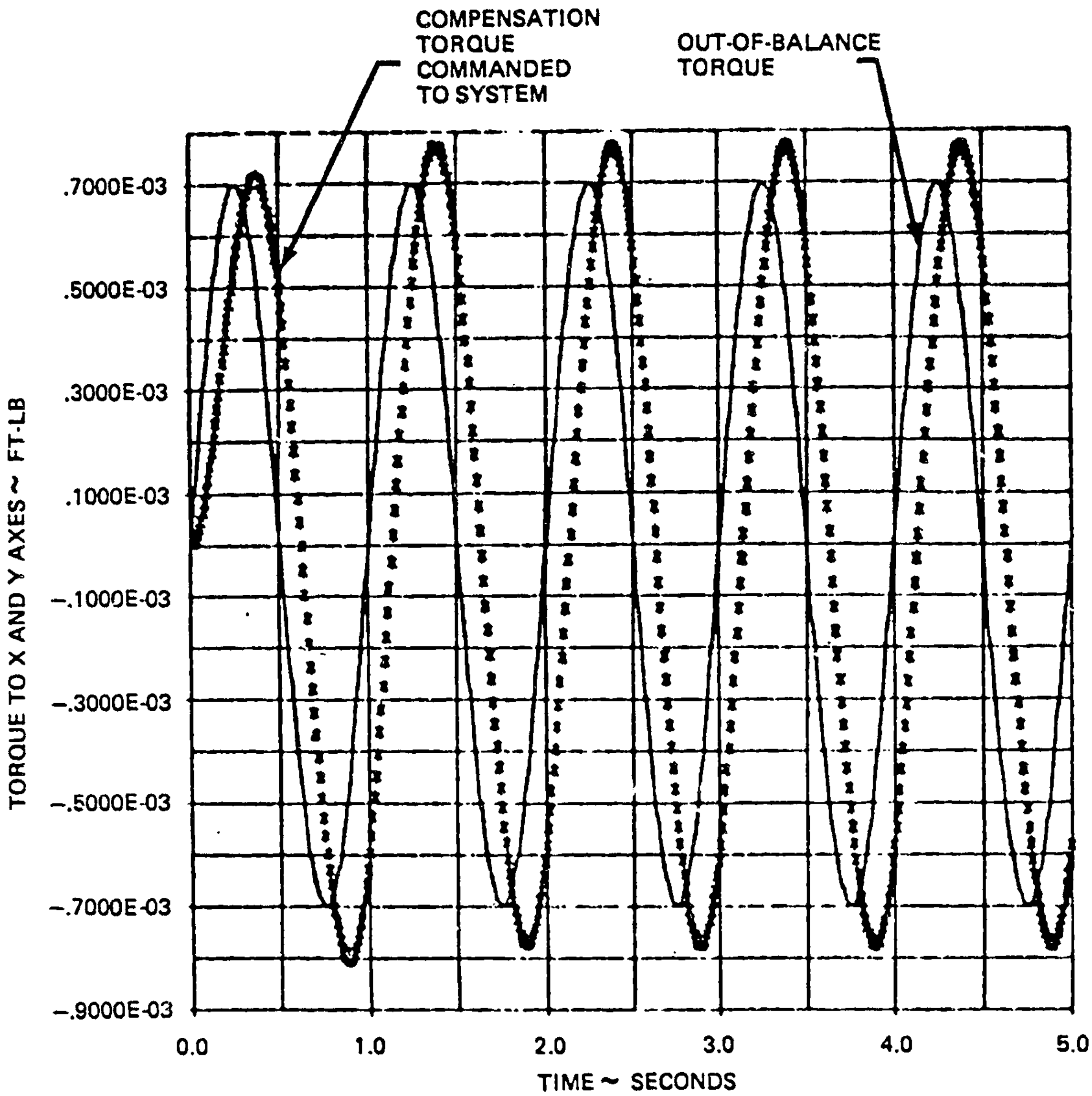

Figure 4.4-1. Out-of-Balance Effects on a P-80-2 Metal Wheel with Attitude Control Compensation

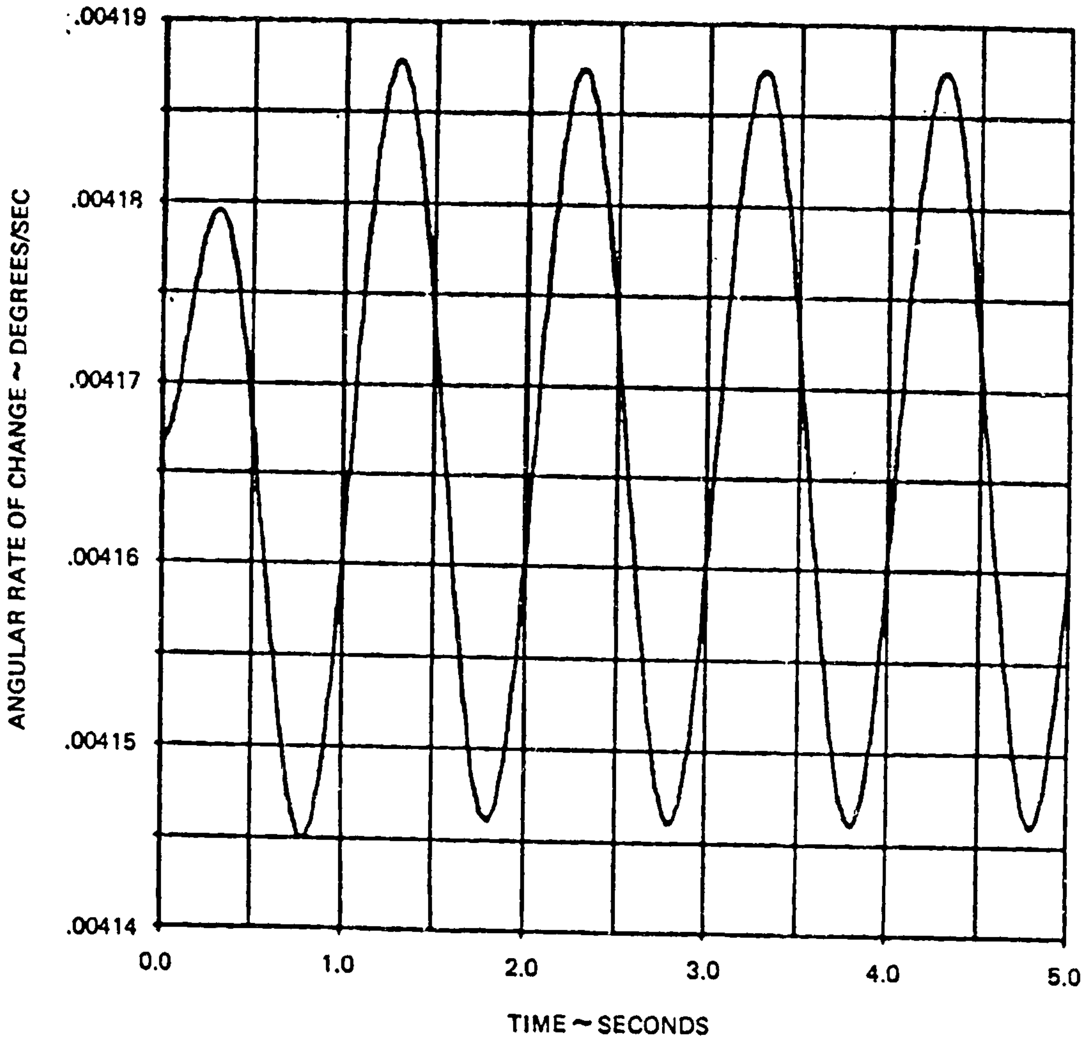

Figure 4.4-2. Effects of Out-of-Balance with ACS Compensation on Structural Perturbation

	0°	30°	60°	90°	120°	150°
Before Cycling	16.009	16.004	16.004	16.006	16.004	16.008
After Cycling	16.016	16.006	16.012	16.009	16.008	16.012

These data show that the change in diameter is not identical with angular position. It is expected, therefore, that this will have some impact or dynamic balance.

One consideration is the influence that magnetic bearings can have on wheel out-of-balance, either to dampen or amplify the effect. Magnetic bearings can be designed to ameliorate the effect of wheel out-of-balance, but studies on this are not available.

5.0 MOTOR/GENERATORS

5.1 GENERAL APPROACHES

A flywheel energy storage system requires a motor to spin up the flywheel rotor, and a generator to extract electrical energy from the wheel during spindown. These two functions can be satisfied either as two separate components, as illustrated in Figure 7.11-1E, or integrated into one bifunctional component as is shown in the other illustrations of Figure 7.11-1. Motors and generators are common in much of their design, and in some applications are interchangeable. Therefore, it is commonly assumed that a combination motor/generator is the lightest and therefore the best approach. That assumption has also been made for this study as a first approach. However, the motor/generator is light compared to the flywheel; also, the electronic controls are somewhat complex in the combined motor/generator mode, so it is not obvious that a bifunctional design is best. Detailed study of this trade is needed, especially from the standpoint of reliability.

Since motor weight is low, aproximately 15 percent of system weight, some weight may be sacrificed in order that high efficiency may be stressed in the motor/generator design. This requires that the motor operate at essentially constant power, using solar array power evenly and efficiently during the sunlit part of the orbit. In addition, the motors for all the flywheels should be controlled to the same accelerating speed to minimize momentum unbalance, assuming non-integration with the attitude control system. Additional motor requirements are that it operate at about 200 volts dc with a two-to-one speed ratio, and that the generated noise (electromagnetic interference) shall be minimized. Though the motor operates normally at a two-to-one speed ratio, there is also a requirement that it must start from zero speed. Speed reversal is also a possible requirement.

The generator output can be either ac or dc, though regulated ac output is less efficient with a variable speed generator. A 200 volt dc output is assumed, giving direct comparison with batteries. Voltage regulation of approximately ± 2 percent and ± 4 percent for transients are typical requirements, with a two-to-one speed range and peak power of approximately 2.0 times the average power. Both motor and generator requirements would include paralleling, with equal speed control as well as equal generator voltage.

An acceptable match is needed between the design speed of the motor/generator and the design speed of the flywheel rotor. Although there is a theoretical relationship between maximum momentum per unit weight and wheel diameter (large diameter is favored), there is no theoretical relationship between energy density and diameter. Thus, within limits, there is some flexibility in the flywheel design speed, trading large outside diameter and lower speed for a smaller outside diameter, a thicker wheel, and a higher speed. For the motor/generator, the trades on design speed involve motor size, weight, efficiency, and motor type.

An important attribute of the flywheel energy storage system is the ability to extract the flywheel energy in a very short time, and deliver especially high power. This could be useful for military applications and special experiments. For such applications, a configuration as shown in Figure 7.11-1E would be appropriate, with a small spinup motor and a separate, large generator. Special generators are the key to very high pulse power. The homopolar dc generator, also called an acyclic generator, is suitable for extracting energy in a fraction of a second, although the generator is capable of continuous operation if cooled adequately. This type of generator has no rotating windings, and can be designed in several different configurations, though the drum rotor configuration has the lowest internal impedance and the lowest stress. This type of generator inherently has only one turn, and thus develops very low voltage, but can produce extremely high current because the inductance is very low. The brushes must be designed for very high current, which is an important design consideration with this type of generator.

Special lightweight, high power, high voltage generators have also been built, which could be suitable for use with flywheels for short bursts of high power. One such unit was designed for over 3 megawatts with a nominal 1500 Vac, operating at a 1.6 to 1.0 speed ratio (maximum to minimum), and weighing 775 lb. Other special generator types are also possible for pulse power, such as the compensated pulsed alternator, also referred to as a compulsator, which can extract flywheel energy and convert it into electric power in less than a second.

One of the factors a flywheel motor/generator system must cope with is proper operation over a wide speed range, approximately two-to-one. With today's electronics technology, this is not a difficult problem, though it adds considerably to the electronics complexity. For example, about one third of the weight of a flywheel motor/generator will be the control electronics for a dc output. The generator actually produces ac power, and because of the variable speed, the frequency is variable also. Conversion from ac to dc is done electronically. To produce ac output of controlled frequency would require even more electronics and lower efficiency, for conversion from ac to dc and then back to ac would probably be involved; an alternative approach would be the use of cycloconverters. An additional complexity would be the need for paralleling the output of a number of such ac generators, with matching required of voltage, frequency and phase.

One of the functions of the motor/generator control electronics is to provide regulated output voltage for the generator mode, which occurs during spacecraft occultation and peak conditions. During the motor mode, which corresponds to the sunlit portion of the orbit, the voltage control electronics are not being fully used. Therefore, there is the potential that this electronics could be used to perform the solar array voltage regulation function. Thus, solar array voltage control would be integrated with the motor/generator control electronics. Further study is needed to determine if this is a worthwhile possiblility.

For military applications, the motor/generator with flywheel has some useful characteristics. Both the motor/generator and the flywheel probably could easily be hardened against high power lasers or nuclear radiation. For very high power, in the megawatt range, generator size and weight can be minimized by operation at high voltages and high speeds; even super-cooling of the armature windings can be considered for weight and size reduction.

5.2 PERMANENT MAGNETIC MATERIALS

Permanent magnets are useful in small to medium sized electric motors and generators to create the needed magnetic field. For very large motors and generators, electromagnets are commonly used. For motor/generators of the size needed for the space station, permanent magnets are the most likely approach.

High performance motors have frequently used rare earth-cobalt magnets for the field. These materials, especially samarium-cobalt compounds, represent a new generation of capability and performance. They have a high energy product and a high coercive force. Alnico magnets formerly were used, and they can provide the greatest flux density B, but their magnetizing force H is very low. Much higher magnetizing force and energy product are possible with the rare earth-cobalt class of permanent magnets. The two most common types are $SmCo_5$ and Sm_2Co_{17}. These materials in the sintered version have energy products of approximately 18 and 25 MGO_e (mega Gauss-Oersteds) respectively; bonded constructions are worse. Typical demagnetization curves of these materials are shown in Figure 5.2-1, as given in Reference 5.2-1. It will be noticed that there is a knee in the Sm_2Co_{17} curve just below the point of maximum BH product. This is an undesirable characteristic, and forces the design to operate above the maximum BH product, or more commonly, it causes the lower-performing $SmCo_5$ material to be used.

Progress within the last year has eliminated the knee in this curve in the Sm_2Co_{17} sintered material. Prototypes are now available from Japan with an energy product of 30 MGO_e. The theoretical limit is approximately 60 MGO_e, so further improvements may be expected. Also significant is the recent development at General Motors Laboratories of neodynium iron permanent magnet material with an energy product of 30 MGO_e. With improved materials, higher motor/generator efficiencies and higher power densities should be possible. It is recommended that these advanced materials be considered in future design studies on flywheel motor/generators and flywheel magnetic bearings.

5.3 TEMPERATURE CONTROL CONSIDERATIONS

Temperature control can be an important consideration in the design of motors or generators. Large units can generate much heat, and depending upon the design, there can be ineffective transfer of thermal energy from the point of generation to an external location for heat removal. In a conventional motor design, the heat that is generated is transferred by conduction to the exterior surface of the motor. The heat is then dissipated by natural convention or forced convection to the ambient air. Forced air or liquid cooling is also used.

For spacecraft applications, there are five major considerations in temperature control of motor/generator systems: (1) temperature control of the control electronics; (2) the amount of heat generated by the rotating equipment; (3) the nature of the heat path to the exterior of the motor/generator; (4) removal of heat from the motor/generator exterior surface; and (5) the allowable temperature. These items are discussed below.

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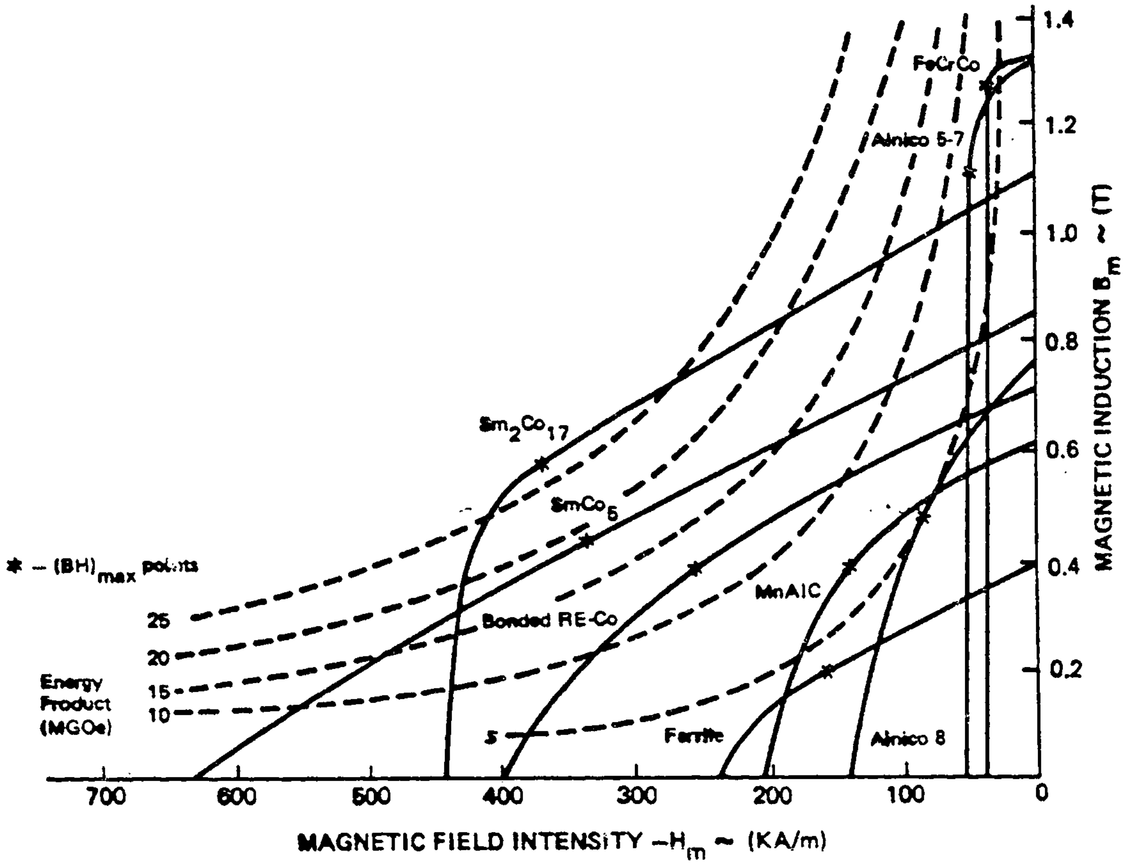

Figure 5.2-1. Demagnetization Curves for Permanent Magnet Materials

Temperature Control of Control Electronics

The control electronics is expected to be mounted external to the motor/generator, though preferably in close proximity to minimize losses. In-flight replacement of the electronics will likely be a requirement. Conventional cold plate cooling will be adequate, similar to most of the other spacecraft electronics. In fact, as seen in Figure 5.4-2, the efficiency of the motor control electronics will be very high, which would minimize thermal problems.

Heat Generation By Rotating Equipment

The general objective to obtain a high overall efficiency for the motor/generator system is consistant with the desire to minimize heat generation for good thermal control. As discussed in Section 3.0 the overall efficiency can range from 81 percent to 93 percent. From the data given in Sections 5.4 and 5.5, most of the heat generated with efficient designs will be in the rotating equipment.

Thermal Path to Motor/Generator Exterior

A key factor in temperature control of the motor/generator is whether the majority of the heat produced is generated in the interior rotor or the exterior stator. A preliminary look at this shows that approximately 25 percent of the heat generated is in the center rotating member, the remaining 75 percent being generated in the stationary outer section. With most of the heat generated close to the point of heat removal, this suggests few problems. Some motor/generator design concepts could have a high amount of heat generated in the central rotating section, requiring heat transfer by radiation across the gap; thermal studies should be made early if such designs are postulated.

Heat Removal From Motor/Generator Exterior Surfaces

With a high efficiency motor/generator, radiation from the exterior surfaces to the surroundings may provide adequate temperature control. The addition of cooled enclosure surrounding the motor/generator would provide closer temperature control and tolerate a higher heat dissipation rate; this radiant cooling approach would be applicable whether the exterior surface were stationary or rotating. If a greater level of cooling were required, then heat pipes on the motor/generator exterior surface is a feasible solution, as has been demonstrated (Reference 5.3-1). Cooling by heat pipes may not be practicable for a gimbaled flywheel system with integrated energy storage and momentum management.

Allowable Motor/Generator Temperature

The maximum allowable operating temperature of motors is determined mostly by the temperature limitations of the insulation on the windings. Motors with commercial insulation typically are limited to 120°C. If high temperature insulation is used, such as the fiberglass ribbon used on transformers, then 250°C would be acceptable from an insulation standpoint. Other considerations, including the need for derating, would not permit such a high temperature for spacecraft use unless for exceptional applications. However, it appears that designs for higher than usual temperatures would be possible if there were a need or an advantage to do so.

5.4 PERFORMANCE WITH CONVENTIONAL DESIGNS

Conventionally designed motors and generators use a radial air gap. This technology is very well developed, and though it is referred to here as conventional design, the field of motor/generator design based on conventional principles is very dynamic and innovative today. Solid state controls make it feasible to run an AC motor off a DC line by gating the currents into the proper windings. Motors can be designed which have the high torque and good control of DC motors coupled with the ruggedness of AC motors. Because of the competitive nature of this industry, however, few of the recent advancements appear in the open literature. Section 5.5 treats the performance of motor/generators of novel design, the most obvious design innovation being the use of an axial air gap rather than a radial air gap, with the objective of this innovation being to obtain high efficiency.

