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MERITS OF FLYWHEELS FOR SPACECRAFT ENERGY STORAGE

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SUMMARY
Flywheel energy storage systems have a very good potential for use in spacecraft. 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 lighter weight, longer cycle and operating life, and high efficiency which minimizes solar array size and 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 characteristics which would be useful for military applications.

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. In net balance, the potential advantages of the flywheel energy storage system far outweigh the disadvantages.

INTRODUCTION
Energy storage systems for spacecraft in the past have used nickel-cadmium and nickel-hydrogen 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). Though flywheel systems have been suggested for spacecraft for many years (Refs. 2 to 4), only recently have they been given serious consideration for spacecraft (Ref. 5).

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 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. Either magnetic bearings or mechanical bearings may be considered for flywheel systems.

EFFICIENCY CONSIDERATIONS
Energy storage efficiency is a key factor in the optimization of spacecraft energy storage systems, and also in the choice between one system and another. The problems of large sized solar arrays are well out of proportion to the modest weight involved, and an efficient energy storage system reduces the size of the solar array. This is shown parametrically in Figure 1. For high-power spacecraft with large solar arrays, significant quantities of propulsion fuel must be resupplied regularly to offset the effects of solar array drag and maintain the spacecraft within the selected orbit. Inefficient energy storage systems require greater solar area and hence more propulsion fuel. This is shown in Figure 2 for a typical space station design using either hydrazine or hydrogen-oxygen propellants. This penalty can be considerable over the life of the spacecraft.

The calculated efficiency of the flywheel energy storage system is shown in Table 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. Electrochemical systems, by comparison, are on the order of 55 to 65 percent efficient.

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, depending on the time to reach steady sunlit temperature, which is determined mostly by the unit thermal mass of the solar array. Typical solar array performance in low earth orbit is shown in Figure 3. The incremental power due to the low temperature transient is seen to be an increase in solar array output of approximately seven percent. This potential for extra power usually is not used. In a shunt regulated power system, the excess voltage is not used; 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.

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 generator, on the other hand, will control voltages very closely, within approximately two percent. This makes the design of internal power supplies lighter and more efficient. An estimate of the typical improvement in efficiency of these loads is shown in Figure 4. It is seen that most of the loads could be reduced 0.8 percent 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.

WEIGHT COMPARISON

Flywheel energy storage system weights are shown in Figure 5. It is seen that both the intermediate and advanced design flywheels are lighter than any of the battery systems when comparisons are made at the design depth-of-discharge, for the flywheel can cycle repetitively at deeper depths-of-discharge than can batteries. This 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 6, applicable for comparison of emergency power capability. Even for this condition the flywheel system is lightest.

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 depth-of-discharge, and a flywheel system at approximately 75 percent depth-of-discharge. On the other hand, if the emergency requirement is very large, then it must be supplied independently by a primary battery system; the power system trade then focuses on the main load, being essentially between batteries at 25-35 percent depth-of-discharge, and a flywheel system at approximately 75 percent depth-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 greater than for batteries, resulting in less heat to be dissipated (for overall 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 system 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.

Typical weight comparisons have been made at the spacecraft level between flywheel, regenerative fuel cells, and battery systems (Table 2). The power system load for this comparison is arbitrarily set at 50 kW for both sunlight and occultation. It is seen that the flywheel energy storage system is lighter than batteries. 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. Lower propellant resupply over a period of many years can be a major advantage for the flywheel system.

LIFE AND RELIABILITY

Life and reliability of nickel-cadmium batteries are important concerns 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.

Flywheel systems 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 a space station, which is in the range of 10 to 30 years. Flywheel system lifetime probably is limited by the associated electronics, which can be designed to be replaceable.

In assessing the life and reliability of the flywheel motor/generator system, those items considered to be key to long life and reliability 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 units.

Suitable derating factors can be applied to allow for fatigue over the design life. Figure 7 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. These data suggest that a derating factor for 15 years should be approximately 0.942, excluding 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 can be important in causing wheel unbalance, but little information is available on this.

