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Feasibility of Flywheel Energy Storage Systems for Applications in Future Space Missions

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Prepared for
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1.0 Summary

The objective of this study was to examine the overall feasibility of deploying electromechanical flywheel systems in space used for excess energy storage. Results of previous Rocketdyne studies have shown that the flywheel concept has a number of advantages over the NiH2 battery, including higher specific energy, longer life and higher roundtrip efficiency. Based on this prior work, this current study was broken into four subtasks. The first subtask investigated the feasibility of replacing the NiH2 battery orbital replacement unit (ORU) on the international space station (ISSA) with a flywheel ORU. In addition, a conceptual design of a generic flywheel demonstrator experiment implemented on the ISSA was completed. An assessment of the life cycle cost benefits of replacing the station battery energy storage ORUs with flywheel ORUs was performed. A fourth task generated a top-level development plan for critical flywheel technologies, the flywheel demonstrator experiment and its evolution into the production unit flywheel replacement ORU.

This section summarizes the results of each subtask.

Task 1: Flywheel ORU Concept Interface Definition

The two areas of primary interest in this task were the integration of the flywheel pair in the battery subassembly ORU box and the selection and integration of the flywheel power processing unit (FPPU) in the battery charge/discharge unit (BCDU) ORU box. The FPPU consists of the flywheel magnetic bearing control unit, a power converter/starter for the motor/generator, and health monitoring subsystems. Our conclusions from this phase of the study are:

- It is feasible to mount the flywheel pair in the battery box and the FPPU in the BCDU box.

- The battery box ORU base plate must be modified for flywheel usage. The major changes to the existing base plate are:
    - Elimination of the heat rejection fins.
    - Elimination of the battery cell sleeves.
    - Addition of flywheel mounting hardware

- Increasing base plate wall thickness for more support.

The ORU walls and top plate do not require any modifications and the ORU box retains its original shape and dimensions. No changes to the structural interface between the flywheel box and the Integrated Equipment Assembly (IEA) will be required.

- Active cooling of the flywheel box is not necessary because of the wider operational temperature range and inherently high efficiency of the flywheel. Our preliminary calculations indicate approximately 10 watts of thermal energy per flywheel are released during the normal charge/discharge cycle. This means the ORU base plate fin configuration is not needed to transfer waste heat from the ORU to the IEA fin assembly. In addition, the battery heater subassembly is eliminated because of the wider operational temperature range of the flywheel pair (-100 F to +100 F).

- The primary electrical interfaces between the flywheel box and the FPPU include:
    - The three-phase AC power cables from the flywheel to the FPPU converter.
    - Magnetic bearing control and power lines.
    - Flywheel health monitoring and diagnostic lines.

- A preliminary analysis for the power converter (variable voltage variable frequency to DC) was completed. Electronic circuit parameter data was calculated to derive power losses, packaging size volumes and weights.

The AC to DC power conversion bidirectional power converter controller approach was selected as the preferred power conversion approach.

The advantages of the bidirectional power converter controller approach include an inherent bidirectional power flow between the Halbach array motor/generator and Station DC bus. The variable frequency, variable voltage AC characteristics of the flywheel motor/generator voltage step-up/ step-down is handled by the unipolar series resonant link circuit. Efficiencies up to 96% have been achieved with this approach and 15 - 100 kw designs have been demonstrated by Electronic Power Conditioning Incorporated. This approach also employs natutal commutation switching in the input and output switch assemblies.

Our basic design philosophy in fitting the flywheel system into the Station battery storage infrastructure is to utilize the existing design to the greatest extent possible with minimal design changes. The examination of the existing electrical interface between the flywheel box and FPPU showed that changes to the existing battery charge/discharge unit (BCDU) interface are necessary to fit the flywheel system into it. Modifications to the BCDU include the following major differences:

- There is a three phase AC power flow between the flywheel box and FPPU, instead of the original DC interface.
- Battery heater controller lines are no longer utilized for thermal management control purposes.
- Flywheel rotor, bearing and motor/generator controller lines were added.
- Flywheel bearing power lines were added.

The primary DC power input/output interface between the FPPU and Station DC bus remains the same.

Task II: Flywheel ORU Demonstration Unit Concept Interface

Task II was initiated by examining possible deployment strategies of the flywheel demonstrator unit. The demonstration unit itself consists of a full powered flywheel pair ORU with the power processing unit (PPU) ORU. The possible deployment strategies are:

1. Replace an operational battery/BCDU ORU within the IEA with the demonstration package. The power and load are provided by the Station.