The major concerns with motor/generator design for spacecraft use are: (1) bearing design, emphasizing high reliability and low friction - this is discussed in Section 6.0; (2) high reliability in both the rotating equipment and the electronics control - this is deferred to later study; (3) high efficiency operation - this is the subject addressed here.

Manufacturers experienced in motor/generator design were consulted in the course of this study. Our findings in general were that designing to very high efficiency is not a common objective, whereas low weight and low volume are common needs. For this reason, it may be expected that a large amount of analysis will be required before optimized, high efficiency motor/generators can be made.

Analyses were conducted to determine the effects of design variables on efficiency. The performance of currently available devices and parts was used in this analysis, with no projections to future performance. Variables investigated were design voltage, number of poles, RPM, and the particular different switching devices. The permanent magnets were assumed to have an energy product of 21 MGO_e.

Figure 5.4-1 shows the results of one set of parametric analyses on motor efficiency, based on 28 volts input. The number of poles used is seen to be important, with highest efficiency being favored by the fewest number of poles. Over the speed range analyzed, efficiency is seen to decrease with increasing RPM. The switching devices used have an important effect on overall efficiency, with the better devices also showing the least sensitivity to RPM.

A second set of parametric analyses is shown in Figure 5.4-2 based on 270 volts input. The high voltage is responsible for part of the improved efficiency compared with the 28 volt case, for a given voltage drop across a device is a smaller percentage loss at high voltage. This study also shows the importance of the specific devices used for switching. Another analysis based on an input voltage of 100 volts showed only a slight difference in efficiency compared with 270 volts, so it is concluded that the 270 volt data given here closely represents the expected performance at 200 volts. Thus, it is seen from this data that controller efficiencies in the high nineties of percentage are possible with state-of-the-art devices.

Although the controller efficiency reduces with increased RPM, this is offset at medium to high speeds by improved efficiency of the motor itself. The overall effect is seen in Figure 5.4-3 which shows minimum efficiency at about 4000 RPM. Efficiencies above 10,000 RPM are expected to reach a maximum and then fall off. This is shown in Figure 5.4-4 for another set of motor designs which varied the number of poles with RPM.

Weight of a motor/generator system has also been estimated as a function of RPM. This is shown in Figure 5.4-5. At 200 volts and motor speeds of about 5000 RPM and above, the motor is approximately 60 percent of the total motor/generator weight, the remainder being required for the electronics, its heat sinking, and packaging. Considering that a 5 kW motor/generator would be tied to a flywheel weighing on the

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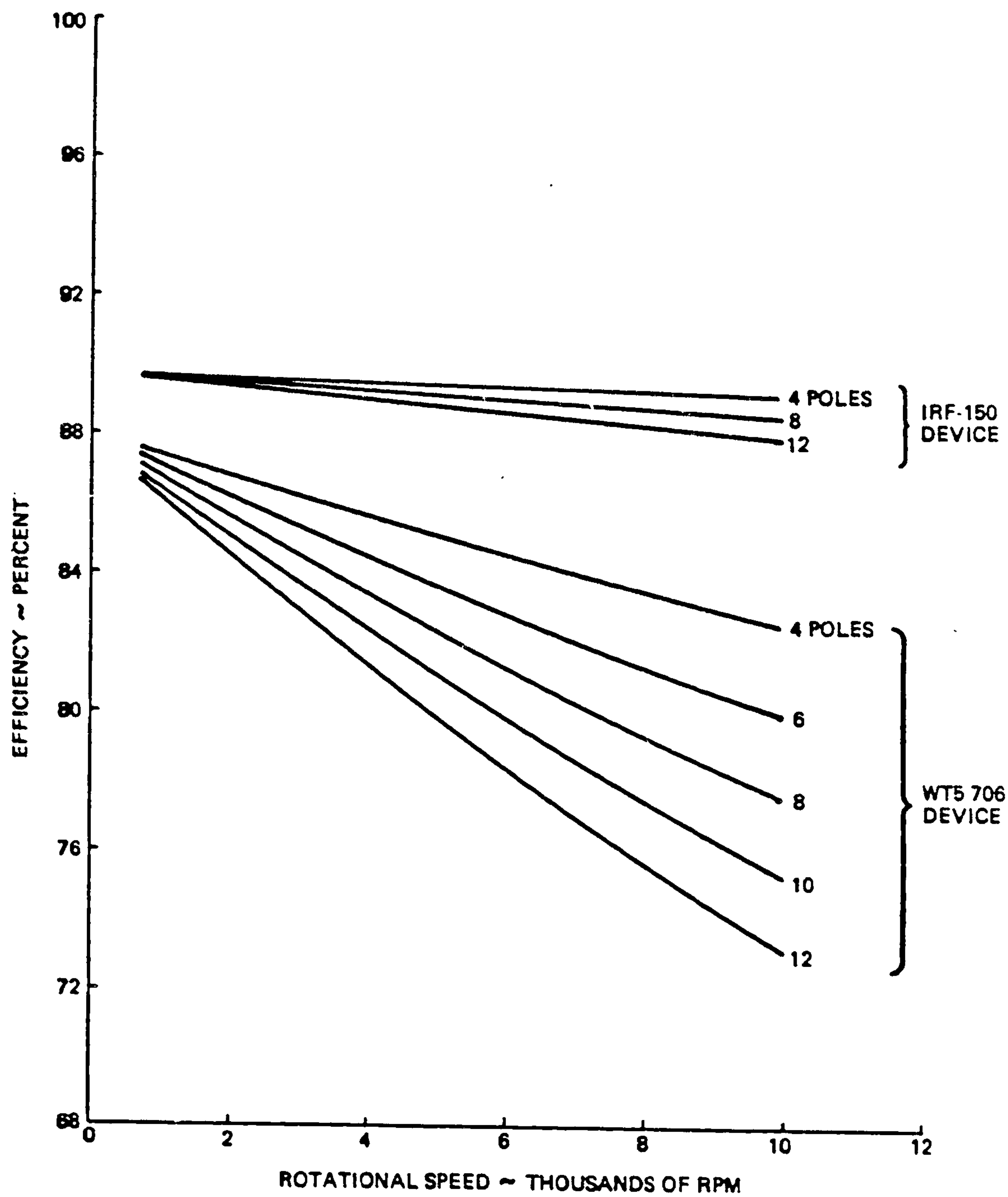

Figure 5.4-1. Efficiency of 28 VDC Motor/Generator Controllers

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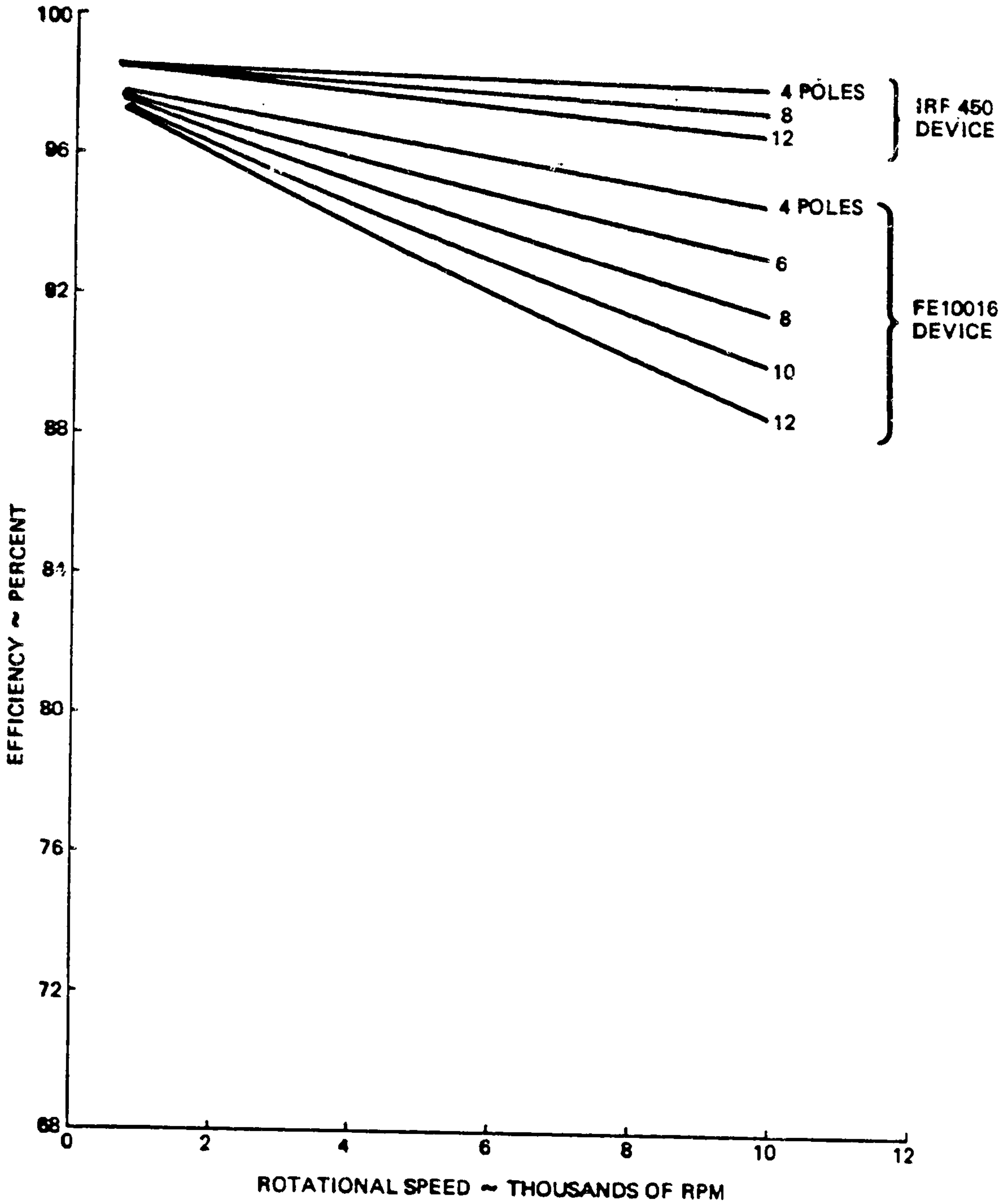

Figure 5.4-2. Efficiency of 270 VDC Motor/Generator Controller

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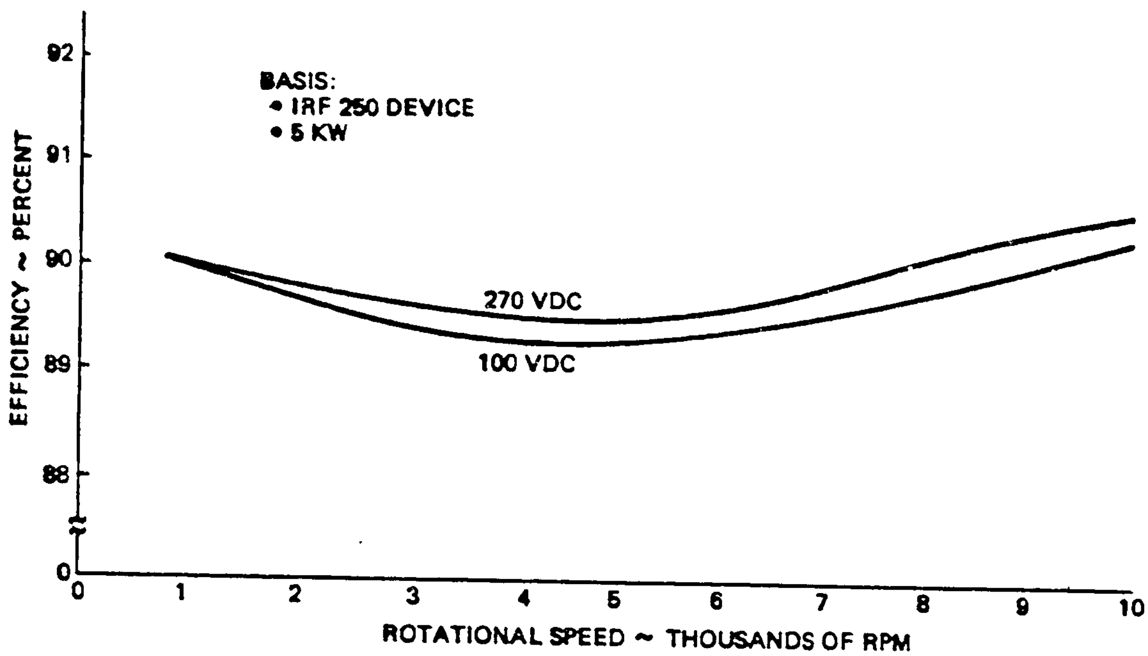

Figure 5.4-3. Efficiency of Conventional Design Motor/Generators

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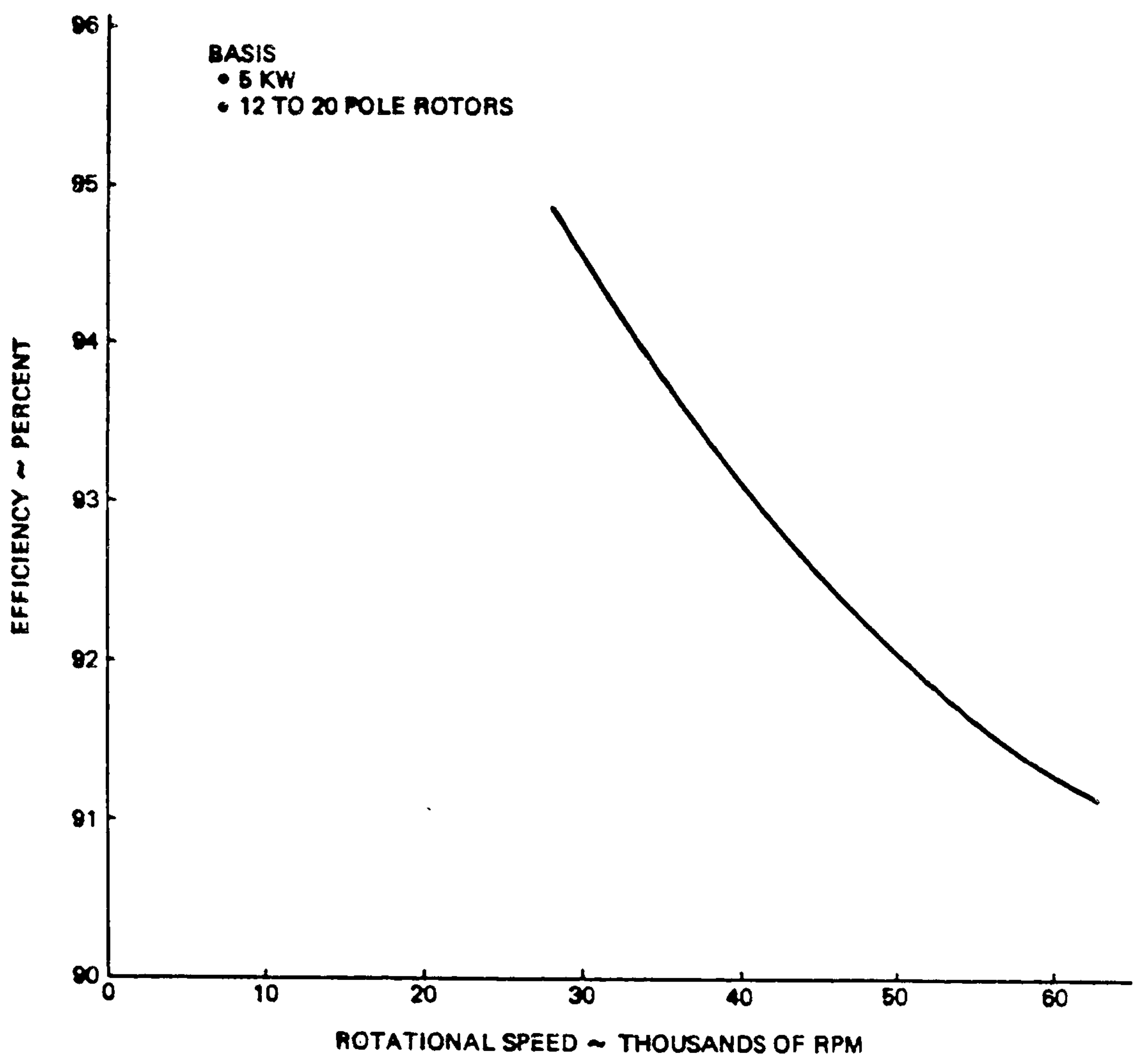

Figure 5.4-4. Efficiency of Conventional Design High Speed Motor/Generators

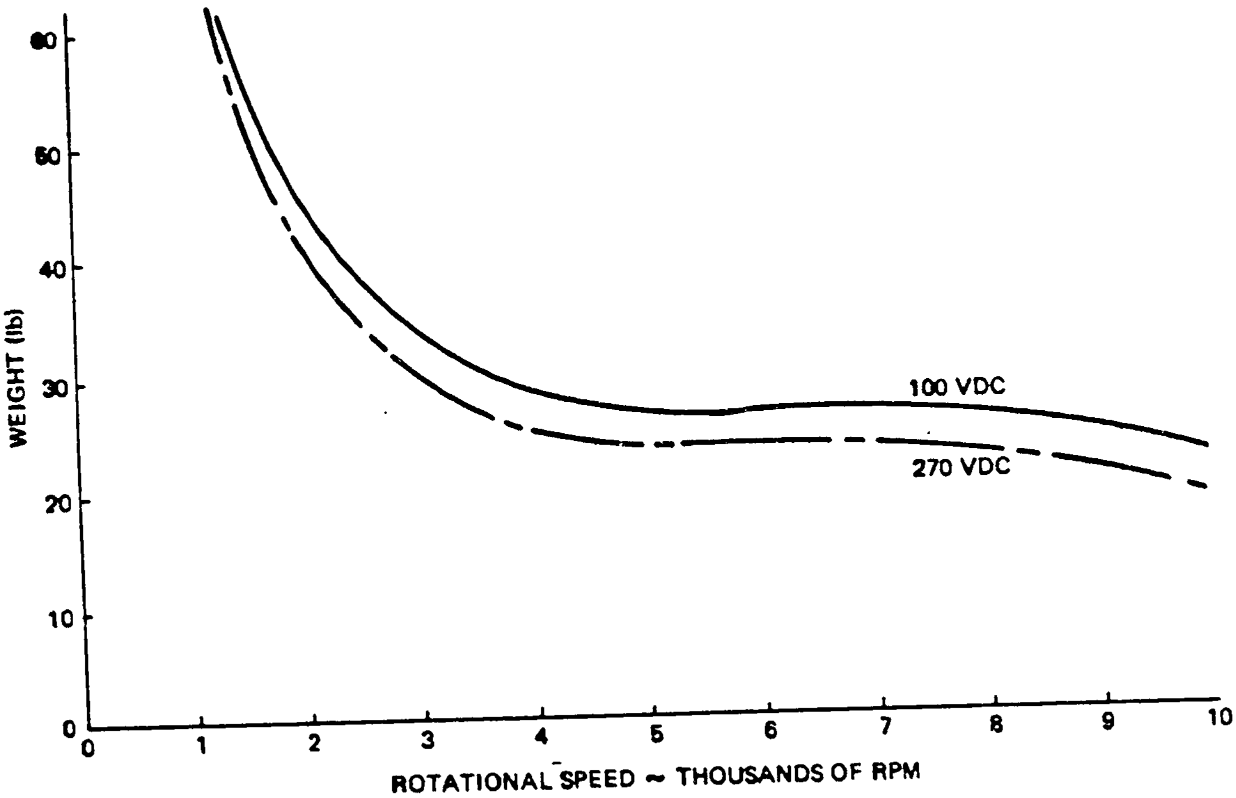

Figure 5.4-5. Weight of Conventional Design Motor/Generators and Controls

order of 160 lb, it is seen that the motor/generator section is only about 15 percent or less of the flywheel system weight.

5.5 PERFORMANCE WITH NON-CONVENTIONAL DESIGNS

High overall efficiency of the motor/generator is an important design objective. To obtain high efficiency, it is desirable to minimize eddy-current and hysteresis losses in the rotor, and also losses associated with the commutation process, such as interpole windings. To achieve this, an important step is to adopt a completely ironless armature.

The construction of a motor/generator with an ironless armature is difficult with a conventional drum rotor. One approach is with an axial field permanent magnet motor, using a disc-shaped armature. This design has an axial air gap, as contrasted with the conventional radial air gap. Rare earth magnets can be useful in this design. This type of pancake design eliminates magnetic drag, permits high speed operation, and can result in high efficiency. The losses are mainly copper losses, which can be minimized by increasing weight.

Using this axial field principle, a prototype 1 kW motor was built at Lincoln Labs. The efficiency of this motor was 98 percent. Some small additional losses would be expected in order to design for a two-to-one speed ratio for a flywheel. It is estimated that an overall efficiency of 96.5 percent is attainable with this approach for a practical design. Overall system efficiency is given in Section 3.2.

6.0 BEARINGS

6.1 MECHANICAL BEARINGS

It is generally acknowledged that flywheels can be equipped with-magnetic bearings for low power demand, and that with this weak link addressed, very long life may be expected. This is an over-simplification of an important and somewhat complex problem. It appears that there is an application area where magnetic bearings are best, another where contact bearings are best, and an intermediate zone where it is not clear which is best. Bearing considerations can have an influence on whether or not energy storage and momentum management systems should be integrated. Cost, power, life and reliability are all factors in the trades between these two bearing approaches. As a general simplification, magnetic bearings can be profitably used where side loads are minor, such as non-gimbaled wheels.