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 may be the critical long life item for the bearings. With suitable electronics redundancy, very long life should be achievable for bearing control and for operation of the motor/generator.

Flywheel systems have an advantage over batteries with respect to temperature control. The components of flywheel systems tolerate higher temperatures (about 35°C) and accept much wider temperature control (estimated about ±35°C) than do batteries, which require low temperature (5°C) and close control (±5°C). Though it is easier to meet the temperature control needs of flywheels, once a satisfactory thermal design has been made for either batteries or flywheels, good reliability is expected for both systems.

With a system not integrated with attitude control, counter-rotating flywheels are appropriate to prevent interference with the spacecraft momentum management system. In order to prevent angular momentum unbalance, failure of a flywheel unit would appear to require that a second equipollent unit, rotating in the opposite direction, will also have to be shut down. This doubling effect is an important limitation of flywheel systems. Spin direction reversal can limit the number of good units which are forced to be shut down, however.

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. Flywheel systems, in contrast to batteries, have nearly indefinite shelf life.

PEAK POWER CONSIDERATIONS

A major difference between batteries and the flywheel systems is that system voltage with battery systems drops during power peaks and also reduces with time as batteries degrade, whereas output voltage is always regulated for the flywheel motor/generator system. Thus, flywheel system performance at high power is always constant and predictable.

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 if voltage limits are not too restrictive. The flywheel system can be designed also for very high peak power and can in fact be expressly 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, however, the motor/generator must be increased in rating to meet the specific requirements.

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 satisfying 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 would put a demand on the energy storage system which batteries are not well equ' ped to cope with, partly due to the increased number of cycles, but primarily from th .igher charge rates needed with multiple discharges and charges. The most strenuous needs for multiple charges and discharges per orbit are expected to be military applications.

EMERGENCY POWER CONSIDERATIONS

A flywheel energy storage system can be inferior to a battery or regenerable fuel cell system with regard to emergency power unless specifically designed with capability for emergencies. 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.

For a manned space station, 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 reserve power limitations of a flywheel energy storage system would be a minor factor.

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 cannot be operated during the high vibration environment of launch unless a suitable bearing can be developed for operation during the high vibration environment of launch. An alternative approach would be a separate battery provided for the launch phase.

RECONDITIONING

Reconditioning is proven to be a worthwhile and even necessary procedure for nickel-cadmium batteries, especially in synchronous orbit. Flywheel systems do not require reconditioning discharges.

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. Even if the ampere-hour capacity were known, discharge voltage for both battery systems 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.

EVALUATION OF ENERGY STORAGE METHODS

A simplified comparison between batteries, regenerative fuel cells, and flywheels is shown in Table 3. 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 3 that the flywheel system is best in most of the important categories. Its capability for emergency power is limited unless specifically designed for, and it may present limitations in providing power during the launch phase. Possible forced shutdown of good counter-rotating units when a unit fails is a 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.

ACKNOWLEDGEMENT

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Table 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 2. Weights for Energy Storage Sy:'cms - - 50 KW Continuously

	BATTERIES			REGENERATIVE FUEL CELLS		FLYWHEELS	
	NiCd (25% DOD)	NiH$_2$ (35% DOD)	NiH$_2$ (30% DOD)	WEIGHT OPTIMIZED	EFFICIENCY OPTIMIZED	INTERMEDIATE DESIGN OBJECTIVE	ADVANCED DESIGN OBJECTIVE
SOLAR ARRAY WEIGHT	3,246	3,401	3,246	3,817	3,246	2,799	2,639
(SOLAR ARRAY POWER)	(108.1 KW)	(111.2 KW)	(108.1 KW)	(124.8) KW	(108.1 KW)	(81.5 KW)	(86.3 KW)
RADIATOR	980	1,047	980	521	386	316	121
FUEL CELLS ①	—	—	—	880	1,830	—	—
ELECTROLYSIS CELLS ①	—	—	—	385	636	—	—
BATTERIES ①	8,760	6,796	6,762	—	—	—	—
PROPELLANTS ② (H_2-O_2 ANNUAL REQMT)	3,281	3,430	3,281	3,860	3,281	2,828	2,668
COLD PLATES	985	638	744	—	—	18	18
HEAT EXCHANGERS	—	—	—	60	40	—	—
TANKS	—	—	—	282	240	—	—
FLYWHEEL SYSTEM	—	—	—	—	—	1,761 ③ 4,831 ④	1,273 ③ 3,564 ④
TOTAL, LBS	17,220	14,321	14,882	8,736	9,486	7,723 ③ 10,883 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