This scenario is schedule independent and requires minimal Station hardware changes to implement. The schedule independence and minimal Station changes implies a lower cost (compared to the other alternative scenarios). It increases operational risk if the excess energy stored by the demonstration unit is needed by the Station load.

2. Place the demonstration package in an empty IEA battery ORU/BCDU slot during station construction during October 1999 through December 2000. The power and load are provided by the Station.

There is a higher schedule risk due to the early deployment of the demonstration package, but a lower risk to normal station operations. As in the first scenario, there are minimal changes to the Station hardware since the IEA is the experimental platform.

3. Place the demonstration package exterior to the IEA with the power and load provided by the station.

There is lower inherent risk to station operations in this scenario since the station load is not dependent upon the demonstrator excess energy storage. It is also schedule independent but can incur extra cost by additional Station hardware modifications (control and power lines).

4. Place the demonstration package exterior to the IEA with the power and load provided by autonomous systems.

This case is similar to number 3 above except the power and load is independent of Station capabilities. This minimizes risk to Station operations but requires additional hardware for the power source and load. The simulated load provides a better opportunity to exercise the flywheel demonstrator capabilities.

5. Place the demonstration package exterior to the IEA with power provided by the Station and the load simulated.

This scenario is similar to number 4 except power is provided by the Station EPS. Station hardware modifications may be necessary to route power and control lines to the flywheel demonstrator.

The objectives and specifications of the flywheel demonstrator experiment were refined during the search for an adequate hookup location to the Station EPS.

The primary objective of the flywheel demonstrator experiment is to demonstrate in a space environment that dynamic flywheel energy storage is a feasible alternative to the traditional energy storage methods such as fuel cells and batteries.

Other technical objectives include:

1) Validating space operation of all flywheel mechanical and electrical components.
2) Minimizing dynamic disturbance impacts upon the Station.
3) Minimizing risk to the Station and EPS.
4) Maintaining stable electrical and mechanical operation.
5) Demonstrating flywheel orbital charge/discharge performance.

Primary flywheel experiment specifications include:

1) The demonstrator will consist of two flywheel motor/generator units rated at 2.14 kW-hrs total energy storage and 1.61 kW-hrs useable energy storage per flywheel. The total demonstrator energy storage capability is 3.22 kW-hrs. The operational flywheel speed will be 26 - 52 kRPM. Note that this energy storage capability is the same as the Station flywheel replacement ORU.

2) The flywheel input voltage will be 120 - 126 VDC, which is the specified Station secondary side voltage of the DCSU. Note that this is different from the BCDU input voltage range of 134-173 VDC, which would also be the input voltage for the flywheel replacement ORU. It is not an objective of the flywheel demonstrator experiment to test the wider voltage range of the primary side station EPS because that can be adequately tested on the ground.

3) The flywheel pair, associated power converter electronics, and magnetic bearing control units will be physically packaged in one ORU to minimize EVA time by expediting installation and removal to the Station truss.

4) No special thermal management requirements were identified to conduct this experiment.

5) The flywheel demonstrator will be hooked external to the Station EPS on the secondary power side using the external utility ports. This location offers enhanced safety and operational stability and minimizes Station structure scars.

Task 3 Flywheel ORU Life Cycle Cost

The PRICE model input assumptions were adjusted for the parametric study of Space Station cumulative cost for flywheels versus batteries. Three parameters are varied in this study: launch cost, flywheel life, and station life. The cumulative costs of an all battery station versus replacing batteries at year 5 with flywheel ORUs for these cases are summarized in the table below.

Costs are in Millions of 1994 dollars.

$2,000/lb launch cost

	Battery/BCDU	**5-year Flywheel**	**10-year Flywheel**
10 Year Station	$116	$120	-
15 Year Station	$272	$166	$120
20 Year Station	$388	$213	$166

$4,000/lb launch cost

	Battery/BCDU	**5-year Flywheel**	**10-year Flywheel**
10 Year Station	$143	$135	-
15 Year Station	$333	$196	$135
20 Year Station	$476	$257	$196

Table 1-1

Parametric Cost Comparison between Space Station Battery Storage System and Flywheel System

Task IV Flywheel ORU Development Plan

A preliminary version of the development plan was completed. Milestones for each task and subtask were defined and scheduled. The development plan is split into three tasks; technology development, flywheel demonstrator, and flywheel ORU replacement. The technology development task commences in CY1995 and is completed in mid 1997 by demonstrating the four basic flywheel technologies; composite flywheel, Halbach array, power processing unit electronics, and magnetic bearing. Twenty-two milestones during this time period were defined.