Mechanical bearings, especially contact bearings, are expected to be required on all flywheel systems, either as the primary bearing or more likely as auxilliaries for low speed wobble, start up, let down, and back-up to the magnetic bearing. Mechanical bearings may also be appropriate where side loads are high, such as high torque gimbaled wheels which might occur with an integrated system. Bearing seals and lubrication control may be needed to minimize friction. Friction depends much on the type of bearing and the lubrication; small bearings give lower friction loss, but also result in lower life.

Bearing life is inversely proportional to the bearing load to approximately the third power, as given in the following equation:

$$L = (C/P)^k \qquad \text{EQN (7)}$$

where:
- L = rated life in 10^6 revolutions,
- C = basic load rating (lb or kg) of the bearing
- P = operating load (lb or kg) of the bearing
- k = 3 for ball bearings and 10/3 for roller bearings.

The tabulated data of Reference 6.1-1 shows that the basic load rating is approximately proportional to the diameter to the 1.9 power. The torque M required to overcome friction in ball and roller bearings (Reference 6.1-2) in consistent units is:

$$M = frR$$

where f = 0.001 to 0.002 for ball bearings

f = 0.002 to 0.003 for roller bearings

r = bore radius of bearing

R = radial load

The friction therefore goes up linearly with bearing radius diameter. Thus, it is seen that as bearing size increases, both bearing life and friction increase, but bearing life increases faster. Statistically, the first failures occur at about one tenth of the average life (Figure 6.1-1), so substantial safety factors are needed in bearing design.

Bearing drag, or friction, is roughly proportional to shaft speed, and is highest at low temperatures due to lubricant viscosity effects (Reference 6.1-3). Much of the friction measured in tests is due to loading from the weight of the part being supported. In space, gravity loads disappear except for minute gravity gradient loads. Thus, bearing losses in space can be very small.

Mechanical bearings have a lubrication problem because the seal is exposed to the space environment, and evaporation can occur. Typical approaches to this problem have been to use low vapor pressure oils and labyrinthine seals. Teflon and other dry lubricants have been used, though Teflon has problems with deformation under load. Completely sealed systems are possible with small momentum wheels.

Mechanical bearings have speed limitations, which could present problems with the high performance, high speed flywheel systems anticipated. Roller bearings are limited primarily due to thermal problems at high speed. Hydraulic bearings are capable of higher speeds, but are limited due to viscosity problems. Also, the suspension and dynamic characteristics are much different with mechanical bearings than with magnetic bearings. Mechanical bearings are very stiff, and the response to any disturbance is determined by the deflection of the mechanical parts.

An example of flywheel bearing losses is seen from the AiResearch experience on the Flywheel Bus Program. With a total capacity of 16 kW-hr, their flywheel would typically deliver 12 kw-hrs. Losses from bearings and windage are expected to be 2.5 kW, of which the windage loss is 0.5 kW. Expressed as an equivalent initial self-discharge rate, similar to battery practice, the self-discharge rate in vacuum would be

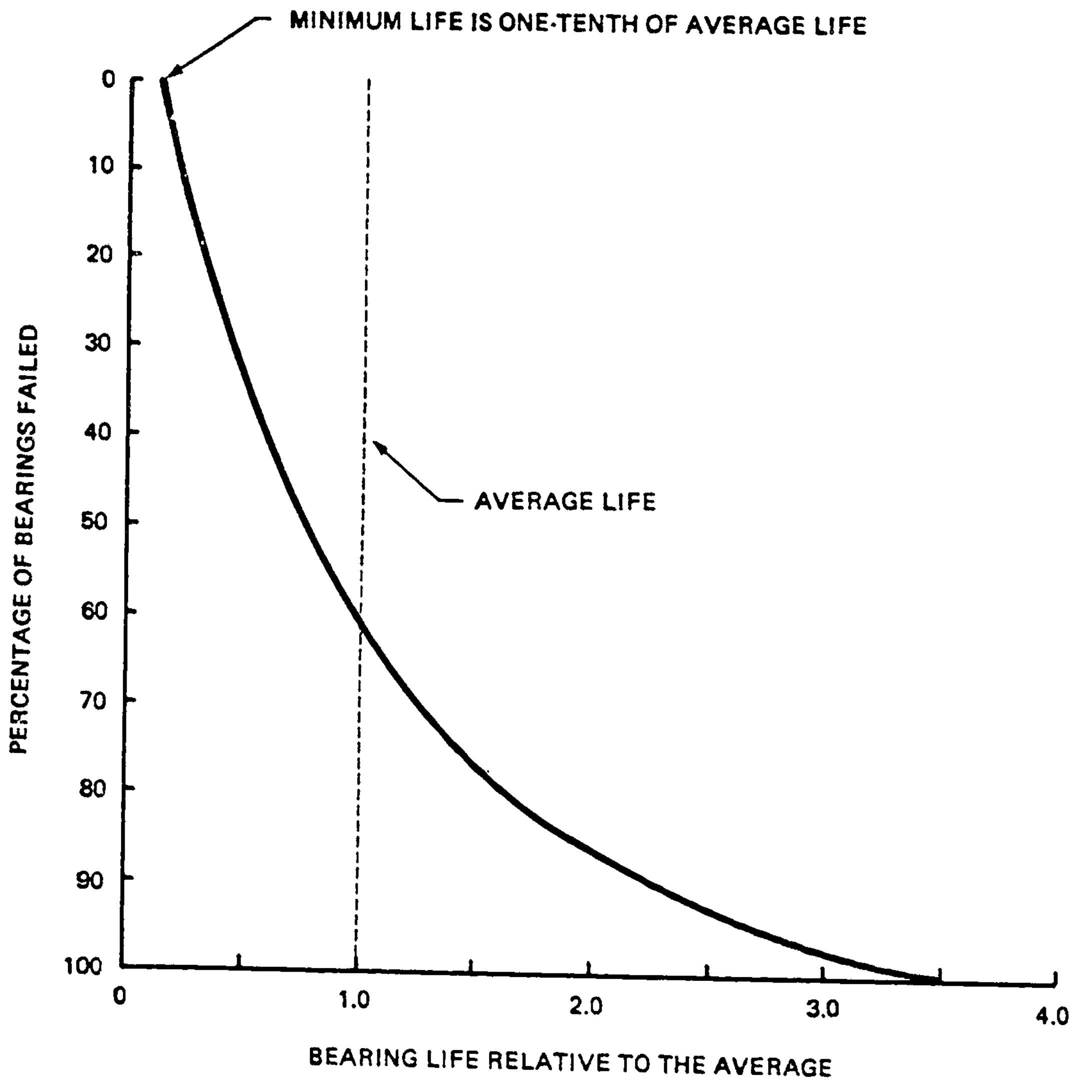

Figure 6.1-1. Typical Distribution of Life of Terrestrial Mechanical Bearings

12 kW-hr/2.0 kW = 6.0 hr. With the main bearing off-loaded, as in zero gravity, the bearing loss is expected to be reduced by a factor of five. Thus, the expected initial self-discharge rate in space, in battery terminology, would be approximately 30 hours. Design calculations also show bearing losses can be very low, however (Reference 6.1-4). Rockwell tests (Reference 6.1-3) showed that bearing drag could be reduced to an equivalent self discharge rate of about 100 hours.

Life and reliability of bearings is an important concern for the space station. The life expectancy for bearings on attitude control systems is approximately five years, though up to nine years life has been obtained. The reputation of mechanical bearings has been marred by a number of incidents where bearings of various types have failed in space. Sometimes the failures would occur during operation, and other times the bearing would freeze after the device was temporarily stopped. For example, in Skylab, two of the three control moment gyros developed bearing problems, one of which caused complete failure of the unit. Bearing lubrication in space is a difficult problem, and undoubtably inadequate lubrication has been involved in many of the failures. It can be speculated that with appropriate design and suitable oil lubrication, elastohydrodynamic operating conditions can be obtained; this would result in enormously extended bearing life. Replaceable contact bearings probably are not feasible, because of the expected need for precision balancing.

6.2 MAGNETIC BEARINGS

6.2.1 Principles of Operation

A magnetic bearing uses forces created by magnetic fields to levitate a flywheel rotor without mechanical contact between the stationary and moving parts. These have been developed for both radial and axial loading, and can be either active bearings or passive bearings. One of the laws derived from Maxwell's equations, known as Earnshaw's Theorum, states that no static assembly of permanent magnets and ferromagnetic materials can suspend a device in stable equilibrium. The practical consequence of this is that at least one degree of freedom of the rotor supported in a magnetic bearing assembly must be stabilized by active feedback electronics. For example, one control arrangement with magnetic bearings for flywheel rotors is a system with passive radial bearings and active axial bearings. Permanent magnets provide the passive containment, whereas electromagnets provide the active containment. Thus, the magnetic bearing system consists of axial and radial bearings and the associated control electronics. Passive bearings have on the order of 15 percent of the load capacity and stiffness of active bearings.

Active magnetic bearings, such as radial bearings, typically consist of two sets of opposing pairs. Current is provided to the four or more electromagnets through amplifiers, controlling the rotor position in response to signals from the sensors. Typically only pulling forces are used, with no pushing forces. The sensors are usually induction devices which sense variations in the magnetic fields caused by displacements; capacitative and optical sensors can also be used. The error signal from the induction sensors is a voltage which is proportional to the variations in the magnetic field. These signals are processed by an electronic control system, which modifies the force of the pulsed magnetic fields and returns the rotor to its nominal position. It should be noted that magnetic bearings can be used either inside the stationary element (stator) or on the outside and concentric to the stationary element.

The error signal from the sensors is directly proportional to the difference between the instantaneous position of the rotor and its nominal position. The nominal position normally is at the geometric center, but this can be shifted off center if desired to improve controllability; this could be important in the flywheel application, for this can compensate for some kinds of rotor out-of-balance which might result from repetitive cycling; vibration-free operation should also be possible. The return of the displaced rotor to its nominal position must be a properly damped movement. This is accomplished by the control system, which determines and controls the bearing dynamic stiffness and the damping values for the magnetic suspension. Stiffness can be altered by changing the gain of the control loop; damping ratio can be altered by changing the phase advance. This flexibility is in sharp contrast to the behavior of mechanical bearings which often respond to a disturbance by the deflection of the parts independent of disturbance frequency. Figure 6.2-1 illustrates the control of radial magnetic bearings using induction sensors.

Rotors with magnetic bearings show three ranges of stiffness, depending primarily on the frequency of the applied external forces which generate the disturbance. This is illustrated in Figure 6.2-2. The lowest stiffness occurs at disturbance frequencies from 0.2 to 1.0 of the natural frequency. At lower or higher disturbance frequencies, greater stiffnesses are obtained as a result of the action of the control system. The fact that the stiffness and other dynamic characteristics can be predicted in advance

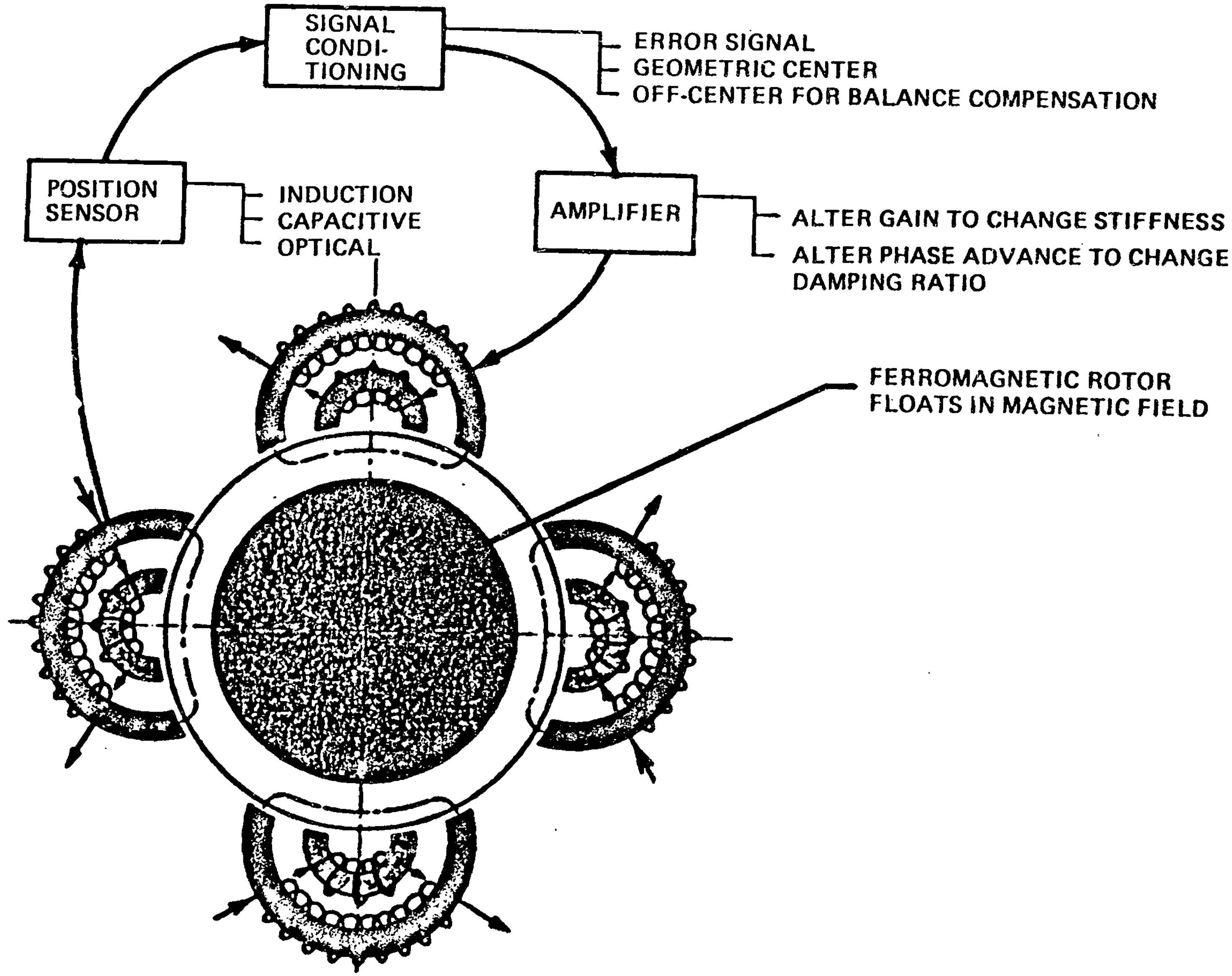

Figure 6.2-1 Radial Magnetic Bearings

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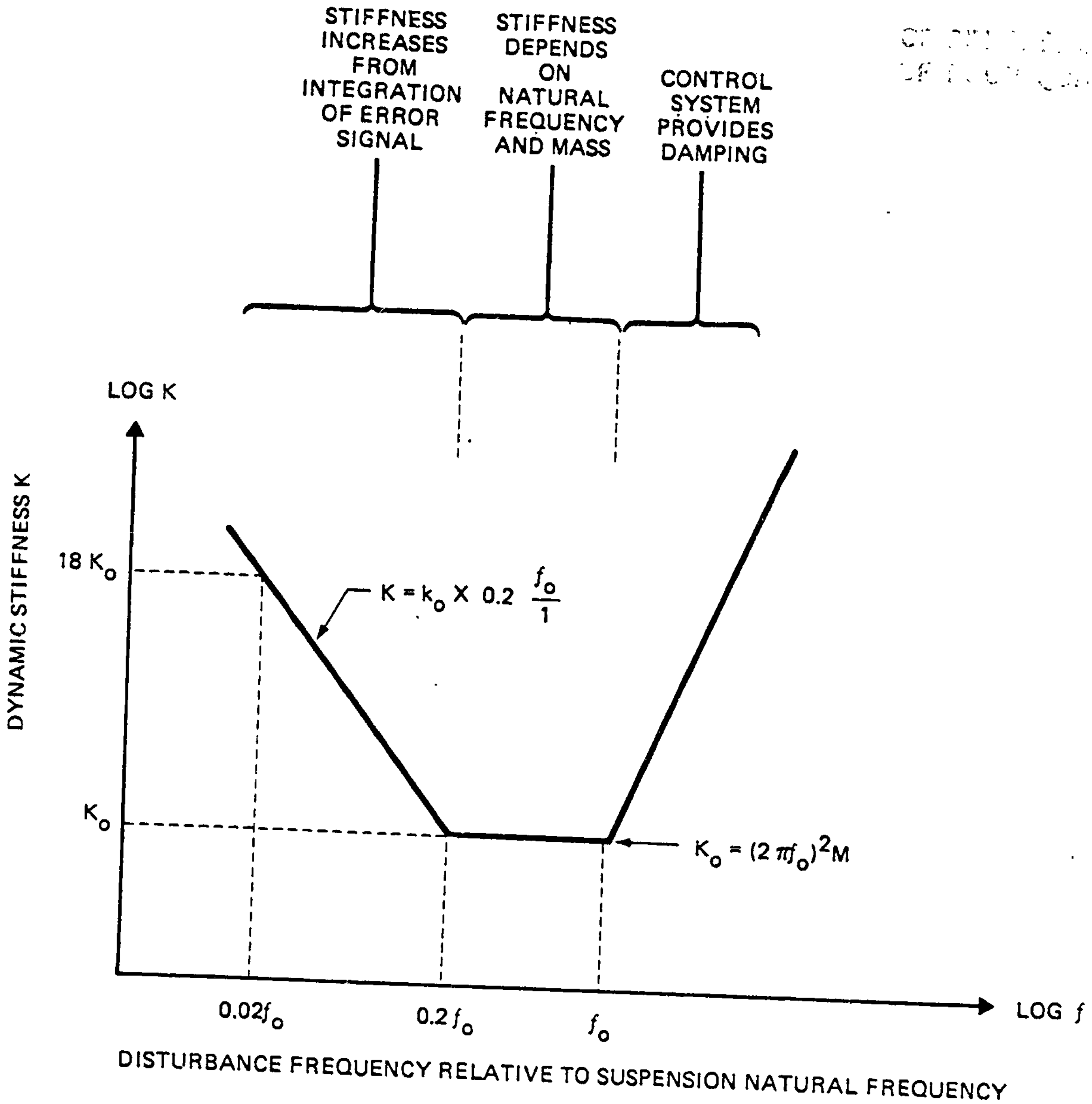

Figure 6.2-2 Stiffness with Magnetic Bearings Depends on the Frequency of the External Disturbance Force

of testing is an important attribute of the magnetic bearing approach. Hickey has shown (Ref. 6.2-1) that bearings are a major factor in determining how well a flywheel-rotor system actually performs, having a major effect on the critical speeds. He has shown that each bearing will require a different stiffness since the mounting generally is asymmetric. Magnetic bearings are able to provide this tailored stiffness.

Magnetic bearings have the capability for automatic balancing, forcing the wheel rotation around its main axis of inertia rather than around the geometric center of the axis. Another very important feature is the ability to provide information needed for diagnosis on the rotation characteristics of the flywheel, using information from the position sensors and the electronic control system. Information obtainable includes: rotational speed; loads on the bearings; position of the rotation axis; eccentricity; out-of-balance; and disturbance frequency. This capability would be especially useful for diagnosis of flywheels during development testing, and for automatic shutdown in flight from threatening failure. Still another possibility is to use the magnetic bearing system to provide small amounts of control torque to the spacecraft; this could possibly be useful for attitude control with small spacecraft.

6.2.2 Magnetic Materials

The development of samarium-cobalt permanent magnet materials has been a key factor in the success of magnetic bearings. This material has an energy product which is considerably greater than previously used materials, and it also has a very high coercive force. These properties permit smaller, improved geometry and results in much less drag than was possible previously. Improvement of these materials is continuing, and as discussed in Section 5.2, much better materials have recently been developed at the laboratory stage, with good prospects for even further improvement. Samarium-cobalt permanent magnetic materials, especially the older materials available, have limited stress capability, but ways have been developed to operate satisfactorily within stress limits. Further study of this potential problem is needed, particularly with regard to the newer materials being developed, such as sintered Sm_2Co_{17}.

6.2.3 Design Considerations

There are many factors to be considered in the design of magnetic bearings, and the specific design evolved for an application depends on which of the requirements is given the greatest emphasis. The design trades involve the overall complexity, weight, bearing stiffness, the drag, and the overall power consumption. For spacecraft use, it is important to determine how specific requirements-affect the design, for example, the penalties associated with the different levels of bearing stiffness. Some of the factors involved in a design are the number of axes controlled; the number of bearings, magnetic dampers, sensors, and magnetic loops; magnetic pole structure; sensor location relative to the magnetic coils; uniformity of the field; bandwidth; weight; air/vacuum gap thickness; magnetic flux topology and field uniformity; and control electronics design and degree of miniaturization. Generator design can have an important influence on bearing requirements, especially with respect to side loads and disturbances.

Rotor suspension in the near-zero gravity of space is a much easier design requirement than for one-G terrestrial needs. Because of the need for ground tests and prelaunch checkout, there will be a requirement to design for one-G; this need could dominate the size, weight, and power consumption of the bearings. Study is needed of this problem so that both the zero-G and one-G needs can be met with a minimum of overdesign and complexity, yet without compromising risk or reliability.

6.2.4 Power Consumption

Power consumption of a magnetic bearing results from the drag it produces, which is determined by the non-uniformity of the field and the conductance of the reacting structures. Drag can be kept to very low levels by careful attention to design, such as geometry of the pole pieces and damper design to avoid conductance in the associated structure. Power consumption also increases with bearing stiffness.

An example of a design with very low power consumption is the brassboard unit built and tested for the Lincoln Experimental Satellite flywheel system, designed for an experimental communication spacecraft. The suspended mass was approximately 200 pounds, and the power used in the bearings was one watt; this amounts to a run-down duration of four months to a rotation speed one third of the initial speed (90 percent energy reduction). A real system would have additional losses associated with the motor/generator and control electronics. However, this test point is illustrative of the very low power consumption possible with magnetic bearings.