Table 3. 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
	SAFETY				
	PRELAUNCH TESTING	BEST	BEST		
	THERMAL REQUIREMENTS				BEST
	STATE-OF-CHARGE				BEST
	UTILIZATION OF EXCESS SUNRISE PWR				BEST
	POWER DURING LAUNCH PHASE	BEST	BEST		

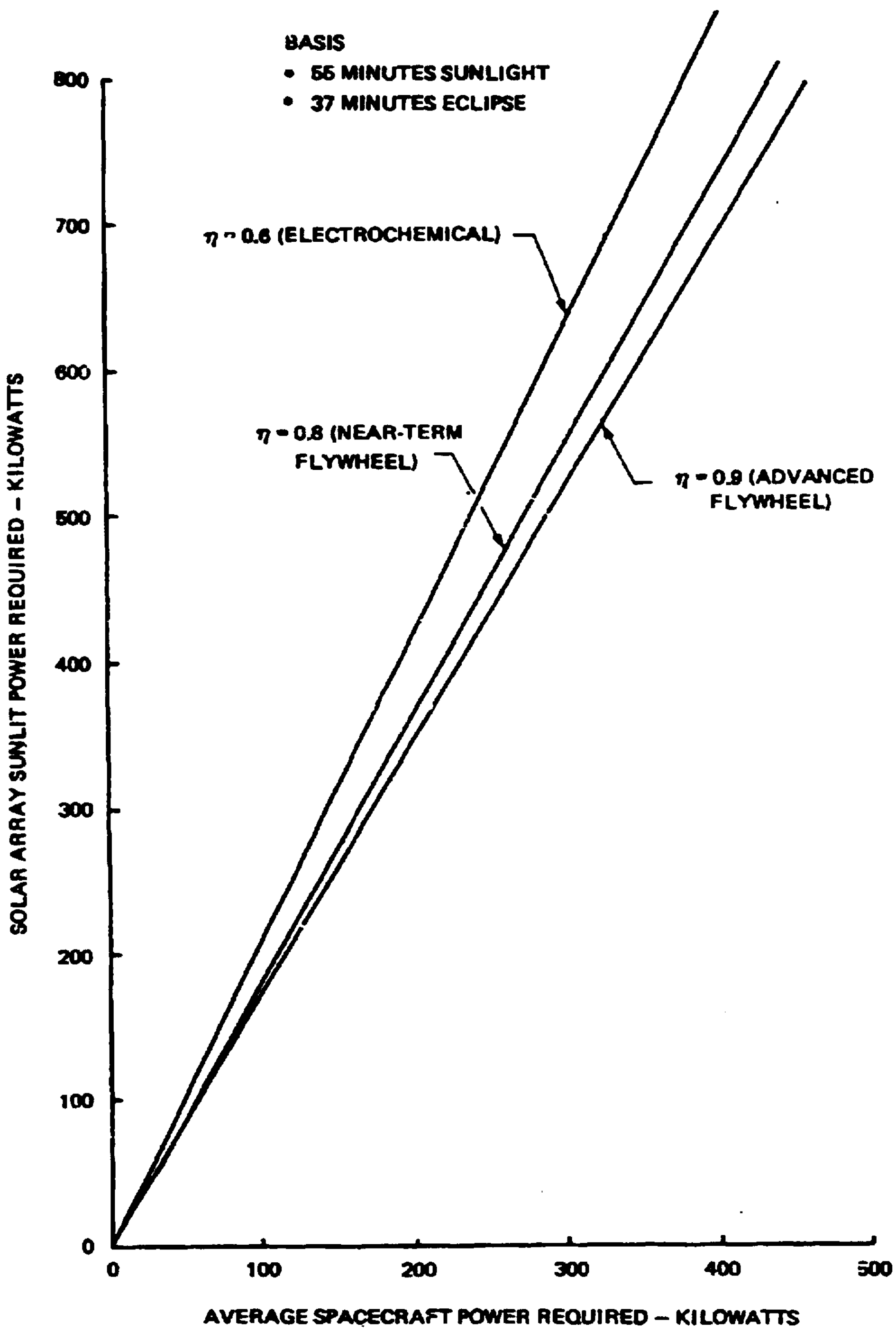

Figure 1. High Efficiency Energy Storage Systems