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National Aeronautics and
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ABSTRACT

This paper documents the starting point for the assessment of a spacecraft power system utilizing inertial (flywheel) energy storage. It defines both general and specific guidelines for the assessment of a modular flywheel system, operationally similar to but with significantly greater capability than the multimission modular spacecraft (MMS) power system. Goals for the flywheel system are defined in terms of efficiency train estimates and mass estimates for the system components.

The inertial storage power system uses a 5 kw-hr flywheel storage component at 50 percent depth of discharge (DOD). It is capable of supporting an average load of 3 kw, including a peak load of 7.5 kw for 10 percent of the duty cycle, in low earth orbit operation.

The specific power goal for the system is 10 w/kg, consisting of a 56w/kg (end of life) solar array, a 21.7 w-hr/kg (at 50 percent DOD) flywheel, and 43 w/kg power processing (conditioning, control and distribution).

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INTRODUCTION

The purpose of this paper is to document the "starting point" for task 4–Assessment of Flywheel Energy Storage, under RTOP 506–55–76–Advanced Power System Technology. Since the material presented represents only a starting point, it is both general in nature and limited in scope. However, it is anticipated that, as the task progresses, revision of the material by additions, elaborations or modifications will make technical accomplishments more readily apparent. Furthermore, documentation of the starting point will aid both in highlighting areas of uncertainty and technical problem areas and in defining the impacts of later conceptual improvements.

The starting point is described in four elements. They are:

General Guidelines
Initial Specific Guidelines
Efficiency Train Estimate
Mass Estimate.

The General Guidelines set the stage for the three remaining elements. They indicate the overall scope of the task and the planned approach. The Initial Specific Guidelines represent the primary direction of the effort to be emphasized initially in order to develop reference conceptual power systems. The Efficiency Train Estimate provides an initial look at what electrical characteristics might reasonably be achieved for a power system with inertial energy storage. The Mass Estimate provides an initial look at the mass characteristics of the power system components that need to be achieved in order to meet the target system mass as given in the Initial Specific Guidelines. As such it is an optimistic estimate.

GENERAL GUIDELINES

1. Assessment of flywheel energy storage will be considered on an overall systems basis. This includes:

   a. Meeting projected spacecraft requirements such as launch restrictions, orientation requirements, power quality requirements, etc.

   b. Analysis of impacts, both positive and negative, on other spacecraft subsystems such as attitude control, mechanical systems, propulsion systems, etc.

   c. Determination of effects within the power subsystem such as component interfaces, power distribution, throughput efficiency, reliability, etc.

2. Assessment will be limited to power systems for spacecraft in earth orbit.

   a. Initial and primary emphasis will be on power systems for spacecraft in low earth orbit (LEO).

   b. Geosynchronous equatorial orbit (GEO) missions will be considered in the light of trends indicated by the LEO studies.

   c. Elliptical orbits will be similarly considered (after 2a and 2b).

3. Several concepts for spacecraft power systems utilizing inertial energy storage will be developed and analyzed.

   a. Concept types will include dc, ac, and hybrid systems.

   b. Ranges for electrical characteristics will be:

      Power: 2-25 kW
      Voltage: 0-400 volts
      Frequency: DC-2 kHz

   c. Trends within the above ranges will be analyzed with regard to potential impact beyond the ranges.

4. For the various concepts developed, feasibility and tradeoff studies will be made to determine the most desirable candidates for further evaluation.

5. Selected concepts will be evaluated in comparison to systems using chemical energy storage. Comparisons will definitize the pros and cons with respect to:

Efficiency	Reliability and Lifetime
Mass	Complexity
Volume	Power quality
Cost	Peak to average power ratio

and other appropriate parameters.

6. Finally, a task for system definition for an inertial energy storage system will be defined and scoped.

INITIAL SPECIFIC GUIDELINES

Initially, in order to derive a detailed system to be used as a baseline or reference system for the feasibility studies, the tradeoff studies and comparative analyses, the following guidelines will be used.

1. Low earth orbit mission.
    a. 90 minute period
    b. 60 minutes sunlight; 30 minutes eclipse.
2. Multimission modular spacecraft (MMS) load cycle but higher operational load. (See Table 1)
3. Modular, 5 kw hr, storage system.
4. Two counter-rotating flywheels (2.5 kW hr each).
5. Maximum discharge of 50% (2.5 kW hr).
6. Target of 10 w/kg for total power system.

EFFICIENCY TRAIN ESTIMATE

The efficiency train estimate for the simplified power system is shown in Figure 1. Loss factors and power or energy requirements are also shown. In addition, loss factors are briefly described in Table 2. For these estimates it is assumed that the peak power portion of the duty

Table 1
Spacecraft Loads and Load Cycle

	MMS Loads	Inertial System Loads
Operational Load	1 kW	2.5 kW
Peak Load	3 kW	7.5 kW
Duty Cycle:		
Operational Load	90% (81 minutes)	90% (81 minutes)
Peak Load	10% (9 minutes)	10% (9 minutes)
Energy Utilized:		
Operational (81 min)	1.35 kW hr	3.375 kW hr
Peak (9 min)	.45 kW hr	1.125 kW hr
Total (90 min)	1.80 kW hr	4.50 kW hr
Average Load	1.20 kW	3.00 kW

Table 2
Assumed System Losses

Component	% Loss	Loss Mechanism
Solar Array	25	Radiation Degradation
Peak Power Tracker	10	Efficiency
Flywheel Input	15	Circuitry, Switching, Motor
Storage	5*	Internal (Standby) Losses
Output	10	Circuitry, Switching, Generator
Control and Distribution	5	Regulation and I^2R

*Standby losses in flywheel are assumed to be 5% (of nominal stored energy) per hour.

cycle occurs during eclipse, maximizing the load on the flywheels. The estimates are then derived so as to be consistent with the Initial Specific Guidelines and with Table 1.