The Societe de Mecanique Magnetique in France specializes in magnetic bearings for industrial applications. There is not a large incentive to minimize power consumption for commercial applications, yet their experience is that power consumption is very low, to the extent that a small battery is usually provided for emergency power in case utility power shuts down. Typically, power consumption is 10 to 100 times less than the drag from conventional bearings.

Eisenhaure (Reference 6.2-5) reports the power for a magnetic bearing system with a ten-pound wheel spinning at 25,000 RPM. Total power consumption for the suspension, windage losses and control electronics was 0.1 watt per pound of suspended weight. If this design criterion were valid for large spacecraft wheels, then the calculated loss for a flywheel energy storage system based on the intermediate objective (Section 4.0) would be 6.5 watts/kilowatt; this is based on a useful flywheel weight of 15.74 kg/kW-hr, a motor/generator weight of 3.46 kg/kW-hr, power level based on a discharge to 70 percent DOD per orbit, and an orbital period of 92 minutes. Though this is a small loss, it is much greater than the especially low loss experienced at Lincoln Labs. Also, a 10-watt unit is quite miniature, and better efficiency would be expected for larger sized equipment for space, which in addition would have no windage loss. Thus, a power consumption of 60 percent of this extrapolated value is estimated to be reasonable. This results in an estimated design power consumption of 3.9 watts/kilowatt for the intermediate objective; for the long-term objective, this reduces to an estimated 2.8 watts/kilowatt because of the lower suspended weight.

6.3 COMPARISON OF MECHANICAL AND MAGNETIC BEARINGS

Magnetic bearings are considered superior to mechanical bearings for flywheel energy storage systems. The main advantages of mechanical bearings are:

(1) Low weight and volume
(2) Passive control
(3) Low complexity
(4) Well understood technology
(5) Tolerates launch vibration
(6) Low cost

The main advantages of magnetic bearings are:

(1) No mechanical contact between fixed and rotating parts
(2) Very long life potential

(3) Low power consumption
(4) Absence of liquid lubricants, hence no contamination potential
(5) Very wide operating temperature capability, exceeding -100°C to +200°C
(6) Automatic balancing
(7) No vibration
(8) Tailored stiffness
(9) Diagnosis of rotation characteristics and detection of problems
(10) Linear drag-speed characteristics (ball bearings are non-linear)
(11) Low maintenance
(12) Potentially high reliability

The potential for long life and high reliability of magnetic bearings is of the greatest importance. For example, Boeing has recently designed, built, and tested a magnetic bearing system to replace mechanical bearings for the purpose in that application of greatly increasing bearing life and reducing maintenance. The U.S.S.R. is said to have flown a magnet bearing system in space, but details are not available.

A difficult design task for magnetic bearings is operation where high side loads can occur, such as a high torque gimbaled wheel. Further study of this problem is needed. It should be noted that the emergency or let-down bearings needed with the magnetic bearing system may employ lubrication, and it remains to be determined if the advantage of magnetic bearings in this regard could be compromised.

7.0 ASSESSMENT OF FLYWHEEL ENERGY STORAGE SYSTEMS VS. BATTERIES

7.1 WEIGHT COMPARISON

Flywheel rotor system weights are estimated in Section 4.0, and motor/generator weights are estimated in section 5.0. Combining this data results in the flywheel energy storage system weights shown in Figure 7.1-1. Shown for comparison are weights of nickel-cadmium and nickel-hydrogen batteries. The improved nickel-hydrogen batteries postulated might be realized by either the common pressure vessel technology (WPAFB), or by the bipolar electrode technology (NASA Lewis).

It is seen from Figure 7.1-1 that both the intermediate and advanced design flywheels are lighter than any of the battery systems. Not shown is the flywheel system weight based on the projected technology for the year 2000 (Figure 4.2-3), which would be even lighter. The 100% depth-of-discharge calculation (Figure 7.1-1A) for the flywheel is not obtainable in a practical system, and is shown for comparison only due to the differing depth-of-discharge design points used in Figure 7.1-1B. In addition, the 100 percent depth-of-discharge performance of the battery systems can be approached confidently only near the beginning of battery life.

The potential weight advantage of the flywheel sytem is striking when comparisons are made for the design depth-of-discharge (Figure 7.1-1B), since the flywheel can cycle repetitively at deeper depths-of-discharge than can batteries. Figure 7.1-1B can be a valid comparison only if the reserve capacity of the battery systems is not depended upon for emergency power. The flywheel system is not practical for depths-of-discharge much greater than 75%, and the upper practical limit for battery sytems for occasional discharges is approximately 85% depth-of-discharge for nickel-hydrogen, and 75% for nickel-cadmium batteries. A weight comparison for these design values is given in Figure 7.1-2, applicable for comparison of emergency power capability. Even for this condition the flywheel system is lightest, although the differences are less dramatic than for the conditions of Figure 7.1-1B. Tabulation of these weights is given in Table 7.1-1.

As noted previously, the amount of emergency power required has an important bearing on the weight comparison of flywheels versus batteries. If the emergency requirement is small enough to be handled by the reserve capacity of batteries, then the power system trade essentially is between batteries at about 75 to 85 percent

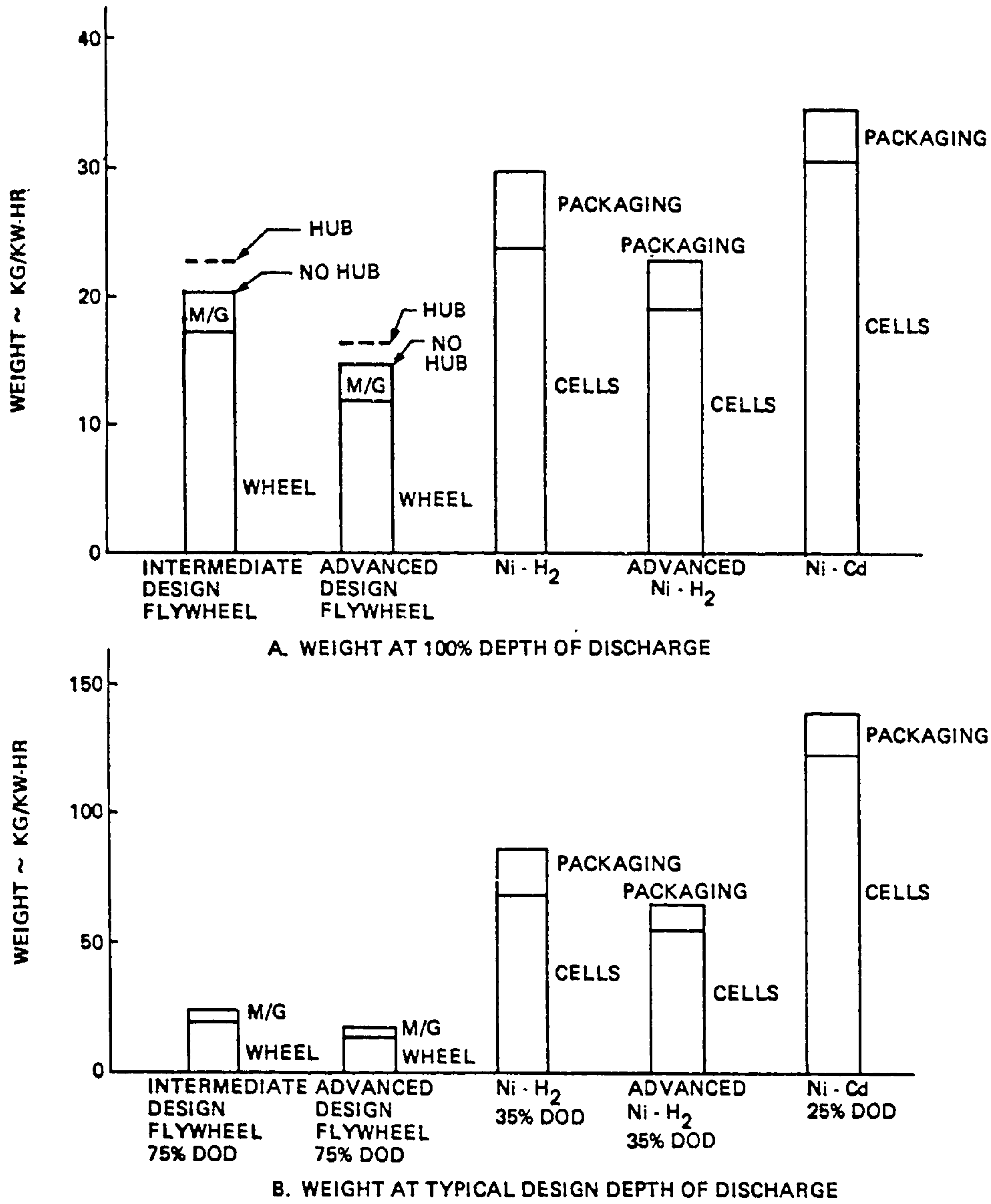

Figure 7.1-1. Comparative Weights of Energy Storage Devices

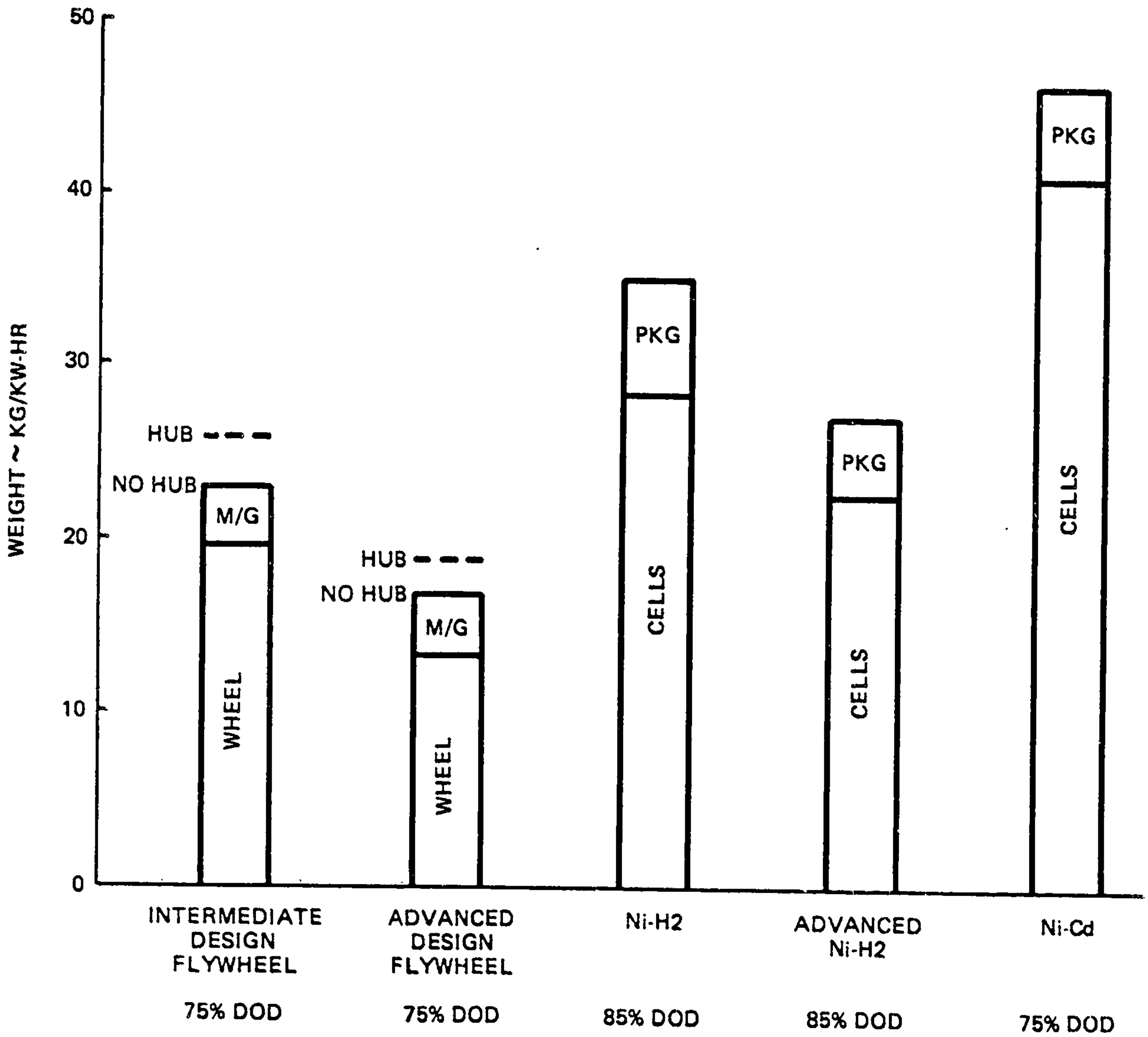

Figure 7.1-2. Comparative Weights of Energy Storage Devices Sized for Emergency Condition

	WEIGHT ~ KG/KW-HR				
	100% DOD (HYPOTHETICAL, REFERENCE ONLY)	SIZED FOR LEO CYCLING		SIZED FOR EMERGENCY	
			(DOD)		(DOD)
INTERMEDIATE DESIGN					
FLYWHEEL – WITHOUT HUB	18.21	23.13	(75%)	23.13	(75%)
FLYWHEEL – WITH HUB	20.29	25.90	(75%)	25.90	(75%)
ADVANCED DESIGN					
FLYWHEEL – WITHOUT HUB	13.49	16.83	(75%)	16.83	(75%)
FLYWHEEL – WITH HUB	14.90	18.72	(75%)	18.72	(75%)
Ni-H2 BATTERIES	29.64	85.25	(35%)	35.10	(85%)
ADVANCED Ni-H2 BATTERIES	22.92	65.47	(35%)	26.96	(85%)
Ni-Cd BATTERIES	34.67	138.68	(25%)	46.23	(75%)

Table 7.1-1. Weight Comparison of Flywheels and Batteries

depth-of-discharge, and a flywheel system at approximately 75 percent depth-of-discharge (Figure 7.1-2). On the other hand, if the emergency requirement is very large, then it must be supplied independently by a primary emergency battery system, and the power system trade focuses on the main load, and is essentially between batteries at 25-35 percent depth-of-discharge, and a flywheel system at approximately 75 percent depth-of-discharge (Figure 7.1-1B).

Though a two-to-one speed range is considered a good typical design point, a detailed trade study is needed to determine the best depth of discharge. It is possible to operate over a three-to-one speed range and increase depth of discharge from 75 percent to 88 percent. However, as depth of discharge increases, motor/generator efficiency decreases. An ideal design would operate at high efficiency over the normal operating depth of discharge range, and reduce to a lower efficiency only when using the reserve energy which would be at the deeper depths of discharge.

Accessory equipment associated with the batteries and flywheels gives a further weight advantage to the flywheel system. There are significant differences in thermal control penalties, namely: (1) flywheel system efficiency is higher than for batteries, resulting in less heat to be dissipated. For typical flywheel and battery system efficiencies of 80 percent and 65 percent, respectively, the flywheel thermal load is 57 percent of the battery thermal load; (2) flywheel system heat is removed at a higher temperature (typically about 30°C) than with batteries (typically about 10°C); (3) the heat load is more uniform with time for the flywheel than for batteries. One thermal advantage batteries have over the flywheel system is a much greater transient heat storage capability.

Another important item is the fact that the flywheel system does not need a separate charge controller, as do batteries, for this function is accommodated in the motor/generator electronic controls. Still another difference stems from the fact that the voltage regulation of the flywheel system is very fine, and essentially provides a regulated bus; this can be reflected in higher overall spacecraft power efficiency, and lower weight power supplies for the user equipment. Of particular importance is the smaller solar array size resulting from the high efficiency obtainable with the flywheel system; this gives important systems advantages in addition to the weight saving (see Section 3.0).

Table 7.1-2. Weights for Energy Storage Systems - - 50 KW Continuously (Pounds)

	BATTERIES			REGENERATIVE FUEL CELLS		FLYWHEELS	
	NiCd (25% ODD)	NiH_2 (35% DOD)	NiH_2 (30% DOD)	WEIGHT OPTIMIZED	EFFICIENCY OPTIMIZED	INTERMEDIATE DESIGN OBJECTIVE	ADVANCED DESIGN OBJECTIVE
SOLAR ARRAY WEIGHT	3,245	3,401	3,245	3,817	3,245	2,799	2,639
(SOLAR ARRAY POWER)	(106.1 KW)	(111.2 KW)	(106.1 KW)	(124.8) KW	(106.1 KW)	(91.5 KW)	(86.3 KW)
RADIATOR	960	1,047	960	521	395	316	121
FUEL CELLS (1)	—	—	—	860	1,630	—	—
ELECTROLYSIS CELLS (1)	—	—	—	365	635	—	—
BATTERIES (1)	8,769	5,796	6,762	—	—	—	—
PROPELLANTS (2) (H_2-O_2 ANNUAL REQMT)	3,281	3,439	3,281	3,860	3,281	2,829	2,668
COLD PLATES	965	638	744	—	—	18	18
HEAT EXCHANGERS	—	—	—	50	40	—	—
TANKS	—	—	—	262	240	—	—
FLYWHEEL SYSTEM	—	—	—	—	—	1,781 (3) 4,931 (4)	1,273 (3) 3,564 (4)
TOTAL, LBS	17,220	14,321	14,992	9,735	9,466	7,723 (3) 10,893 (4)	6,719 (3) 9,010 (4)

(1) ASSUMES 5-YEAR BASIC LIFE

(2) ALTITUDE MAINTENANCE TO COUNTERACT SOLAR ARRAY DRAG ONLY

(3) DESIGNED FOR LEO LOADS ONLY

(4) DESIGNED FOR SAME EMERGENCY CAPABILITY AS BATTERIES - - CAPACITY = 2.8 TIMES OCCULTATION LOAD

Typical weight comparisons have been made at the spacecraft level between flywheel, regenerative fuel cells, and battery systems (Table 7.1-2). The power system load is arbitrarily set at 50 kW for both sunlight and occultation. It is seen that the flywheel energy storage system is lighter than batteries. Also, the weight differential at the spacecraft level is seen to be greater than the weight difference of the energy storage hardware, as shown in Table 7.1-1. The higher efficiency of the flywheel system accounts for an important part of the weight saving. Flywheel equipment weight increases significantly if it is designed for emergency power capability equivalent to that of batteries; nevertheless, total weight remains lightest for the flywheel system even when designed to such a requirement.

Weight summary data derived from Table 7.1-2 is given in Table 7.1-3. After ten years of operation, propellant resupply becomes considerably more important than the weight of the energy storage hardware, which emphasizes the importance of high efficiency. It is seen from this summary that both regenerative fuel cell systems and flywheel systems are lighter than battery systems.

7.2 LIFE AND RELIABILITY

Life and reliability of nickel cadmium batteries is an important concern for all spacecraft applications, including the space station. Nickel hydrogen batteries have the potential for improved life and reliability, and efforts are now being expended to develop that potential. For either system, however, it is expected that periodic battery replacement will be necessary to meet the space station lifetime requirements, which is in the range of 10 to 15 years.

Flywheel systems, on the other hand, have the capability for much longer lifetimes than do battery systems; when developed, the flywheel system should be able to operate without replacement during the life of the space station.

In assessing the life and reliability of the flywheel motor/generator system, those items considered to be key to long life and reliability were identified and individually evaluated. These items are: (1) fatigue and long term creep of the flywheel rotor; (2) bearings; (3) motor control electronics; (4) cooling system; (5) forced shutdown of counter-rotating unit, for designs not integrated with the attitude control system.

Table 7.1-3 Weight Summary

	Ni-Cd 25% DOD	$Ni\text{-}H_2$ 35% DOD	Regenerative Fuel Cells, Efficiency Optimized	Flywheel with Emergency Capability	
				Intermediate Design Objective	Advanced Design Objective
Energy Storage	8,769	5,796	2,545	4,931	3,564
One Year Total Weight, lbs	17,220	14,321	9,466	10,893	9,010
Ten Year Total Weight, lbs	46,749	45,272	38,995	36,354	33,022

Fatigue and Creep

The question of flywheel fatigue resolves essentially into one of weight. When the fatigue-cycle relationships are adequately known, a suitable derating factor can be applied to allow for fatigue over the design life. Figure 7.2-1 gives the fatigue behavior of a typical carbon-fiber composite, and shows the very high resistance of these composites to fatigue. It is likely that some of the degradation seen is due to the epoxy matrix, which is believed not to be optimum for cyclic loading applications. Carbon fiber composites do not show the microcracking observed with glass laminates. These data suggest that derating factors for 5, 10 and 15 years should be approximately 0.957, 0.945, and 0.942, respectively, excluding design margin. This can be compared with a fatigue derating factor of 0.70 used for this study, which includes a design margin. It may be noted that the fatigue effects on other materials sometimes used for flywheels, such as glass or kevlar, are much more severe than for carbon fiber materials.

Creep behavior of composite flywheels was not assessed in this study due to the lack of data. Some data are given in Section 4.4, however. It is believed that carbon fiber has very little tendency to creep, though there is a concern that under cyclic loading some fibers will slide and adjust their positions slightly relative to each other. This could cause some unbalance in the flywheel, which would either have to be of a tolerable level, or at a level which could be compensated for by magnetic bearings.

Bearings

As discussed in Section 6.0, magnetic bearings offer the most promise for long life spacecraft applications. These need involve no mechanical contact between the rotating equipment and the stationary elements. Degradation of the permanent magnet elements in the bearings is believed to be minor over 15 years. Thus, the electronics required for the magnetic bearing control is judged to be the critical long life item for the bearings. No analysis of these circuits was made, but the level of complexity is expected to be well below that of much spacecraft electronics, and with suitable redundancy, very long life should be achievable.