Result in Smaller Solar Arrays

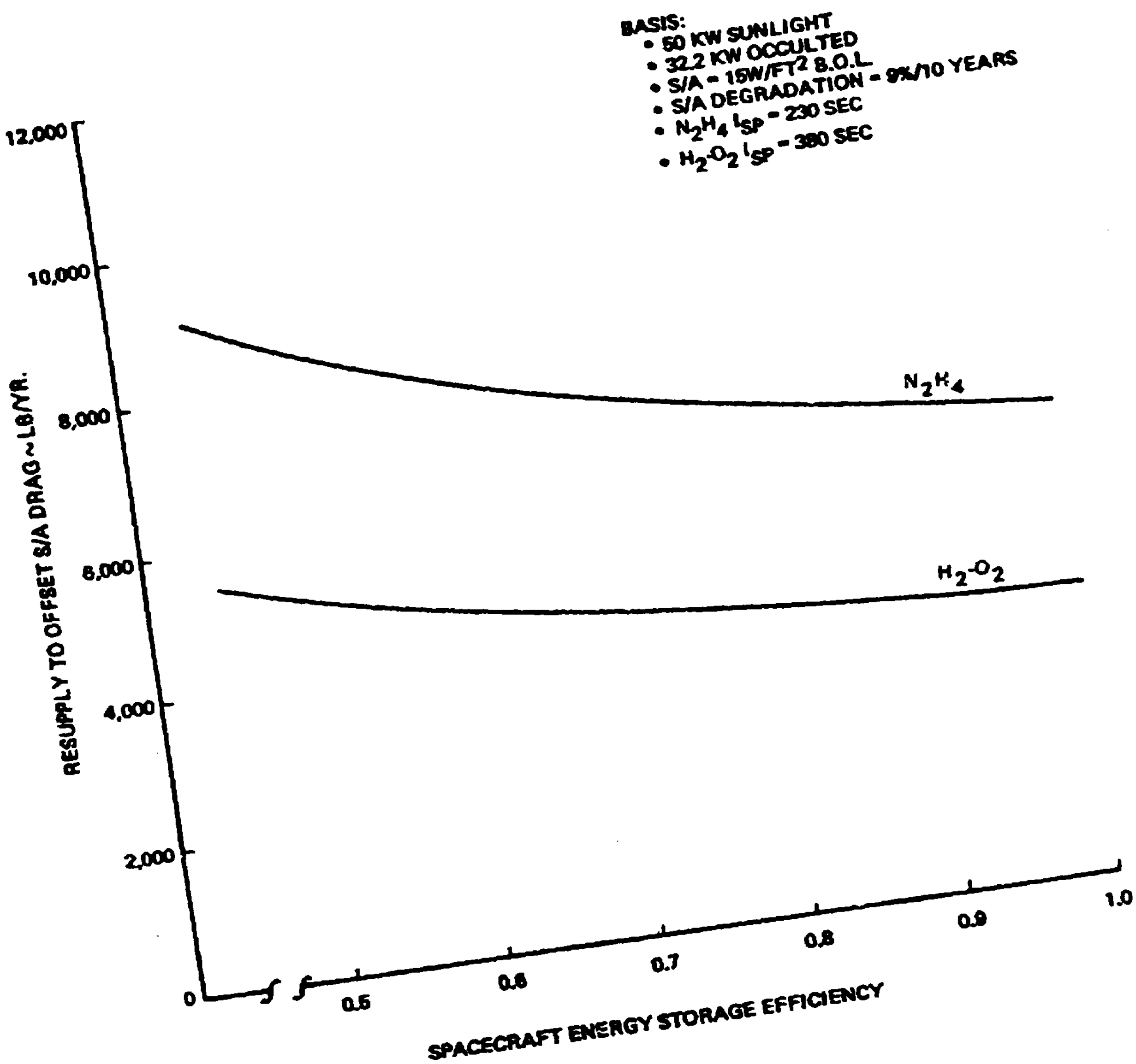

Figure 2. Propulsion Resupply Due to Solar Array Drag

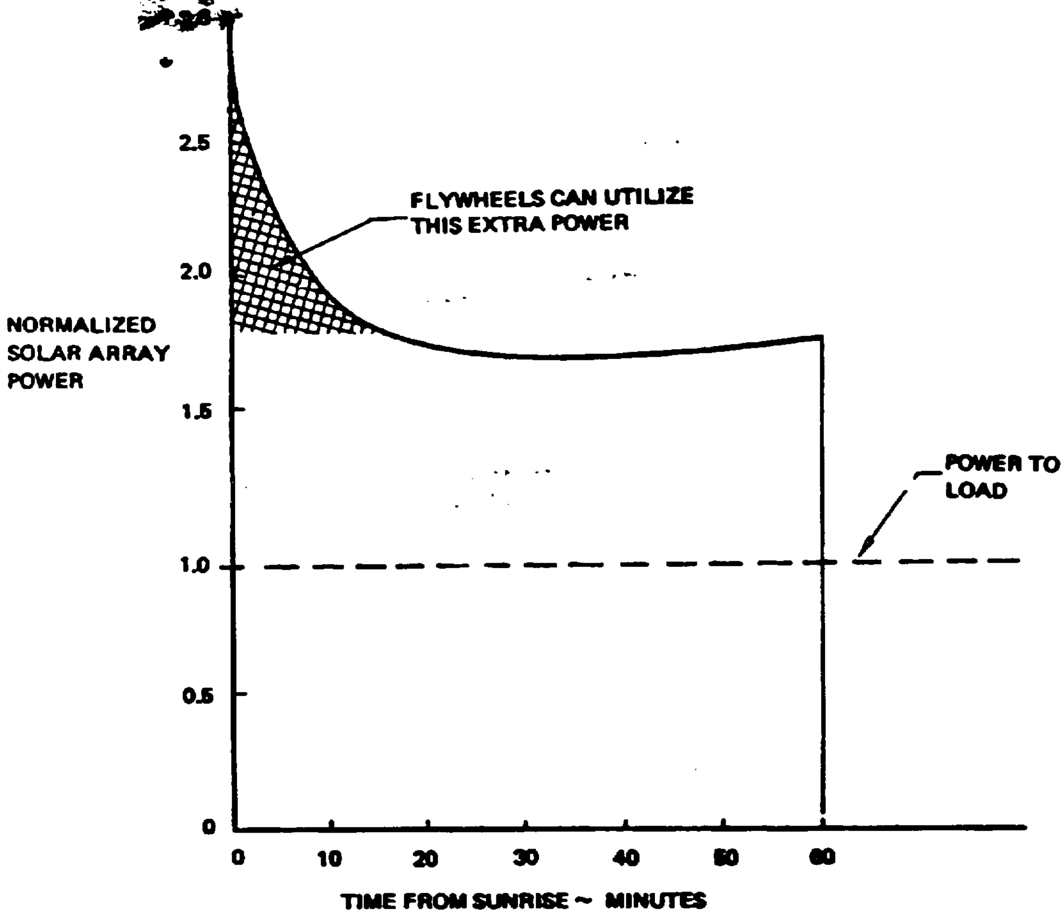