There is, of course, substantial uncertainty in the loss factors for this initial estimate and variations will reflect throughout the system.

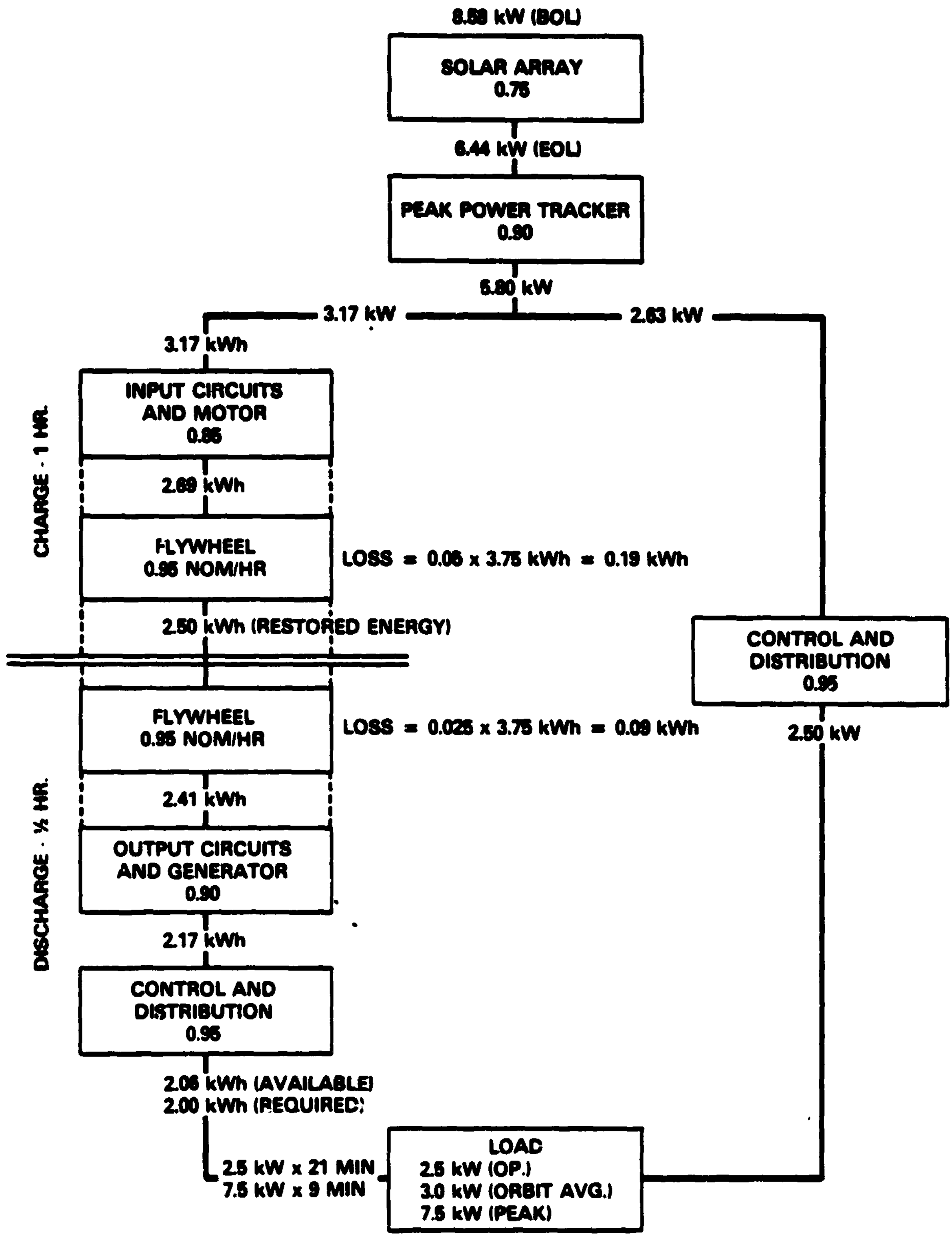

Figure 1. Efficiency Train Estimate for LEO System

MASS ESTIMATE

The mass estimates for the system and its components are given in Table 3. These estimates are somewhat optimistic, being driven by the target of 10 w/kg for the system. The table also indicates the relationship between the estimates and the state of the art. Several elements are worthy of comment. First, any improvement in the solar array area would have to come, indirectly, from efficiency improvements within the system (or from separate R&D, which could result in direct improvements). Secondly, although some gain is anticipated in the energy storage area, major improvements would have to be accomplished in the power processing (conditioning and distribution) area if the target is to be met. Finally, efficiency improvements or improvement in energy storage, beyond the presently optimistic level, would alleviate the requirements for the power processing area.

Table 3
Target-Driven Mass Estimates

Item	Mass	Specific Power/ Specific Energy	Notes
System Total	300 kg*	10 w/kg	State of art is ~6 w/kg
Components			
Solar Array	115 kg	56 w/kg**	SEPS array is 55.6 w/kg
Storage (Total)	115 kg	43.5 w-hr/kg	
(Useable)		21.7 w-hr/kg	NiCd is ~8 w-hr/kg
			NiH_2 is ~17 w-hr/kg
Power Processing	70 kg	43 w/kg	State of art is ~20 w/kg

*Based on 3 kW average load.
**End of life.