Motor/Generator Control Electronics

The electronics controls for the motor/generator use high power switching devices, which require careful design, adequate cooling, and suitable redundancy to assure long life. Reliability studies of these circuits is needed.

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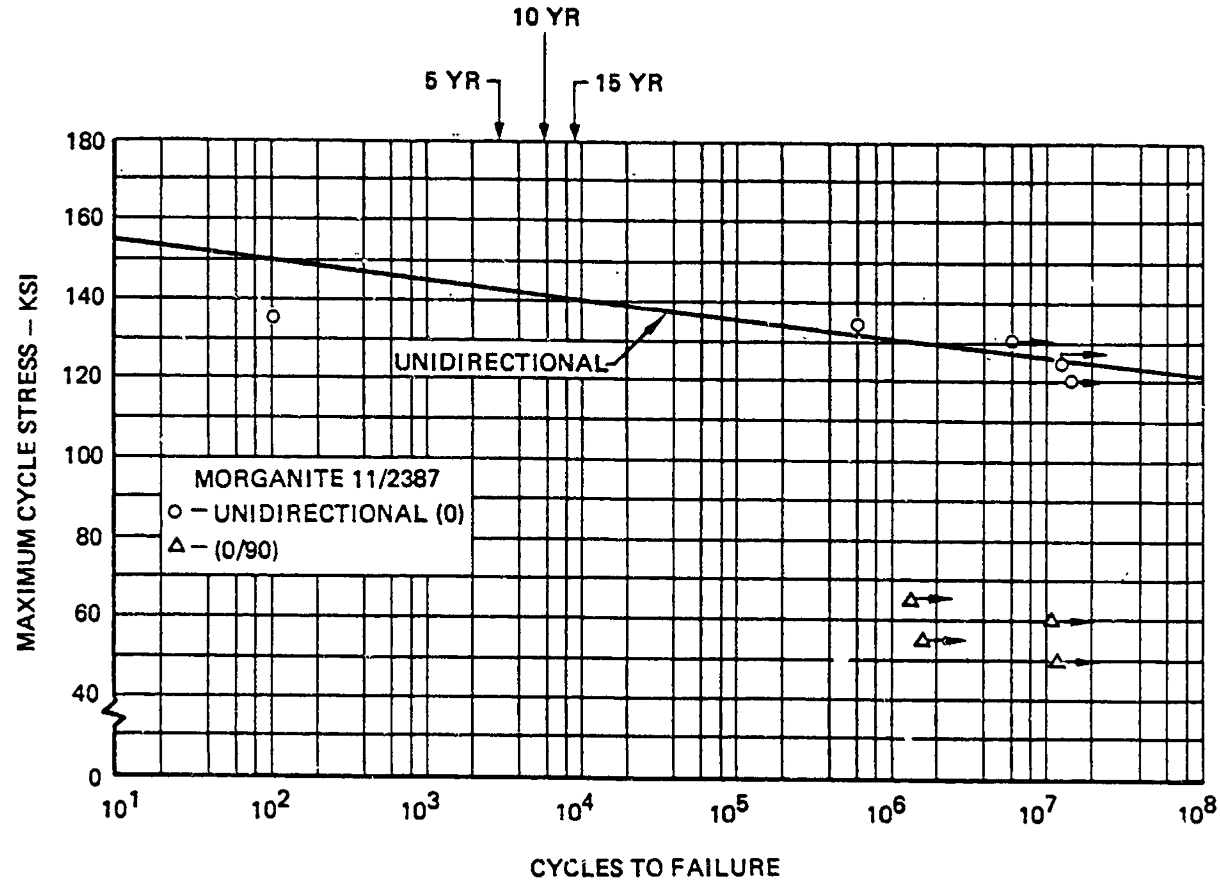

Figure 7.2-1. Constant Amplitude Unidirectional Fatigue Properties of Typical High-Strength Graphite/Epoxy Composite

Cooling System

The expected performance of long life spacecraft temperature control systems is somewhat uncertain. Stability of coatings is questionable, and heat pipes can be affected by impurities which slowly leach into the system. This problem could be severe for battery systems, since low temperature (5°C) and close control (±5°C) are both needed. The components of flywheel systems tolerate higher temperatures (≈30°C) and accept much wider temperature control (estimated about ±35°C).

Flywheel systems have an advantage over batteries with respect to temperature control. However, since any temperature control problem would be a concern for the entire spacecraft, it would not be appropriate to single out the impact on the energy storage system. Therefore, it is concluded that no life and reliability distinction can legitimately be made between the batteries and flywheel temperature control systems.

Forced Shutdown of Counter-Rotating Units

In order to prevent angular momentum unbalance, failure of a flywheel unit not integrated with the attitude control system would appear on first analysis to require that a second equipollent unit, rotating in the opposite direction, will also have to be shut down. Subsequent failures give no relief if the worst case is assumed, where all failing flywheels rotate in the same direction, and spin direction reversal is not provided for. This doubling effect is viewed as an important limitation of flywheel systems. Spin direction reversal can limit the number of good units which are forced to be shutdown. This problem is also related to the number of buses used in the spacecraft (see Section 7.7).

Conclusions

In summary, it is concluded that the flywheel motor/generator system has the potential for long life and high reliability well in excess of battery systems. Life and reliability are mainly limited by the electronics associated with the system, and by forced shutdown of the possible need for a counter-rotating unit following failures. Though costs have not been analyzed, it is expected that long life would also be reflected in lower costs of the flywheel system, particularly the costs associated with resupply.

7.3 HIGH POWER LEVEL CONSIDERATIONS

The high power level of space stations -- 50 kw and greater -- and the high operating voltage -- about 200 V -- present unique considerations in the trade between batteries and flywheel systems. The large number of cells in series increases the probability of shorted cells in the batteries. Thus, batteries have the problem of load sharing during parallel discharge. Flywheel motor/generator systems can share current easily and accurately with state-of-the-art electronic controls. Load sharing can also be a concern during space station buildup, when additional power modules may be added; this will also be more of a problem for batteries than for the flywheel system.

7.4 EFFICIENCY CONSIDERATIONS

The importance of high energy storage efficiency is treated in detail in Section 3.0. In short, high efficiency reduces solar array size, minimizing aerodynamic drag and orbital makeup fuel, as well as reducing radiator size and system hardware weight. Figure 3.1-1 compares solar array size, and shows that for a near-term flywheel system (eff. = 0.8) the solar array size is 0.868 of the size with an electrochemical system (batteries or fuel cells, eff. approximately 0.6). An advanced flywheel system (eff. = 0.9) is 0.824 of the size. This smaller array is reflected as a considerable weight saving, especially from orbital makeup fuel (see Section 3.0). Thus, efficiency considerations clearly favor the flywheel energy storage system.

7.5 SHELF LIFE CONSIDERATIONS

Batteries begin their degradation at the time of electrolyte addition during manufacture. To minimize shelf life problems, an attempt is often made to schedule manufacture completion as close as possible to the launch date. Nevertheless, for a variety of reasons, battery service may not begin until several years after manufacture. Therefore, shelf life often is an important factor in the use of energy storage systems.

Shelf life requirements for an energy storage system come from the following: (1) there is a need to have suitable margins to cover component manufacture, energy storage system assembly, component and system testing, spacecraft installation, and integration and checkout; (2) there is a desire to provide additional margin to minimize program risk and permit flexibility in scheduling; (3) there is a desire to manufacture all energy storage components for a program from one manufacturing lot to improve quality assurance and minimize assembly costs; (4) there is a desire to conduct long burn-in tests to give added confidence of quality assurance; (5) there is a desire to permit the use of spares on any flight of a spacecraft series or space station buildup.

Batteries have been able to be used in past programs within their limited shelf life capabilities, and they undoubtedly could be used successfully on the space station. Nevertheless, batteries are not adequate to meet all of the above shelf life desires. Flywheel systems, by contrast, have nearly indefinite shelf life, and can meet all of the above shelf life wants.

7.6 PEAK POWER CONSIDERATIONS

Designing for peak power is a necessary requirement for all space power systems. Nickel-cadmium and nickel-hydrogen batteries have an inherent good capability for high peak power, and generally can meet peak requirements easily. The flywheel system can be designed also for very high peak power, and can in fact be designed for special applications to convert all its kinetic energy into electricity in a fraction of a second, using a special generator. Even for moderately high peak power, the motor/generator must be increased in rating, and for extremely high peak needs special motor/generator designs are required; this is discussed in Section 5.1.

A unique difference between batteries and the flywheel systems is that minimum system voltage with battery systems occurs during power peaks, whereas output voltage is always regulated for the flywheel motor/generator system. For the purposes of this study, the generator design was based on a peak power capability twice that of the nominal power output. To meet even higher peak needs, the motor/generator size would have to be increased. This is not a large weight penalty, for the motor/generator is a relatively small fraction of the total system weight. Figure 7.6-1 shows the typical weight increase required by flywheel systems to meet peak power needs.

An important capability of flywheel energy storage systems is the ability for multiple discharges per orbit, augmenting the solar array for high power loads during the sunlit portion of the orbit as well as the usual occultation load. For applications where the load is highly variable, this makes it expedient to reduce solar array area, allowing the array to be sized close to the average power rather than sized to peak power. This puts a demand on the energy storage system which batteries are not well equipped to cope with, partly due to the increased number of cycles, but primarily from the higher

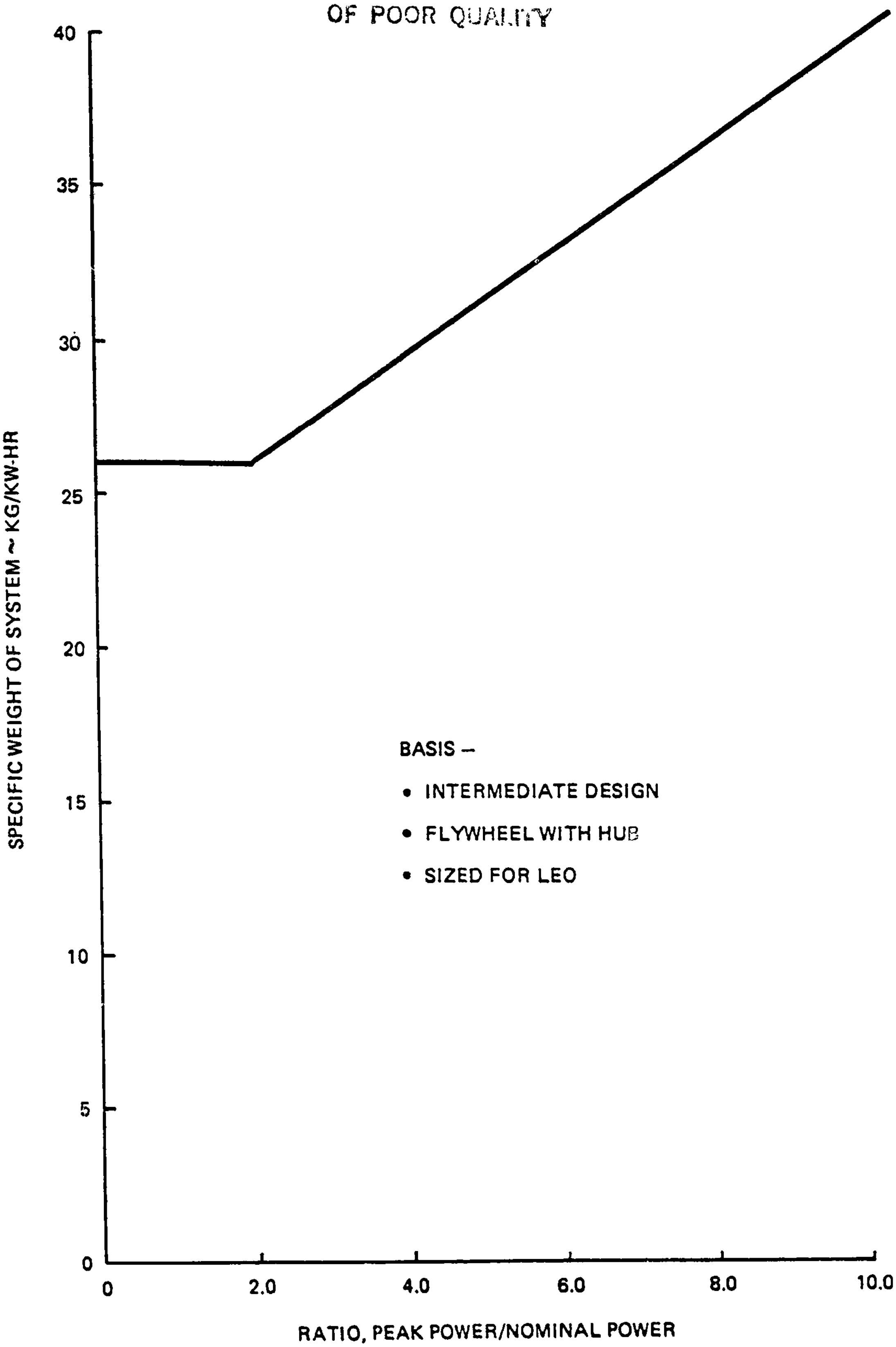

Figure 7.6-1. Effect of Peak Power Requirement on Specific Weight of Flywheel Energy Storage System

charge rates needed with multiple discharges and charges. The most strenuous needs for multiple discharges per orbit are expected to be military applications.

7.7 POWER DISTRIBUTION CONSIDERATIONS

Multiple buses are often used in manned spacecraft to help assure power system integrity. Flywheel energy storage systems pose some special problems with such multiple buses. If it is assumed that all non-integrated flywheel units are installed in the most favorable geometry, that is, with all flywheel axes parallel, then momentum change can be avoided by balancing the momentum sum of all left-handed wheels with the momentum sum of all right-handed wheels; this would be relatively easy to do in a single-bus system. However, if each bus must be electrically independent, then momentum balancing must be done separately for each bus. That requires an even number of units per bus, with equal-speed control at the bus level; again, that poses no special problems provided there are no failures.

Failure of one unit in an independent bus will require forced shutdown of a counter-rotating unit on the same bus. This can severely penalize that bus, and a second failure would likely shut it down (e.g., three buses at four units per bus). Provisions to switch flywheel units electrically between the buses would be helpful, but adds complexity. Minimizing the number of buses is also helpful.

It is not obvious what is the best distribution system for spacecraft using flywheel energy storage when the system is to be designed to survive failures. Further study of this problem is needed.

7.8 SAFETY CONSIDERATIONS

Safety has not been much of a problem with conventional 28 volt battery systems. With higher voltage systems (about 200 Vdc), there is a much greater danger to personnel during all phases of battery handling and in-flight maintenance or replacement. A battery would practically always present a high voltage, whereas the flywheel motor/generator does so only under operation. Nevertheless, procedures can be developed which should assure safe handling of high voltage batteries.

Safety from high pressure rupture of nickel-cadmium and nickel-hydrogen batteries is always a possibility, but is considered to be a very small risk. High pressure in nickel-cadmium cells is generally related to particular combinations of voltage, current and temperature; this could be identifiable by analysis of monitored cell data, however. Safety from possible cell case rupture should not be a problem with nickel-hydrogen batteries, for the cell case materials are selected which are non-fragmentable. Combustion of the hydrogen probably is not a problem because any energy system is expected to be located in an unpressurized area; ground tests could present a hazard, however.

Flywheel systems are suspect with respect to safety because of the potential for rapid release of a large amount of kinetic energy. This problem of flywheel containment is discussed in Section 4.3, and the ground rule proposed is that any rotor which can burst is considered an unsafe design for space. Implementation of this philosophy should rule out significant risks of safety.

When a wheel starts to fail, this will be sensed and the wheel will be shut down. One safety concern is that there could be a second failure which causes the wheel not to be shut down, and allows it to fully destruct. A related type of condition is a failure which fails to terminate wheel spinup, forcing the wheel to self destruct. Redundant sensors and controls will be needed to prevent these kinds of failures.

In summary, it is concluded that safety need not be a major concern with either batteries or flywheel systems.

7.9 EMERGENCY POWER CONSIDERATIONS

A flywheel energy storage system can be inferior to a battery or regenerable fuel cell system with regard to emergency power. A flywheel system typically would be designed for 75 percent depth of discharge, obtained by operating over a speed range of full speed to half speed. Withdrawal of most of the remaining 25 percent capacity is impracticable because of the much increased speed range needed, which would impact overall efficiency. Batteries, on the other hand, would typically be discharged in the 25-35 percent range, and in an emergency could be discharged up to about 85 percent. Regenerable fuel cells can obtain very long emergency capability by increasing the inventory of hydrogen and oxygen without an increase in the other hardware.

Valid arguments can be made that the emergency power system should be a system separate from the main system. This could be necessary to isolate a failure, and provide a level of emergency power well above what could be provided from the undischarged reserve in the secondary batteries. Should this rationale prevail for the space station, then the poor reserve capability of a flywheel energy storage system would be a minor factor.

7.10 SPACECRAFT OPERATION CONSIDERATIONS

Prelaunch Testing. Electrical power systems testing and checkout must be done at the power subsystem level, the spacecraft level, and as part of the prelaunch integration. Some of the magnetic bearings in the flywheel system will have to be designed to suspend the system under one-G, so the orientation of the system must be known in advance to accommodate this. If the logical vehicle orientation for spacecraft ground tests differs from the logical orientation for prelaunch integration tests, then this could impose a burden on the design for the one-G suspension. Further study of this subject is required.

Launch-phase Power. Batteries have the capability to provide electrical power during the launch phase, and frequently power is turned over to the batteries several minutes before launch for additional system verification. Flywheels probably cannot be operated during the high vibration environment of launch unless a suitable bearing design can be developed. Without such a development, a separate battery would have to be provided for this requirement. Launch power levels generally are low so the weight penalty may not be large. Even so, the inability to switch over to flywheel power until some time after launch is a disadvantage. Further study and analysis of this problem is needed.

Reconditioning. Reconditioning is proven to be a worthwhile procedure for nickel cadmium batteries in synchronous orbit. The procedure is seldom used for low earth orbit, being only of temporary value. Full spindown of a flywheel system is not seen to have any remedial value. Thus, neither batteries nor flywheel systems would require reconditioning for the Space Station. Flywheel systems can be considered for synchronous orbit, however, and for such applications the flywheel would have an advantage in this respect.

State-of-Charge. No practical method has been developed to determine the capacity of a nickel cadmium battery in advance of a full discharge. Nickel hydrogen batteries reveal their ampere-hour capacity by the cell hydrogen pressure, though there is a gradual change in end of charge pressure with time which must be accounted for; discharge voltage for the last half of discharge cannot always be well predicted, hence there is uncertainty on the watt-hours available. The flywheel system is superior to both battery types, for after an initial calibration discharge, voltage and energy can be accurately predicted for a full range of operating conditions; except for secondary changes, this calibration should remain constant over the operating life of the system. Thus, the flywheel system offers excellent energy storage predictability, unmatched by any battery system.

7.11 CONCEPTUAL DESIGN APPROACHES

One of the major problems in flywheel technology is the hub design. Many of the development failures have been caused by technical weaknesses in the hub design. Rockwell has evolved for both their composite and metal rotors what may be called a hubless design, thus cleverly solving that problem. The problem is more difficult for composite material rotors. Drilling holes through the rotor to bolt on a hub can weaken the rotor, but appears to be feasible and requires more development. One method is to bond the hub to the sides of the rotor, and this has been done with a few experimental rotors with good success. The rotor can be constructed around a hub, but as the rotor speeds up it tends to pull away from the hub. To solve that problem, the hub can be made of an organic material which is in compression during layup. Nylon has been used for this purpose with glass fiber rotors, but has not been proven experimentally.

It may be possible to use the outside cylindrical surface of the motor/generator as the equivalent hub for the flywheel rotor, as proposed in Reference 1.1-5. The conventional armature and stator positions would be reversed with this approach. This has the potential of being the lightest design, for no hub proper or shaft are required. This has similar problems to the use of a separate hub, however, for the rotor will expand with speed and try to lift off the motor/generator. A specially designed interface would be needed to solve that problem, and the impact on the motor/generator design is uncertain. During this early technology stage there is an advantage to somewhat independent development of the motor/generator and the flywheel rotor/hub. Only after we know how to make workable hubs can we properly assess the question of possible integration of flywheel rotor and motor/generator.

A variety of arrangements of motor and flywheel rotor are possible. Some of these are shown in Figure 7.11-1. The integrated and non-integrated, or tandem, approaches are shown in (A) and (B), respectively. Instead of making one large rotor, several smaller rotor elements can be ganged together, as shown conceptually in (C). The rotor elements can be symmetrically located on both ends of the motor/generator, as shown in (D). Another possibility not shown would be to drive the rotor of the motor/generator in one direction with one flywheel rotor, and drive the stator in the other direction by a counter-rotating flywheel rotor. A rotary transformer would be needed to get power in and out of the motor, however.

To give some idea of equipment sizes involved with a flywheel energy storage system, Figure 7.11-2 has been prepared based on the intermediate objective flywheel technology described in Section 4.0. The system was sized at 5 kW for a 37 minute discharge, using a motor efficiency of 0.92. No energy capacity margin is included in this design; engineering margin must come from extra units.

7.12 EVALUATION OF ENERGY STORAGE METHODS

The information given previously in this section has been evaluated and a simplified comparison prepared between batteries, regenerative fuel cells, and flywheels. Results are shown in Table 7.12-1. Distinctions are made between energy storage characteristics that are very important, and those that are useful but only moderately important. Division into these two categories is a personal judgement, and it could be argued, for example, that the weight penalty for providing emergency power is not very important since this should be a separate power source.