Figure 3. Typical Sun-Oriented Solar Array Performance in Low Earth Orbit

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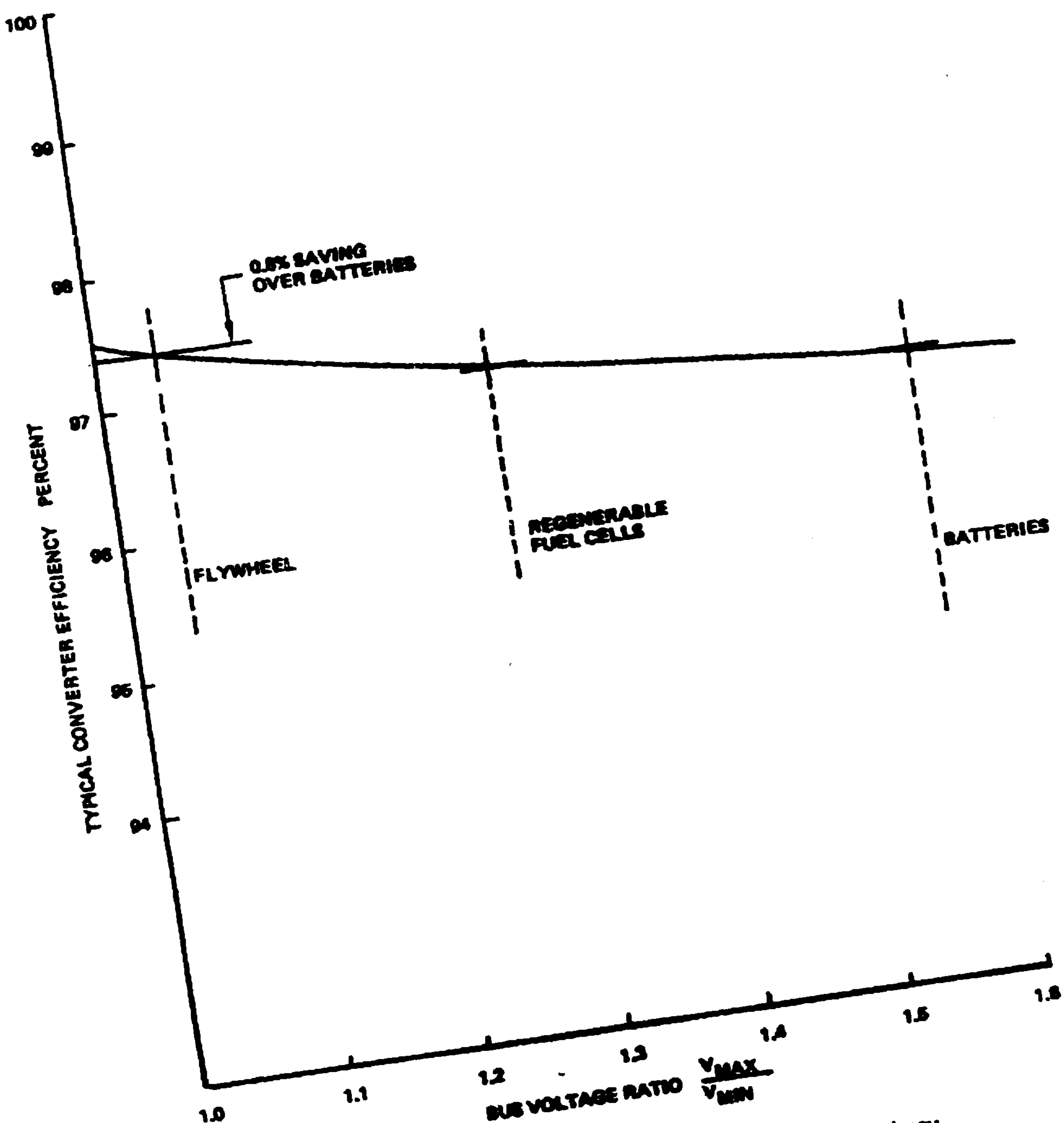