It is seen from Table 7.12-1 that the flywheel system is best in most of the important categories. Its capability for emergency power is limited, and it has no ability to provide power during the launch phase. Forced shutdown of good counter-rotating units (no integration with the attitude control system) when a unit fails is an important disadvantage of flywheel systems, amplifying the effects of failure and limiting the power distribution system options. Nevertheless, the strong points of the flywheel system are so important, such as life, weight and efficiency, that the flywheel energy storage system should command more attention for spacecraft energy storage systems.

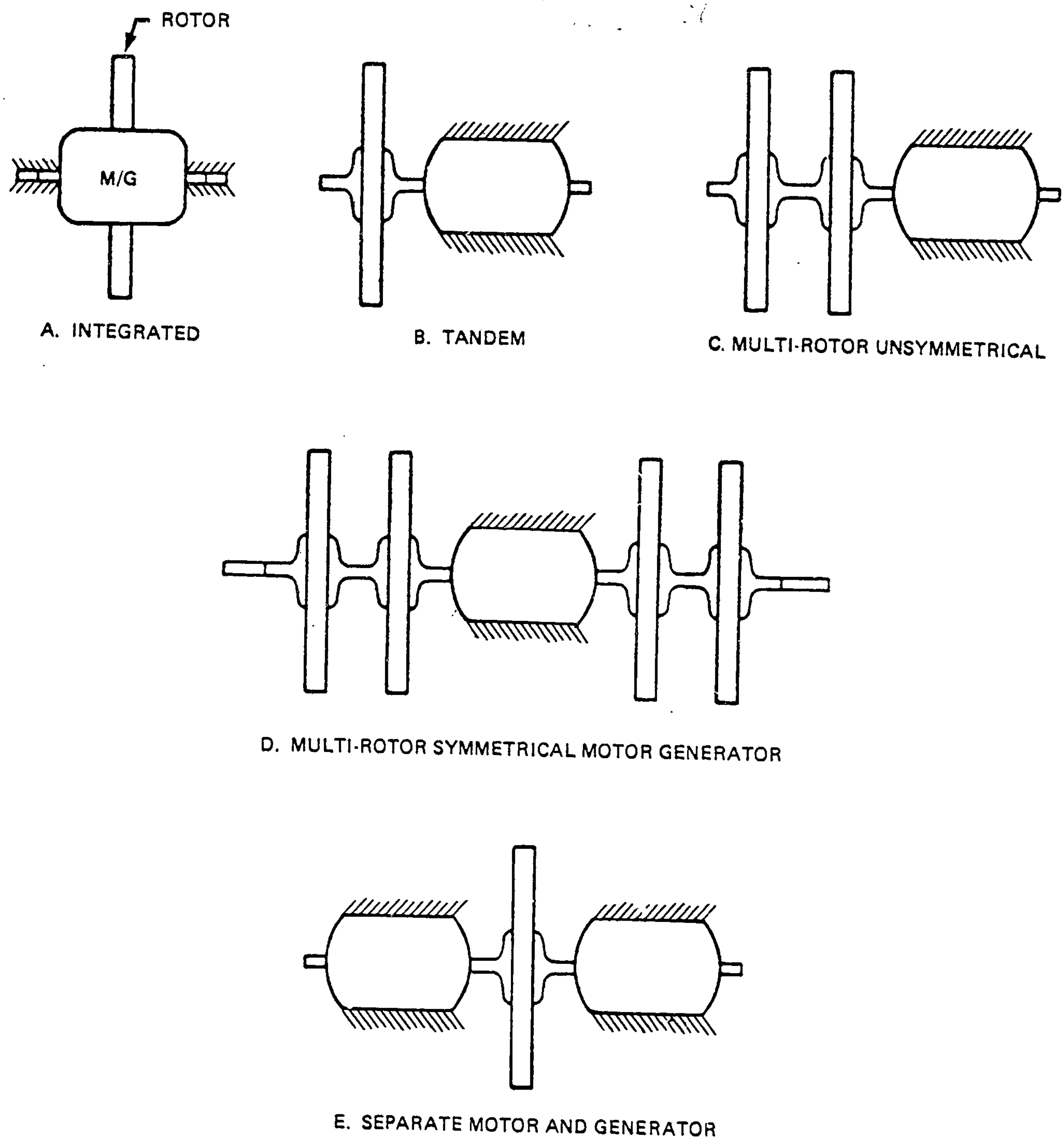

Figure 7.11-1. Motor/Generator — Rotor Design Approaches

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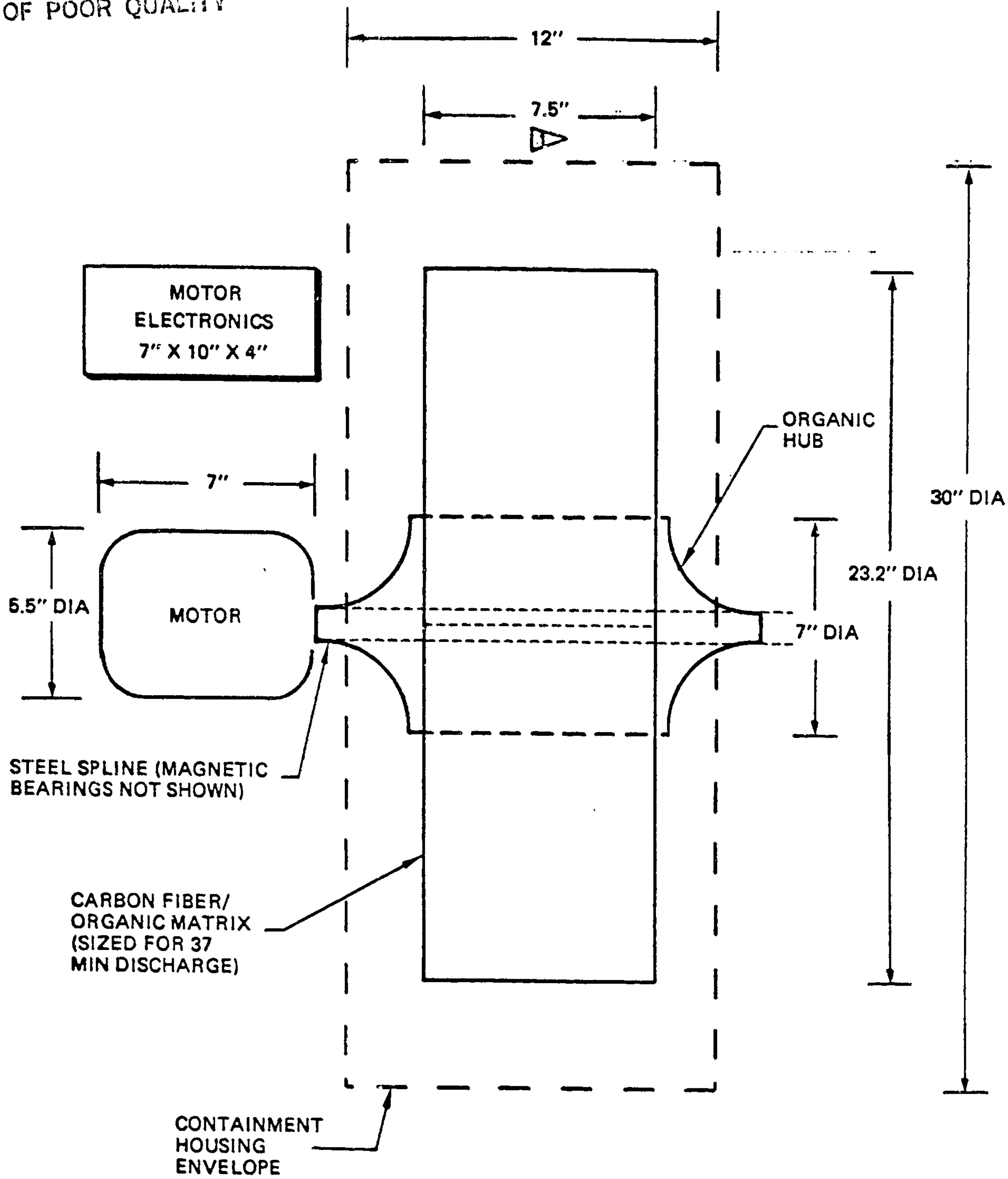

1 FOR ADVANCED DESIGN, THE ROTOR THICKNESS IS REDUCED TO 5.1 INCHES

Figure 7.11-2. Typical Component Dimensions Required for Intermediate Design 5 KW Flywheel Energy Storage Module

Table 7.12-1. Evaluation of Energy Storage Methods

	CHARACTERISTICS	Ni-Cd	$Ni\text{-}H_2$	$H_2\text{-}O_2$ REGEN FUEL CELLS	FLYWHEEL
VERY IMPORTANT ITEMS	WEIGHT, ORBITAL LOAD				BEST
	WEIGHT, EMERGENCY LOAD			BEST	BEST
	LIFE				BEST
	HIGH VOLTAGE CAPABILITY				BEST
	PARALLEL DISCHARGE CAPABILITY				BEST
	EFFICIENCY				BEST
	DISTRIBUTION CONSIDERING FAILURES	BEST	BEST		
MODERATELY IMPORTANT ITEMS	SHELF LIFE				BEST
	PEAK POWER	BEST	BEST		
	MULTIPLE DISCHARGES PER ORBIT				BEST
	PRELAUNCH TESTING	BEST	BEST		
	THERMAL REQUIREMENTS				BEST
	STATE-OF-CHARGE				BEST
	UTILIZATION OF EXCESS SUNRISE PWR				BEST
	POWER DURING LAUNCH PHASE	BEST	BEST		

8.0 INTEGRATION OF ENERGY STORAGE AND MOMENTUM MANAGEMENT SYSTEMS

8.1 BASIC CONCEPTS

An integrated power and attitude control system is based on the principle of using momentum wheels as a means of energy storage. The concept involves using the attitude control system's stored momentum as a source of energy during occult periods, or alternatively, using the momentum exchange of energy storage wheels to aid in attitude control. The main benefit sought would be a possible weight savings of an integrated system over an independent system. Reliability, cost and implementation are factors which must also be considered.

Whether the energy storage and momentum control systems are integrated or not, there will be a momentum change associated with the periodic change in speed of the wheel required for energy storage. For non-integrated energy storage, counter-rotating wheels must be used for in order to not impact the momentum management; the derived requirements are (a) all flywheel units must be in pairs; (b) the axes of the wheels in any pair must be parallel; (c) the wheels of each pair must spin in opposite directions (counter-rotating); and (d) the wheels of any pair must be controlled to the same rotational speed throughout the full speed range. These restrictions are necessary to prevent charge-discharge (retaining battery terminology) of the energy storage system from perturbing the attitude control.

Non-gimbaled reaction wheels sized for the momentum needs are not capable of providing the required torque magnitudes for attitude control. Therefore, only gimbaled reaction wheels were considered. Such a system is similar to a control moment gyro (CMG) except that a CMG customarily uses constant speed wheels. Two options are thus available: a single gimbaled wheel or a double gimbaled wheel. The single gimbal system has greater amplification, giving more control torque output per unit of torque input. The single gimbal system is also simple and often more reliable. The double gimbal system obtains no torque amplification, but gives additional redundancy; its control is complicated, however. Since the motor/generator must also be gimbaled with the wheel, there is a need for either slip rings, roll rings, or a flexible cable, plus possibly the need for a flexible heat pipe for cooling. These interfaces would therefore be more complex for the double gimbaled system than for the single gimbaled system. Thus, in consideration of all these factors, it is postulated that the single gimbaled system would be the most appropriate for integration of an energy storage flywheel system with a momentum management system, should integration be worthwhile.

Space station configurations which were considered in the study were based on varying solar array sizes since they are the dominating effect on the structural dynamics of the system. The configuration analyzed was a 4-6 man station with cantilevered solar arrays shown in Figure 8.1-1. The analysis was done for 110 kW, 220 kW, and 420 kW beginning of life versions of the configuration. The dimensions and characteristics are shown in Table 8.1-1. For each configuration, the boom length from the central raft to the near edge of the solar array was 18.7 meters. An alternate configuration was also considered in which the solar array panels are arranged to reduce the cross products of inertia. This configuration is shown in Figure 8.1-2. Space station characteristics without solar arrays for all configurations is shown in Table 8.1-2. The orbit used was at an inclination of 28^{o} and an altitude of 525 km.

8.2 APPROACH

Momentum control analyses were conducted to determine the feasibility of an integrated system. First, an attempt was made to size momentum systems for the configurations. Mass properties were obtained for the configurations. Then the environmental torques (gravity gradient, aerodynamic, and solar pressure) were calculated to determine the required size of the momentum handling system.

The torques were first categorized as either secular or cyclic in each of the 3 inertial axes for earth-oriented and inertially-oriented vehicles. Cyclic torques are those which average to zero over an orbit while secular torques are those which result in a net buildup of momentum over an orbit. Secular components of torque are not good candidates for CMG control, and must be controlled by some other means. Magnetic torquing rods are a possibility for this. A simplistic analysis of this possibility is described in the paragraph on magnetic torquing rods.

Environmental torques were calculated for an earth-oriented vehicle with the solar arrays "straight-out" and "hinged". The straight-out orientation refers to the case when the hinge angle is zero. The "hinged case" is for the solar arrays at their maximum hinge angle of 53 degrees. The solar pressure torques are negligible compared to the gravity gradient and aerodynamic torques, and are not categorized.

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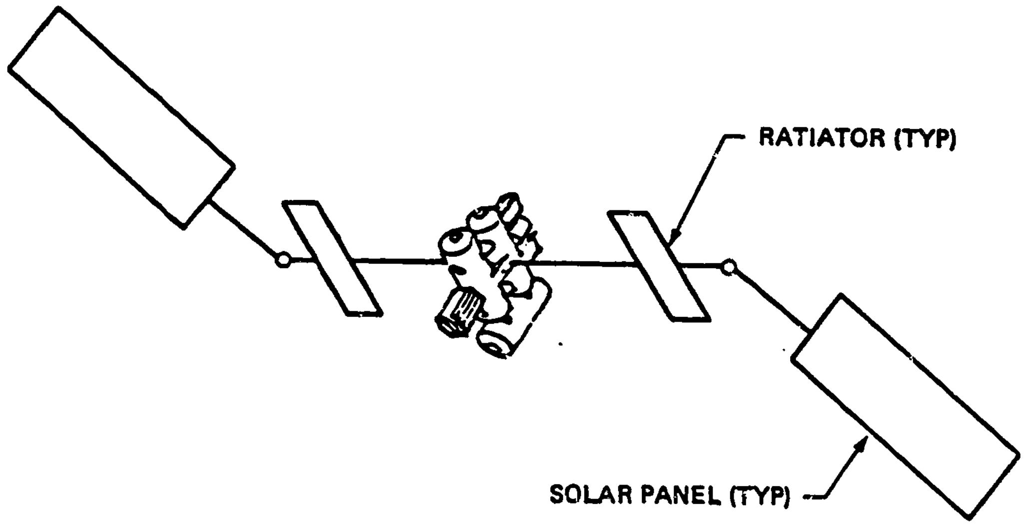

Figure 8.1-1. Typical Space Station Configuration with Cantilevered Solar Arrays

Table 8.1-1. *Solar Array Characteristics*

	NOMINAL 110 KW SOLAR ARRAY	NOMINAL 220 KW SOLAR ARRAY	NOMINAL 420 KW SOLAR ARRAY
NUMBER OF PADDLES	2	2	2
SIZE OF ONE PADDLE	18 m X 29.04 m	18 m X 55.56 m	36 M X 55.56 m
TOTAL SOLAR ARRAY AREA	1,046 m^2	2,000 m^2	4,000 m^2
SOLAR ARRAY DENSITY	1.5 KG/m^2	1.5 KG/m^2	1.5 KG/m^2
SOLAR ARRAY MASS	2,631 KG	4,947 KG	9,994 KG
BEGINNING OF LIFE POWER	110 KW	220 KW	420 KW
END OF LIFE POWER	88 KW	176 KW	336 KW

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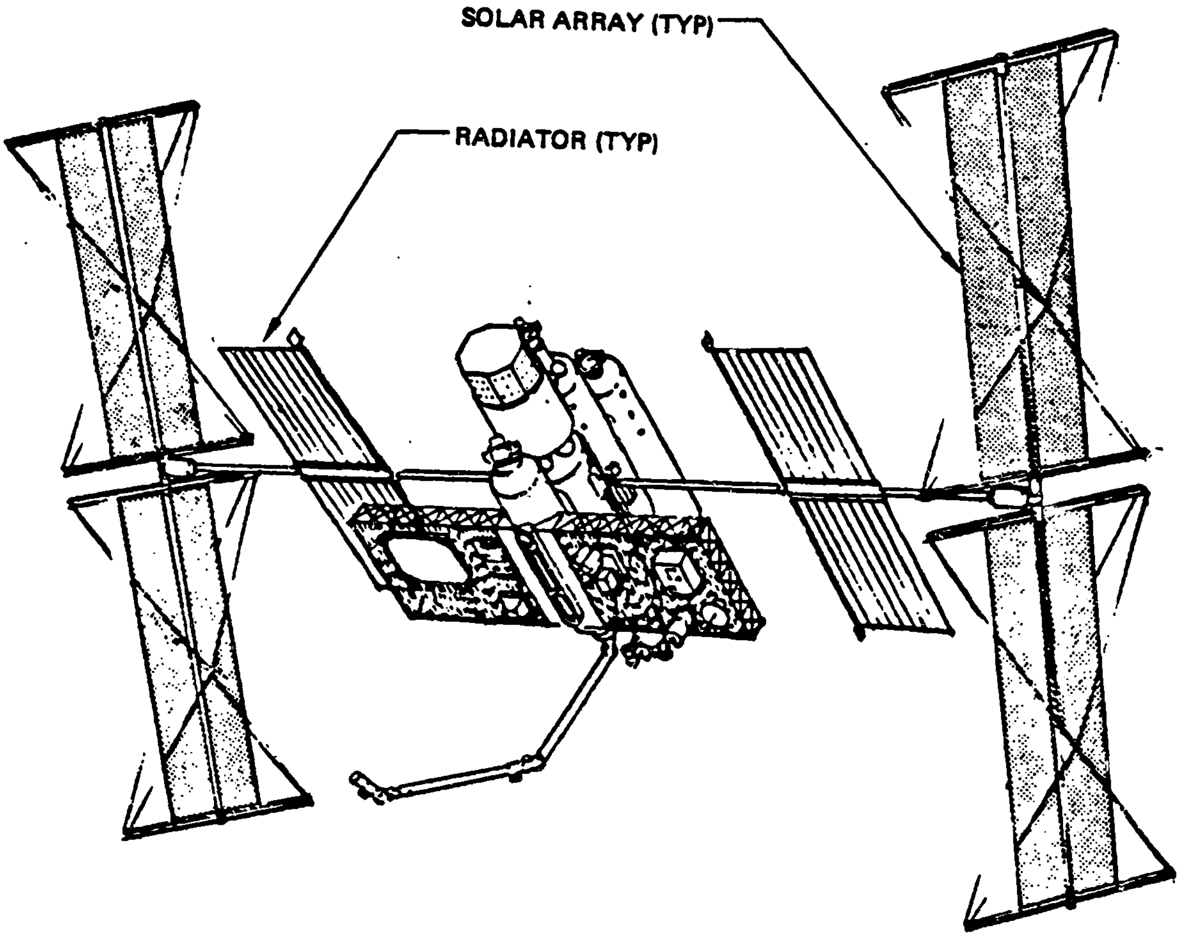

Figure 8.1-2. Space Station With Balanced Solar Array

Table 8.1-2. Space Station Characteristics Without Solar Arrays

INCLUDES 5 MODULES:
COMMAND CONTROL
LOGISTICS
CREW QUARTERS
LABORATORY
CREW QURATERS EXTENSION
OTHER UNITS INCLUDED:
LARGE PROPELLENT TANK
EXPERIMENTAL FRAME
TOTAL MASS = 115,100 KG
MASS MOMENTS OF INERTIA
I_{xx} = 2.88 E6 $Kg \cdot m^2$
I_{xy} = 2.89 E5
I_{yy} = 3.79 E6
I_{xz} = 7.48 E5
I_{yz} = 4.04 E5
I_{zz} = 2.55 E6

The distinction between which torques are cyclic and which are secular is given in Table 8.2-1.

The maximum gravity gradient and aerodynamic torques calculated and the resulting momentum storage required are summarized in Table 8.2-2. The momentum shown for the secular torques are those which will build up over one orbit period, approximately 92 minutes.

Since the secular torque components are impractically large for the cantilevered solar array design, an alternate design (Figure 8.1-2) was considered which reduces the gravity gradient contribution. The gravity gradient contributes a significant portion to the secular torques, so the secular torques are reduced considerably.

For the alternate configuration, the y-axis torque is secular due to the cross products of inertia in the raft portion of the spacecraft. The gravity gradient torques in this configuration are zero in the X and Z inertial axes since no cross-products of inertia are present. The aerodynamic and solar pressure torques are negligible for this analysis. The Y axis torque is a reasonable value for control consideration.

8.3 ANALYSIS USING STATE-OF-THE-ART TECHNOLOGY

One analysis conducted was the determination of the design and performance using equipment based on currently available hardware. For this purpose, a Sperry CMG model M4500 was taken as the basis for the attitude control system configuration. The M4500 stores 4500 ft-lb-sec of momentum at a rotor angular rate of 6000 RPM, and weighs 650 lb/unit.

The amount of energy stored in the system is:

$$E = \tfrac{1}{2} H \omega \qquad \text{EQN (8)}$$

$$E = 558 \text{ W-hrs.}$$

If the wheel is spun down to half of its maximum speed, 75% of the total energy is available for use. This means that 418 W hr/wheel is available for a 50% change in wheel speed.

Table 8.2-1. Torque Characteristics in Inertial Axes.

TORQUE & ORIENTATION	X	Y	Z
EARTH ORIENTED			
GRAVITY GRADIENT	CYCLIC[1]	SECULAR	CYCLIC[1]
AERODYNAMIC	CYCLIC[1]	SECULAR	CYCLIC[1]
SOLAR RADIATION	SECULAR	CYCLIC[2]	SECULAR
INERTIALLY ORIENTED			
GRAVITY GRADIENT	SECULAR	CYCLIC[1]	SECULAR
AERODYNAMIC	SECULAR	CYCLIC[1]	SECULAR
SOLAR RADIATION	CYCLIC[1,2]	SECULAR	CYCLIC[1,2]

1 – CYCLIC TORQUES ARE TRULY CYCLIC ONLY IN CIRCULAR ORBITS. IN ECCENTRIC ORBITS TORQUES WILL HAVE BOTH CYCLIC & SECULAR COMPONENTS.

2 – PARTIALLY SECULAR DURING ECLIPSE

Table 8.2-2 . Momentum and Torque Requirements for Attitude Control System

S/A TYPE, NOMINAL KILOWATTS	SECULAR					CYCLIC + POINTING (100 ARC-SEC)				
	TORQUE (Nm)			NUMBER OF TORQUE RODS	POWER (W) • •	MOMENTUM (NmS)			REQUIRED NUMBER OF SKYLAB CMG'S (3,000 NmS/CMG)	REQUIRED NUMBER OF SPERRY CMG'S (6,100 NmS/CMG)
	T_x	T_y	T_z			H_x	H_y	H_z		
CANTILEVERED, EARTH-ORIENTED										
110 KW	2.6	• • •	.0012	26	416	5,000	6,100	5,000	5.4	2.6
210 KW	7.5	• • •	.0016	75	1,200	4,000	7,200	4,000	5.1	2.5
420 KW	23.3	• • •	.0024	233	3,728	3,000	13,000	3,000	6.3	3.1
CANTILEVERED, INERTIAL-ORIENTED										
110 KW						14,200	9,000	11,500	11.6	5.7
210 KW						41,000	7,500	42,000	30.2	14.8
420 KW						84,000	7,700	88,000	59.9	29.5
BALANCED (BANTELL/ GRIFFIN), EARTH-ORIENTED										
110 KW	• • •	• • •	1.42	14	224	1,800	1,800	1,800	1.8	0.9
210 KW	• • •	• • •	2.57	26	416	5,000	5,000	5,000	5.0	2.5
420 KW	• • •	• • •	3.03	30	480	9,900	9,900	9,900	9.9	4.9

ASSUMPTIONS:

MAXIMUM TORQUE = 0.1 Nm
ITHACO TORQUE RODS, 96 LB EACH
NOMINAL DIPOLE MOMENT = 1,200 Am^2
CONSTANT EARTH MAGNETIC FIELD
525 Km; 0^{o} LAT

• • 18 W/ROD (ITHACO TORQUE ROD)

• • c NEGLIGIBLE VALUES OF TORQUE

Shown in Figure 8.3-1 is the rotor speed vs. the number of M4500 type CMG's to store 20 kW-hr, 50 kW-hr, and 100 kW-hr of useable energy (75% of total energy). A stored energy requirement of 20 kW-hr is used as the basis for this comparison. From this it can be seen that about 45 CMG's are necessary for a 20 kW-hr requirement if the nominal speed is 6000 RPM, for a total weight of 29,250 lb, without motor/generators, which at 30 lb each would add 1350 lb. Sperry is experimenting with spinning the wheel at 10,000 RPM. At this spin rate, the number of CMG's required for 20 kW-hr of energy is about 18, (11,700 lb. plus 1350 lb. for motor/generators). Less than six of these (3900 lb) would be necessary to provide 100 arc-sec of pointing accuracy for the 420 kW system, whereas three units (1950 lb) would be required to provide the same pointing accuracy for the 110 and 210 kW systems.

This can be compared to two energy storage wheel systems sized independently of the ACS. As an example, a Rockwell steel wheel contains 5.0 kW-hr of useable energy and weighs 1242 lbs. Four of these are necessary to store 20 kW-hrs for an energy storage system, for a total unit weight of 2692 lbs, and a total system weight of 10,768 lbs. (Table 8.3-1). A second Rockwell wheel made of composite material also contains 5.0 kW-hr of useable energy and weighs 340 lb. Four of these are necessary to store 20 kW-hrs for an energy storage system for a total unit weight of 498 lbs. (Table 8.3-1), and a total system weight of 1952 lbs.

This analysis illustrates several facets of the question of integration of momentum management and energy storage. It is seen that the need for energy storage dominates; when momentum control and energy storage are integrated by using common CMG momentum control equipment, then the total weight is much greater than using separate, dedicated equipment. Weight comparisons are given parametrically in Section 8.7.

8.4 INTERNAL DISTURBANCE TORQUES

The torque requirements to maintain pointing with the presence of spacecraft internal disturbance has been analyzed. The system was modeled as a second order system with an impulsive disturbance applied. A block diagram is shown in Figure 8.4-1. The damping ratio is assumed to be 0.7. The inertia used is the inertia of the configuration being considered. System momentum values used are those for which the momentum systems have been sized to handle the external disturbance torques.

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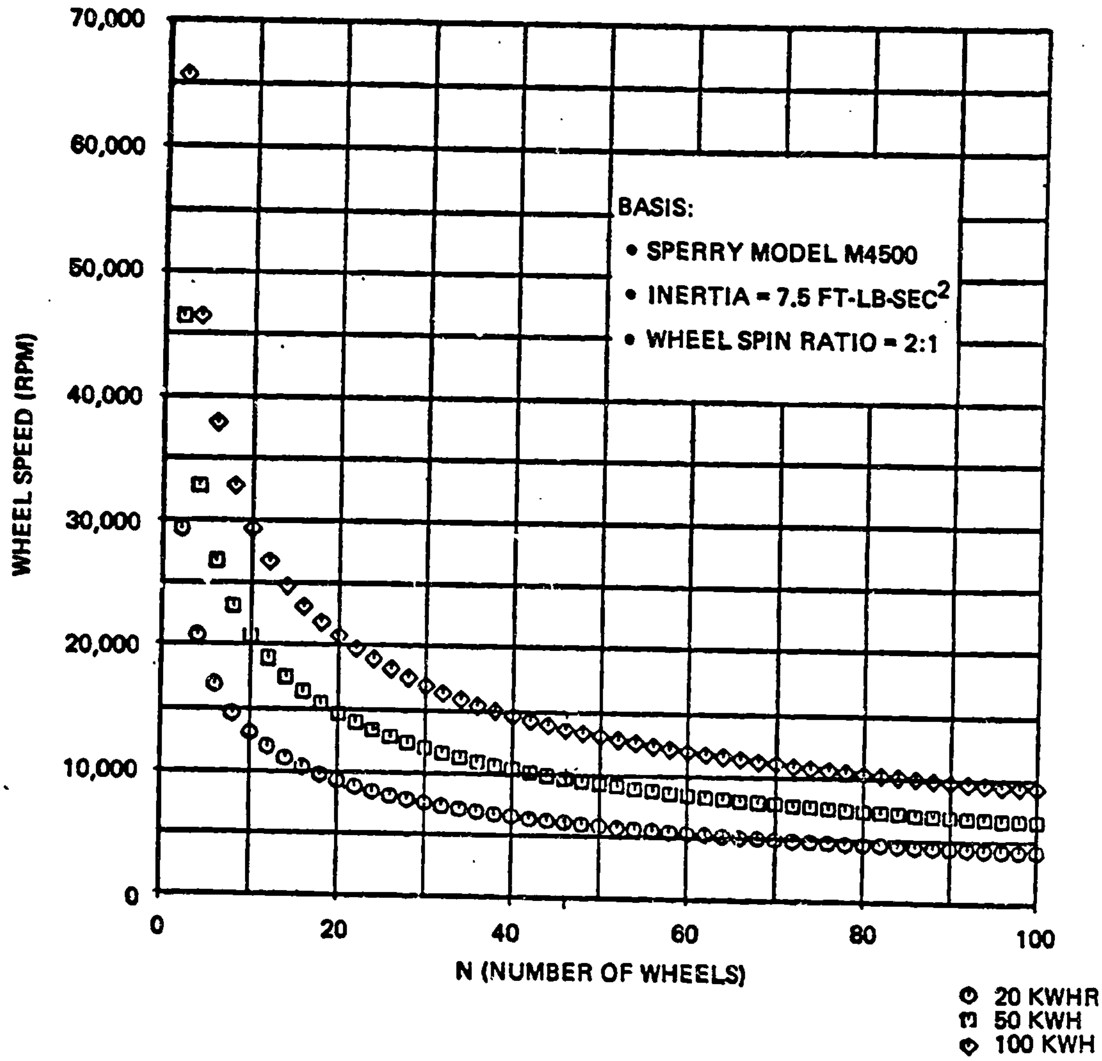


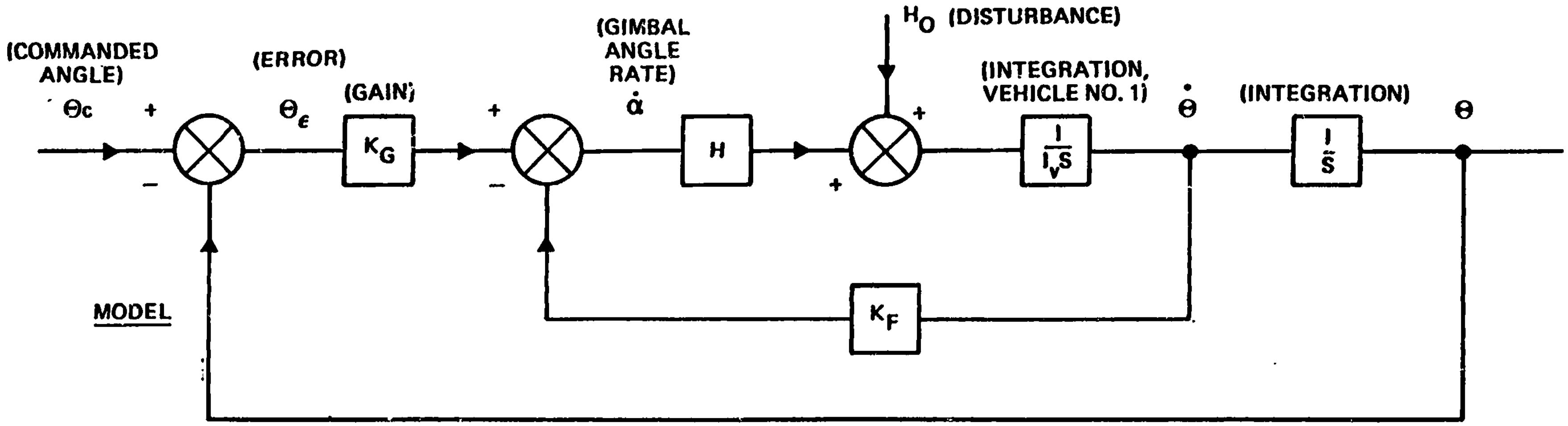
Figure 8.3-1. CMG Requirements to Provide 20 KW-HR of Energy

Table 8.3-1. State-of-the-Art Energy Storage System Based on Rockwell Technology

	METAL WHEEL	COMPOSITE WHEEL
DESCRIPTION		
MATERIAL	STEEL	GRAPHITE FIBERS PLUS MATRIX
WHEEL DESIGN	MODIFIED CONSTANT STRESS	HOLLOW TWIN-DISC
DIAMETER	47 INCHES	31 INCHES
RPM	8,500 RPM	18,000 RPM
ENERGY		
STORED ENERGY	6.7 KW-HR	6.7 KW-HR
USEABLE ENERGY (2 TO 1 SPEED RATIO)	5.0 KW-HR	5.0 KW-HR
WEIGHT		
WHEEL WEIGHT	1,242 LB	340 LB
HOUSING 1	110 LB 1	60 LB 1
BEARINGS	80 LB	24 LB
CONTAINMENT 1	1,200 LB 1	34 LB 1
MOTOR/GENERATOR	30 LB	30 LB
TOTAL UNIT MAX WEIGHT	2,692 LB 2	488 LB 2
TOTAL UNIT MIN WEIGHT	1,352 LB	394 LB

1 THESE ITEMS EXCLUDED IN MINIMUM WEIGHT SYSTEM

2 THIS WEIGHT IS CONSIDERED MOST APPROPRIATE FOR THE WHEEL TYPE



PERFORMANCE

$$\Theta^{*}_{\epsilon} = \frac{0.46\,H_o}{I_v W_o} \rightarrow$$

$$\dot{\alpha}_{MAX} = \frac{1.4\,H_o W_o}{H}$$

MAX POSITION ERROR

OVERSHOOT $\zeta = \frac{\sqrt{2}}{2}$

Figure 8.4-1. Block Diagram of Attitude Control Effectiveness for Impulsive Disturbances

Nastran analyses were done to determine a range of structural frequencies for each of the configurations as a function of varying boom length and astromast diameter. The magnitude of the disturbance impulse is approximated as those of Skylab. For the analysis, the impulse from medical experiments was approximated at 1000 Nms; a 400 Nms impulse was also considered. For each impulse, the maximum angular error and maximum gimbal angle rate were calculated for a range of control frequencies corresponding to the structural range of frequencies. This was done for each of the three cantilevered solar array configurations. These analyses determined the ability to meet angular error limits without exceeding a maximum gimbal angle rate for a range of structural frequencies. Results are discussed in Section 8.5.

8.5 POINTING ACCURACY CONSIDERATIONS

CMG's have limited capability for gimbal angle rate. The limiting value used for the study was the gimbal angle rate limit used for the Skylab CMG's of 4^{o}/sec. Analysis shows that this is adequate to achieve a high pointing accuracy. For example, a pointing accuracy of 60 arcsec can be achieved in the 110 kW system given an 1000 Nms impulsive disturbance. For the 420 kW system, pointing accuracies of 40 arcsec can be obtained.

For the earth-oriented spacecraft in which the environmental torques are primarily secular, the torques needed to maintain pointing in the presence of the internal disturbance torques will determine the size of the ACS. Consequently, sizing of the CMG's systems was done for the three configurations based on the pointing accuracies required.

Using the modeling equations, a pointing accuracy was chosen, and for the given configuration and disturbance, a control frequency was calculated. The equations were also used to determine the system momentum. For 100 arc-sec of pointing accuracy, the 110 kW system requires 3000 Nms of momentum per axis. 4000 Nms is required for the 210 kW system, and 5000 Nms per axis for the 420 kW system.

8.6 TORQUE RODS

Basic calculations were done to determine if it is reasonable to consider torquing rods to handle the large secular torques expected in space station configurations.

Ithaco Co. torque rods were considered in this analysis since specifications were readily available for their magnetic torquing rods. Their largest torque rod with a dipole moment of 4 m p-cm was the one considered here.

The magnitude of the earth's magnetic field was calculated as 0.2460 Gauss at the equator for an altitude of 525 km using equation 4.41 from Reference 8.7-1where the earth's magnetic intensity, J, is

$$J = M_e/p^3 \left[\hat{i}\ 3 \sin\beta \cos\beta + \hat{K}\left(3 \sin^2\beta - 1\right)\right] \qquad \text{EQN (9)}$$

where

ρ = density at altitude
β = magnetic latitude angle
M_e = -1.273×10^{10} Oersted/(nautical miles)^3
$\hat{i}$ = unit vector in x direction
$\hat{K}$ = unit vector in z direction

This compares favorably to the value obtained from Figure 5-4 (a) of Reference 8.7-1 which shows the earth's magnetic field at 500 km attitude.

The torque available from the torque rods is 1 Nm. This was calculated using equations 5.75 from Reference 8.7-2 where:

$$\vec{T} = (\vec{m})(\vec{B}) \quad (7.376 \times 10^{-8}) \qquad \text{EQN (10)}$$

where $\vec{T}$ = torque vector (N m)
$\vec{m}$ = magnetic dipole (pole-cm)
$\vec{B} = \mu \vec{J}$ with $\mu = 1$

This analysis showed that the 0.5 Nm secular torque could be controlled under ideal conditions using 14 of these torque rods for the 110 kW solar array case. This is a reasonable number, and is therefore considered feasible. Further analysis needs to include practical considerations such as magnetic field direction and magnetic field variations.

8.7 EFFECTS OF INTEGRATION WITH CMG'S ON WEIGHT

A parametric study was done to determine the relative weight of integrated and independent systems for different momentum requirements for attitude control systems (ACS) and the momentum associated with the energy storage system (ESS). The analysis was done based for a range of estimated weight ratios for an ACS, ESS and an integrated (INT) system.

Assumptions made for the analysis are:

1) The ACS is sized for pointing requirements to handle internal disturbance torques.

2) The unit used for the integrated approach is the same design for attitude control and energy storage functions.

3) The rotor required for energy storage can be spun down to half of its maximum speed.

An important parameter in this analysis is the relative weights of an energy storage unit, an attitude control unit, and an integrated unit, all of which have the same momentum. The major items affected to make an attitude control unit perform energy storage functions also (becoming an integrated unit) are (1) add a motor/generator and controls; (2) add a flexible power cable; (3) use a heavier gimbal; and (4) delete the wheel spinning motor. Based on these considerations, it is estimated that an integrated unit will be 25% heavier than an attitude control unit with the same rotor momentum. This factor (ratio of 2:2.5 for ACS: INT) was therefore used as the baseline for the analysis.

Major items required for an attitude control unit but not needed for an energy storage unit are (1) gimbal; and (2) gimbal control electronics. The major item required by the energy storage unit but not needed for an attitude control unit is the motor/generator and controls. The gimbal and gimbal control electronics are heavy components of an ACS, and constitute about 40% to 70% of the weight of CMG systems. Based on these considerations, it is estimated that an attitude control unit will be approximately twice the weight of an energy storage unit with the same rotor momentum. This factor (ratio of 2:1 for ACS:ESS) was therefore used as the baseline for the analysis.

In order to determine the sensitivity of integration weight savings or penalties to the assumptions made on the relative weight of ACS, ESS, and INT units, analyses were conducted using other ratios in addition to the baseline. The following ratios of ACS:ESS:INT were analyzed:

A) 2:1:2.5 (Baseline)

B) 2:1:2

C) 1:1:1

The relative weights of integrated and non-integrated systems are determined as follows. If the momentum requirements of the ACS are less than half the momentum requirements for the ESS, then the integrated system is sized based on the ESS requirements. Otherwise, the integrated system is sized such that the momentum of the integrated system is equal to the momentum requirements of the ACS plus half of the momentum requirement for the ESS. This is necessary to provide the required momentum for the ACS when the rotors are spun to half of their maximum speed.

The momentum required by the ACS is determined by analysis and is independent of the design wheel speed. The energy storage of a flywheel can be expressed as momentum provided the rotational speed is known, for the momentum is proportional to the energy and inversely proportional to the rotational speed, thus

$$H = 2E/\omega \qquad \text{EQN (11)}$$

Therefore, there is some uncertainty in determining the momentum associated with the ESS requirement. As it turns out, this uncertainty is not of great importance in this trade study.

For weight ratios other than the baseline, it is seen from Figure 8.7-1 that the weight ratio of integrated to independent systems does not fall below one except for some conditions of the case where the ACS:ESS:INT ratio is 1:1:1. This particular ratio is purely hypothetical and not practical, but even for this case integration would offer no weight advantage because the expected momentum ratio for the space station is so low. Thus, it is concluded that integration of spacecraft momentum control and energy storage functions in a flywheel system offers no weight advantage. A typical set of calculations of the data in Figure 8.7-1 is given in Table 8.7-1.