Figure 4. Effect of Bus Volt Regulation on Power System Efficiency

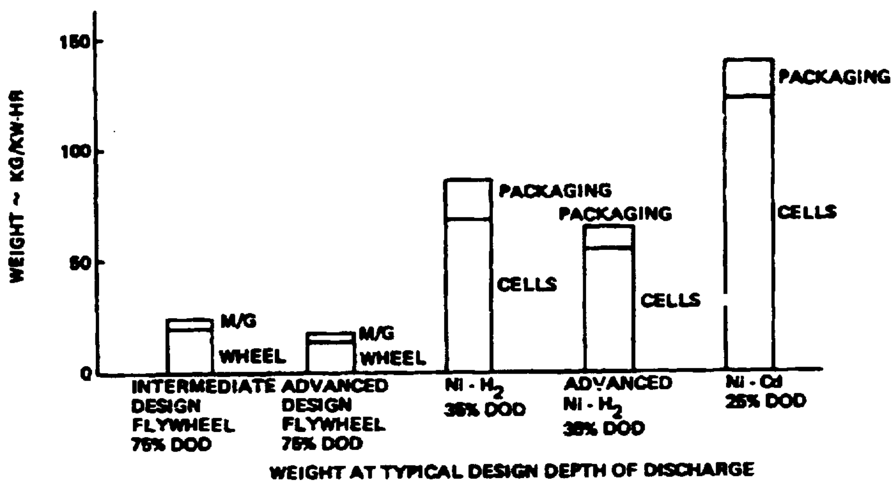

Figure 5. Comparative Weights of Energy Storage Devices

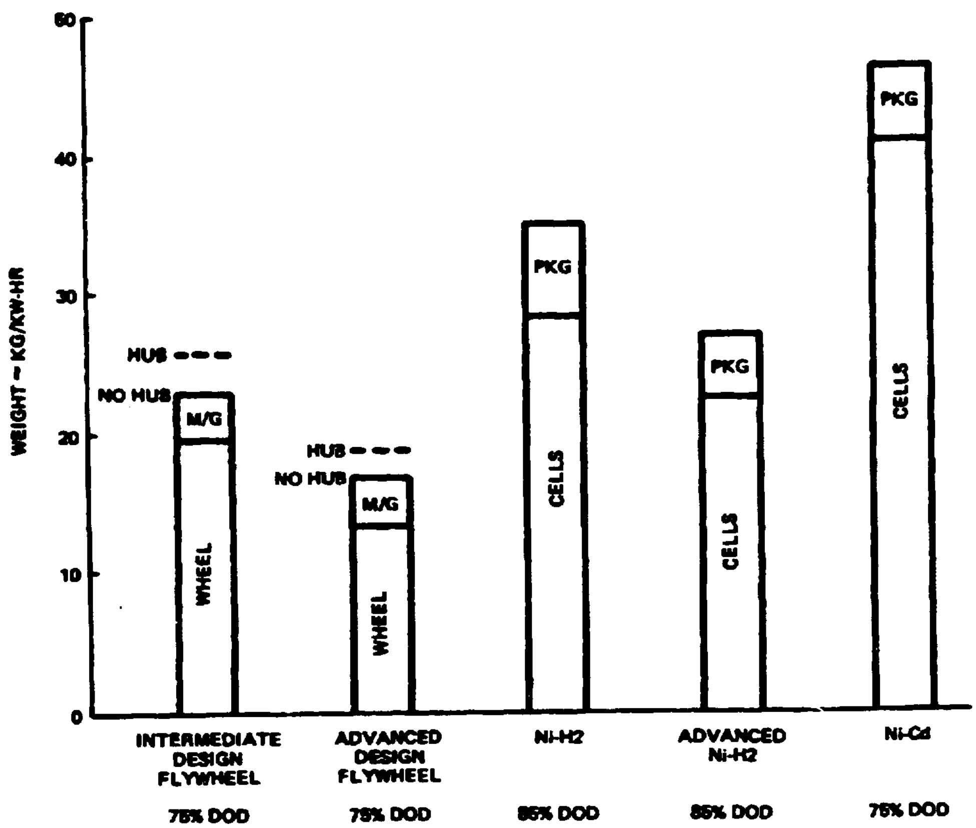

Figure 6. Comparative Weights of Energy Storage Devices Sized for Emergency Condition

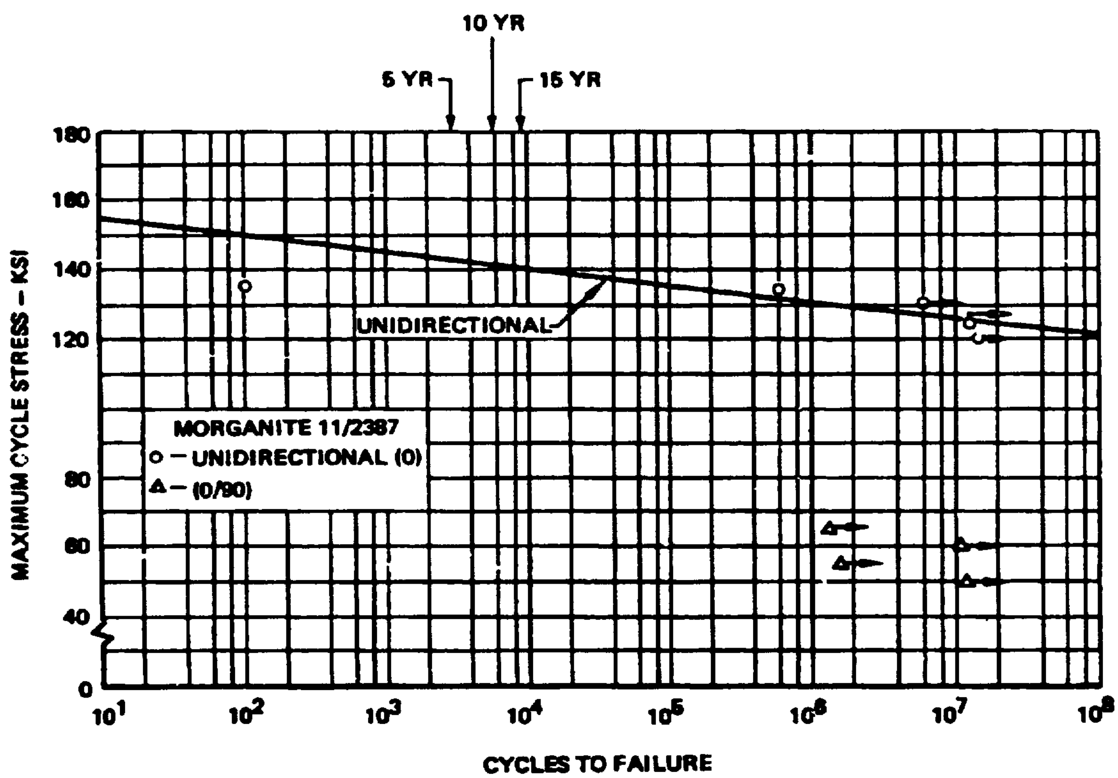

Figure 7. Constant Amplitude Unidirectional Fatigue Properties of Typical High-Strength Graphite/Epoxy Composite