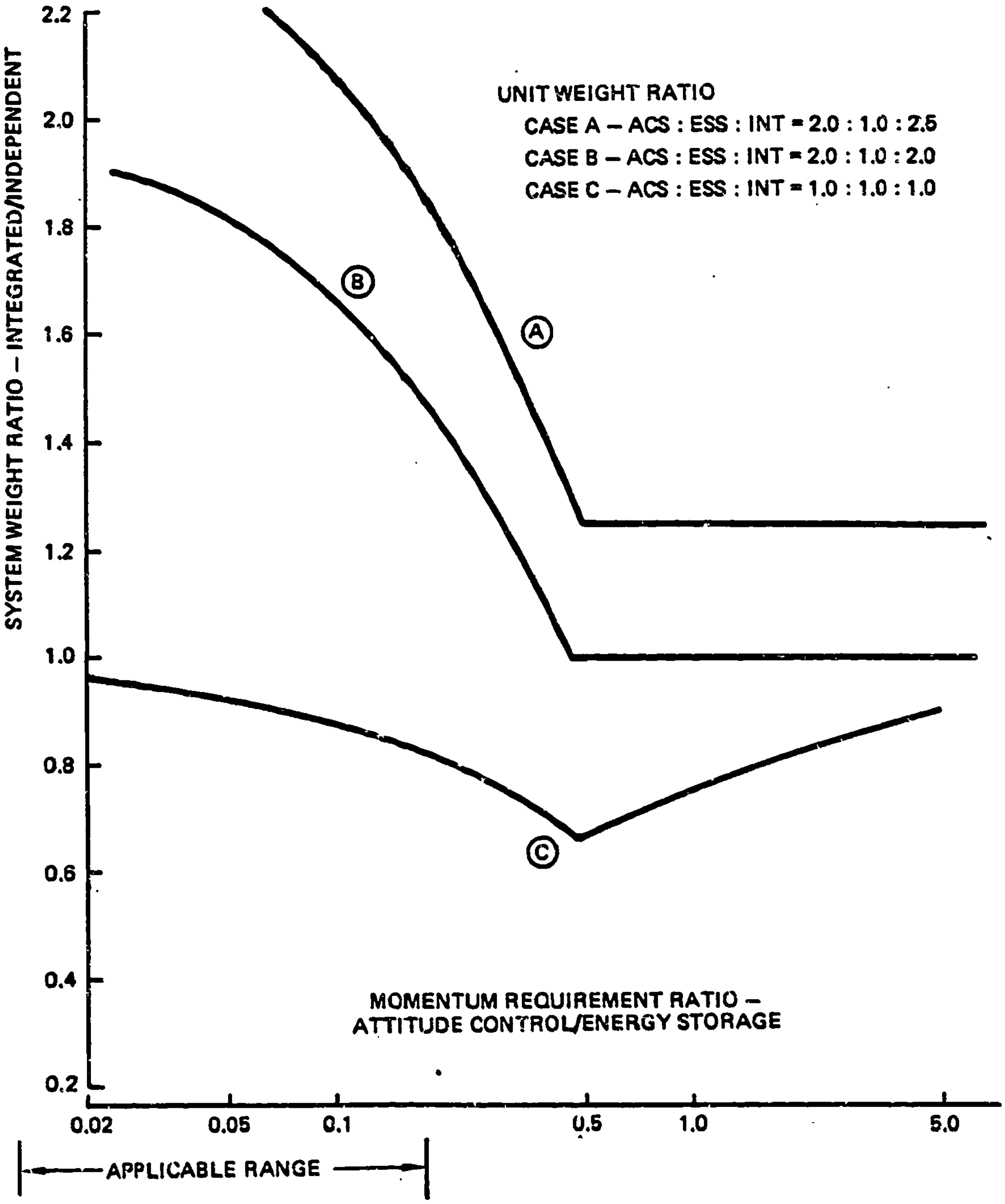


Figure 8.7-1. Parametric Weight Ratios of Integrated and Non-Integrated Systems

Table 8.7-1: Typical Calculations of Parametric Weight Ratios for Integrated and Non-Integrated CMG and Energy Systems

BASIS: ACS: ESS:INT = 2:1:2.5

MOMENTUM RATIO— H_{ACS}/H_{ESS}	$H_{ACS}:H_{ESS}$	ACS WT.	ESS WT.	INDEPENDENT WT.	INTEGRATED WT.	WT RATIO, INT/IND
0.03	3:100	3(6)	100(100)	(106)	100(250)	2.36
0.1	1:10	1(2)	10(10)	(12)	10(25)	2.08
0.125	1:8	1(2)	8(8)	(10)	8(20)	2.0
0.17	1:6	1(2)	6(6)	(8)	6(15)	1.88
0.25	1:4	1(2)	4(4)	(6)	4(10)	1.67
0.33	1:3	1(2)	3(3)	(5)	3(7.5)	1.5
0.375	3:8	3(6)	8(8)	(14)	8(20)	1.43
0.5	1:2	1(2)	2(2)	(4)	2(5.0)	1.25
0.625	5:8	5(10)	8(8)	(18)	9(22.5)	1.25
0.67	2:3	2(4)	3(3)	(7)	3.5(8.75)	1.25
0.75	3:4	3(6)	4(4)	(10)	5(12.5)	1.25
0.857	6:7	6(12)	7(7)	(19)	9.5(23.75)	1.25
1.0	1:1	1(2)	1(1)	(3)	1.5(3.75)	1.25
1.5	3:2	3(6)	2(2)	(8)	4(10)	1.25
2.0	2:1	2(4)	1(1)	(5)	2.5(6.25)	1.25
3.0	3:1	3(6)	1(1)	(7)	3.5(8.75)	1.25
4.0	4:1	4(8)	1(1)	(9)	4.5(11.25)	1.25

From the momentum requirements determined for the Attitude Control System, Table 8.2-1, design momentum requirements were selected. These are shown in Table 8.2-1 as reflected in the number of CMG units of known capacity which would be needed; the design momentum values are also tabulated in Table 8.8-1. The energy storage requirements can be given in terms of momentum if the wheel speed is known, as shown in Figure 8.8-1. Assuming a wheel speed of 20,000 RPM and a 37 minute discharge, the energy storage momentum is given in Table 8.8-1; as it turns out, changing the assumption on wheel speed by a factor of two or three would have no effect on the conclusions. From this data, the ratio of attitude control system momentum to energy storage system momentum is calculated, also shown in Table 8.8-1. For all configurations and power levels, it is seen that the momentum ratio ranges from 0.0128 to 0.176. For comparison, the ratio associated with the NASA study on flywheels (Ref. 1.1-5) was 0.0022, based on a much smaller spacecraft.

The calculated momentum ratios are shown as a band in Figure 8.7-1. From this data, it can be seen that for systems having a weight ratio of 2:1:2.5 for ACS:ESS:INT, the weight ratio of an integrated system to an independent system is greater than unity for all ratios of momentum required for the ACS and the ESS. Thus, for the baseline, the integrated system is always heavier than the independent system. For an integrated system with weight ratios of 2:1:2, the weight ratio for the integrated to the independent system reaches unity, but does not fall below one; a partial integration for these weight ratios would therefore not impose a weight penalty.

If the ACS is sized for cyclic torques rather than internal disturbance torques, the weight ratio study becomes a litle more difficult. The duty cycle of the energy charge/discharge would need to be compared to the torquing duty cycle. A detailed simulation of the integrated system would need to be considered to perform this analysis. A preliminary analysis shows that the effective minimum momentum available to the ACS is about 56 percent of the maximum as compared to the 50 percent value required with this analysis.

8.8 ASSESSMENT OF INTEGRATION OF CMG'S VS. INDEPENDENT SYSTEMS

The major technical factors which would influence a decision to integrate or not to integrate CMG momentum control and energy storage flywheel systems are: (1) weight; (2) reliability; (3) improved performance; and (4) practicality of integration.

Table 8.8-1. *Momentum for Attitude Control System and Energy Storage System*

	DESIGN MOMENTUM FOR CONTROL SYSTEM (NmS)	EQUIVALENT MOMENTUM FOR ENERGY STORAGE. 20,000 RPM, 100% DOD (REF) (NmS)	EQUIVALENT MOMENTUM FOR ENERGY STORAGE, 75% DOD (DESIGN) (NmS)	MOMENTUM RATIO, ACS/ENERGY
CANTILEVERED, EARTH-ORIENTED				
110 KW	16,200	230,500	307,300	0.0527
220 KW	15,300	460,900	614,600	0.0249
420 KW	18,900	880,000	1,173,300	0.0161
CANTILEVERED, INERTIAL-ORIENTED				
110 KW	34,600	230,500	307,300	0.1132
220 KW	90,600	460,900	614,600	0.1474
420 KW	179,700	880,000	1,173,300	0.1532
BALANCED, EARTH-ORIENTED				
110 KW	5,400	230,500	307,300	0.0176
220 KW	15,000	460,900	614,600	0.0244
420 KW	29,700	880,000	1,173,300	0.0128

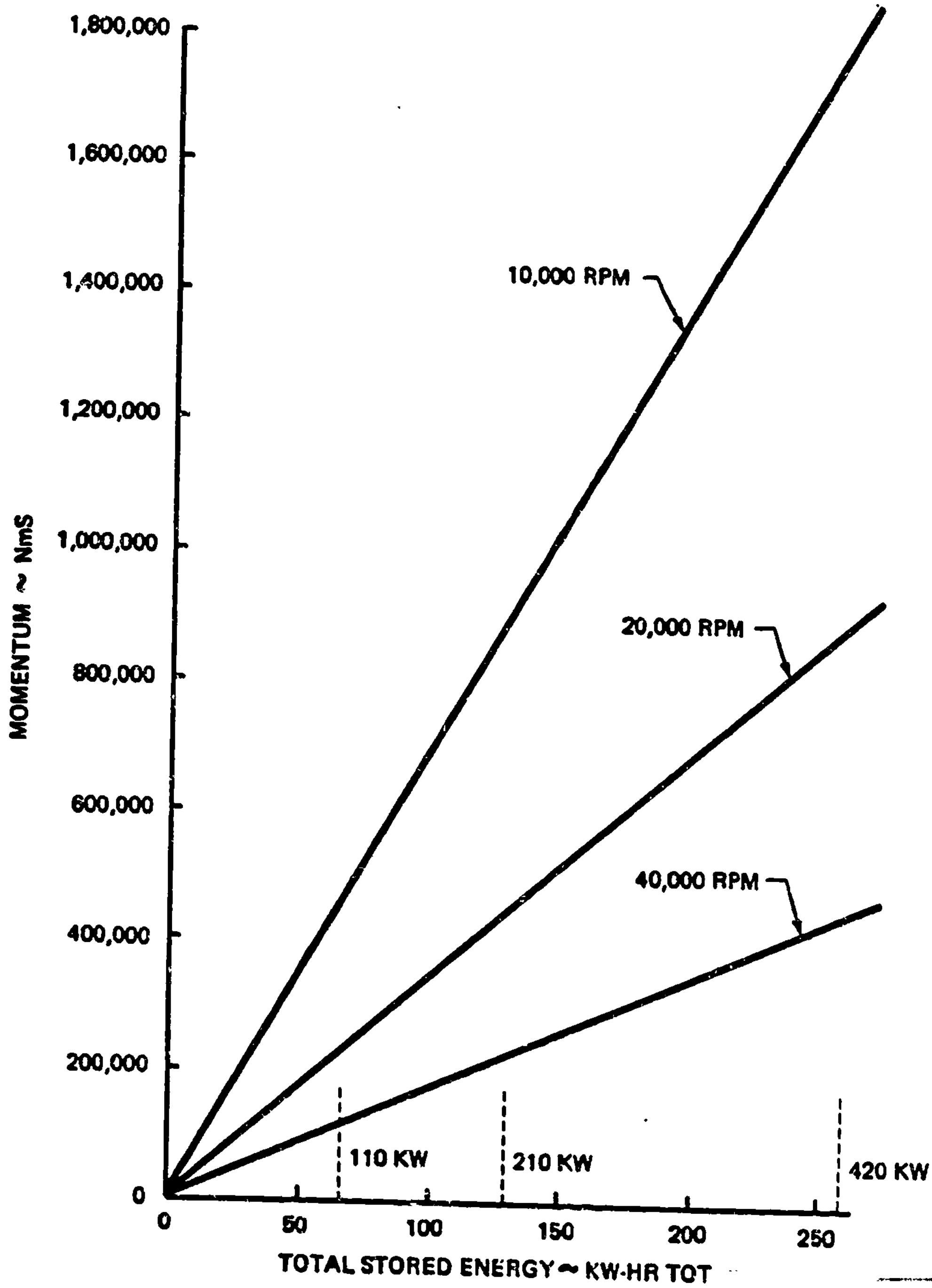


Figure 8.8-1. Momentum and Energy Relationship

Weight considerations clearly favor independent systems. As shown in Figure 8.7-1, the integrated system weight is about twice the independent system weight. This is the major factor in the conclusion that integration is not worthwhile.

Reliability is believed to be made worse by integration. Integration results in much improved redundancy for the attitude control system, essentually by putting gimbals on units used primarily for energy storage. Thus, reliability of the attitude control system will improve by integration. On the other hand, those units used for energy storage are more complex than necessary purely for energy storage needs, and as a result would suffer in reliability. For example, slip rings, roll rings, or flexible cable will be required for transfer of electrical power. It is judged that a reduction in reliability of the energy storage system cannot be offset by an increase in the reliability of the attitude control system. Based on this rationale, it is concluded that integration will result in reduced reliability.

One possible benefit from integration is improved performance of the attitude control system. Integration is a means to a greater amount of attitude control capability for relatively little additional weight. This could be useful for redundancy and also to assist with docking. An analysis of this aspect of integration would be worthwhile.

The practicability of integration is also an important consideration. Even if there were sufficient advantage to integrate on the basis of weight or ultimate reliability, there are some practical problems which appear as disadvantages to integration. To begin with, flywheel energy storage technology is in its infancy and much development remains before it can be in a position to be used in space. This development would logically emphasize the basic problems of flywheel energy storage, and integration should normally come after these problems are solved and the system has been used independently. Thus, integration is considered a possible further step that could be taken after the flywheel energy storage system is developed and proven out. Some of the issues related to the practicability of integration are: a) testing; b) spacecraft program schedule and flexibility; c) optimization; and d) modular growth.

An important problem caused by integration is the very large side loads imposed on the bearings during operation of the gimbal. This imposes difficult requirements on magnetic bearings, if these are used. It is possible that it may not be feasible to use magnetic bearings in such an application. Another practical problem with integration would be the need for a rotary joint to transfer power to and from the flywheel system. Also, integration could impact the design of the main power transfer rotary joint from the solar array to the main bus, for the possibility would be eliminated of putting the energy storage system outboard of that joint in order to reduce the amount of power transferred across it.

Although integration of the hardware for the two systems does not appear to be advantageous, there may be important advantages for close, interlinked operation of the two systems, or for partial integration. The normal operating mode is expected to be one in which the energy storage system causes no net momentum change in the spacecraft. However, the energy storage system can easily produce a cyclic momentum change by having an unequal depth of discharge on the energy storage units, which might be useful to the momentum management system for special needs or following partial failure of its equipment. Similarly, operating with a cyclic momentum change could be a useful option for the energy storage system following failure of one of its units, provided this operating mode is tolerable to the momentum management system.

8.9 INTEGRATION WITH SKEWED REACTION WHEELS

Reaction wheels initially were not considered in this study for attitude control because it was concluded that they would not have the capability to provide the high torque needed. Therefore, the CMG system was emphasized for possible integration with energy storage because the CMG system can provide high torque. After the attitude control requirements were determined, it became evident that the momentum associated with energy storage was much greater than the momentum needed for attitude control. This suggests the possibility that flywheels could operate as reaction wheels, mounted skewed so their axes are not parallel, for example, in tetrahedron groups. If, for example, the power system consisted of a single bus with a dozen wheels, then conceivably all twelve wheels could be worked together to give very large torque. Theoretically, providing three axes of attitude control plus the energy storage function requires four degrees of freedom, which can be accomplished with only four wheels; thus, theoretically the use of more wheels than this allows continued operation in the event of failure of some of the wheels.

The possible benefits of skewed reaction wheels would appear not to lie in weight saving, but possibly in development cost, improved performance, or reliability. Since the attitude control momentum required is on the order of two percent of the energy storage momentum, then even if the attitude control were obtained free the potential weight saving is only on the order of four percent. In fact, there are some weight sacrifices required with integration which might wipe out the potential weight saving. This weight sacrifice comes from the fact that all the wheels cannot be depended upon to be at their full speed at the start of an eclipse, due to the need to simultaneously increase the speed of some wheels and decrease the speed of others in order to manage angular momentum. Likewise, during energy extraction, all the wheels cannot be reduced to their minimum design speed. Transfer of momentum from one wheel to another requires that the generator of one wheel drive the motor of another wheel; this results in a power loss. One possible benefit from integration is improved performance, especially the possibility that important assistance could be provided with docking, thus minimizing propellant use. Finally, the control law required for this type of operation would be very complicated both with respect to attitude control and energy management. This makes computer control a necessity; nevertheless, control complexity would be acceptable if the use of skewed reaction wheels can be shown to have redeeming virtues.

No quantitative analysis has been made of the skewed reaction wheel approach, and it is recommended that such an analysis be made.

8.10 NON-INTEGRATED DESIGN INTERACTIONS

For the condition where a flywheel energy storage system is not integrated with the momentum control system, it will be necessary to design and operate the flywheel system to minimize interference with the momentum control system, or at least to keep its effects within tolerable limits. Even though counter-rotating wheels are used, some unbalanced momentum will result which the momentum control system must counteract. Some of the causes are: (1) all wheels will not be identical with respect to mass and momentum. Multiple wheels with paralleled electrical output will likely be controlled to equal speed rather than equal momentum; (2) counter-rotating wheels must have their rotational axes parallel, collinear location being unnecessary. The axes will not be perfectly parallel, hence there will be a parasitic momentum developed equal to the sine of the misalignment angle times the momentum of the two wheels; (3) wheels may be temporarily reduced in speed or shut down; conservation of angular momentum requires either that the opposing, counter-rotating unit also be slowed or shut down, or that the angular momentum be transferred to the vehicle.

A principal concern is to design for the least problems if one or more flywheel units should fail. To best meet this condition, it is recommended that all flywheels be located in the spacecraft with their spin axes perpendicular to the orbit plane. This will result in the least impact to the momentum control system with one wheel out, either temporarily or permanently. A momentum change will develop along the wheel spin axes which will try to make the spacecraft turn about that spin axes. This will be easier to counteract than if the wheels were in a different orientation, as for example with the spin axis in the orbit plane; for that case there would not only be a torque developed to try to make the spacecraft turn about the spin axis, but also a gyroscopic cross-coupling torque which acts perpendicular to the wheel spin axis.

In addition to parallel axes operation to help survive one failed unit without losing the opposing unit also, there are some other approaches which can be considered. Since the momentum change developed from an unopposed wheel will by cyclic, rather than secular, it may be possible that this can be used to partially balance out other cyclic momentum loads on the spacecraft. It may be necessary to reverse wheel speed to obtain a proper phasing. It is even possible that the unit could be rotated 180° on its mounting to achieve the same purpose, though more especially to help counter a second wheel failure.

9.0 CONCLUSIONS

The conclusions from this study are as follows:

1. The flywheel energy storage system has the potential to be superior to alkaline secondary batteries and regenerable fuel cells in most of the areas that are important in spacecraft applications: (1) weight; (2) life; (3) high efficiency; (4) smaller solar array; and (5) less orbital makeup fuel.

2. Additional advantages of the flywheel energy storage system are: (1) long shelf life; (2) state-of-charge indication; (3) modest thermal control needs; (4) ability to utilize excess sunrise power; (5) capability for multiple discharges per orbit; (6) regulated output voltage; (7) simplified ground handling, and (8) with special generator designs, capability for extremely fast (fractional second) discharges.

3. Disadvantages of the flywheel energy storage system are: (1) power may not be available during the launch phase unless a suitable bearing can be developed for operation during the high vibration environment of launch; (2) some limitations may result during prelaunch testing; (3) failure of units may force shutdown of good counter-rotating units, amplifying the effects of failure and limiting the power distribution system options; (4) unless specially provided for, the peak power capability of the flywheel system energy storage system would generally be less than the natural peak power capability of alkaline batteries; (5) there is no inherent emergency power capability unless specifically designed for; and (6) the system is complex relative to batteries; compared with regenerative fuel cells, flywheels are more complex with respect to electronics, but fuel cell systems are more complex with respect to hardware.

4. A relatively large amount of research and development will be required before the flywheel system can be made available for space use. Key technology areas are: (1) high energy rotor technology, including hub; (2) magnetic bearings; (3) flywheel rotor containment; (4) efficient motor/generators.

5. Integration of flywheel energy storage and CMG momentum management systems is not advantageous on the basis of weight. Partial integration imposes relatively little weight penalty, however, and may be helpful in extending ACS capability, such as for docking. Integration using a double gimbaled system or

skewed reaction wheels may have merit, and warrants analysis. Close interlinking of the energy and momentum systems may offer advantages following failures in either system.

6. An energy margin for reserve and emergency power is an important issue with flywheel systems. Since flywheel systems have no inherent reserve, this can be provided only by making the system larger. It will be important to determine whether emergency power is to be obtained from the main spacecraft power system or whether a separate emergency power system is to be provided.

7. Flywheel energy storage appears to be applicable to other spacecraft applications in addition to the space station, especially GEO spacecraft and military applications. Features of the flywheel system which are particularly attractive for military applications are: (1) very long life; (2) high energy density; (3) very high current capability, with discharges less than one second; (4) multiple discharges and charges per orbit; and (5) good hardening capability. Flywheel energy storage for solar dynamic systems has a special attraction as a competitor to thermal energy storage.

8. Much of the technology which would be developed for spacecraft energy storage would have important applicability to non-spacecraft technology and commerce. These include: (1) high strength composite technology; (2) advanced, high efficiency motor/generator technology; (3) magnetic bearing technology; and (4) terrestrial energy storage. The first three items would be very useful for other spacecraft technology areas in addition to energy storage.

10.0 RECOMMENDATIONS

The following recommendations are made:

1. The planned Phase II of this study should be carried out. This should include in-depth study of the key issues and major technology problems, both at the energy storage level and the power system level. Key energy storage items include high energy rotor technology, magnetic bearings, flywheel rotor containment, and high efficiency motor/generators. Key power system level items include prelaunch checkout, launch power, emergency power, distribution system, design to minimize effects of failure, and interaction with momentum management system.

2. Study should be given of the applicability of flywheel energy storage to spacecraft other than the space station, including LEO and GEO spacecraft, solar dynamic power systems, and military applications. Any special advantages and problems should be identified and studied. As part of the study on military applications, special study should be given to the potential to deliver very high pulse current from flywheel systems.

3. An overall plan should be developed for the logical pursuit of spacecraft flywheel energy storage technology. The plan should identify specific goals and objectives of the individual technologies involved as well as the overall objectives and goals, including demonstration tests. Major technology problems should be identified and broken down into discrete tasks.

4. A study should be made of the appropriate government laboratory facilities required to support a long term flywheel energy storage technology program.

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