The demonstrator experiment development commences in CY1997 and is completed with the post test unit evaluation in CY2000. There are four subtasks (Demonstrator Design, Development, Verification, and Flight) and sixteen milestones scheduled.

The flywheel ORU replacement development begins in CY2001 and ends in CY2006 with the replacement of all battery/BCDU ORUs with flywheel/PPU ORUs. Four subtasks (Design, Development, Qualification, and Flight/Replacement) and fifteen milestones are defined.

2.0 Introduction

This study was performed under NASA Lewis Research Center Task Order Contract NAS3-2808, "Feasibility of Flywheel Energy Storage Systems for Applications in Future Space Missions." This is one of many task order studies that evaluated space-based power system technologies for a variety of postulated future missions.

Over the years numerous studies [Ref. 2-1 is a typical study] have noted the specific weight advantage flywheels hold over batteries. Specific energies for flywheels have been calculated in the 25-35 W-hr/kg range, compared to 10 W-hr/kg for NiCd batteries and 20 W-hr/kg for the Space Station Ni-H batteries. Overall energy charge/discharge efficiencies for the flywheel on the order of of 80 - 93% are predicted, compared to Ni-H efficiencies of 60%. This mass advantage translates into significant launch cost savings in favor of the flywheel. In addition, flywheels also have a longer useful operating life, 10 - 15 years, compared to 5 years for Ni-H battery technology. Because of these three factors alone - specific energy, efficiency and life - there is significant interest to deploy flywheels in place of battery energy storage devices for a variety of postulated space mission scenarios.

The overall purpose of this study was to examine the feasibility of utilizing flywheel technology as a generic replacement for current state-of-the art Ni-H batteries, as designed for the current Space Station Alpha configuration. The total Rocketdyne space-based flywheel concept consisting of a composite flywheel, Halbach array motor/generator, resonant frequency power converter, and magnetic bearings was designated as the replacement flywheel concept. This cursory study was designed to examine four basic engineering issues regarding space-based flywheel deployment: interface issues and feasibility of replacing Space Station Alpha Ni-H batteries with flywheels, conceptualization of a flywheel demonstrator unit experiment for deployment on Space Station Alpha, a life cycle cost analysis of Space Station Alpha flywheels and battery energy storage options, and a proposal for an overall flywheel development program.

This report is divided into four major sections that discuss the results of each study. In addition, there is a short exposition of the Rocketdyne flywheel concept, taken from a previous IR&D study. Conclusions and recommendations for additional study taken from all four subtasks conclude this initial examination of space-based flywheel engineering issues.

3.0 Space Station Requirements

This section briefly describes the Space Station Electrical Power System (EPS) and the current design of the battery storage system. The basic requirements of the battery charge/discharge unit (BCDU) and battery ORU for the IOC station are presented. Much of this material is from the WP-04 Power System Engineering Design Document, Rev. T. [Ref. 3-1]. In addition, the results of a preliminary Rocketdyne IR&D study comparing the battery storage system to a replacement flywheel system for the Space Station are summarized. This study concluded that the flywheel ORU was both lighter than the battery/BCDU system and significantly reduced thermal waste heat.

3.1 Space Station EPS Overview

The Space Station EPS provides utility grade power to the user interface via a modular and expandable network of power generation, energy storage, control and distribution equipment. The distributed system includes all power generation, storage, control, and distribution equipment needed to produce electrical power and distribute it to the user interface.

During insolation, solar array output is fed through a dedicated sequential shunt unit (SSU). The SSUs regulate the array output. The regulated dc voltage, at a nominal voltage of 160 VDC, is transferred through the beta gimbals to the dc switching units (DCSUs.) During eclipse, power is fed from the batteries to the BCDUs. The BCDUs regulate the battery output to the DCSUs. DCSU output is fed through dc-to-dc converters (DDCUs) located in the integrated equipment assembly (IEA) and to the main bus switching units via the solar alpha rotary joint. The DDCU converts the DCSU output to 120 VDC secondary power. It feeds it back through the DCSU, which distributes it to the solar power module loads.

As the Station is assembled, the EPS will undergo several discrete changes in configuration. For purposes of this study we have assumed the EPS is fully functional and configured in the Permanently Manned Configuration (PMC). This represents a configuration that has a rated capacity of 56.25 kW average and 75 kW peak. Fig. 3-1 (taken from Ref. 3-1) depicts this configuration.

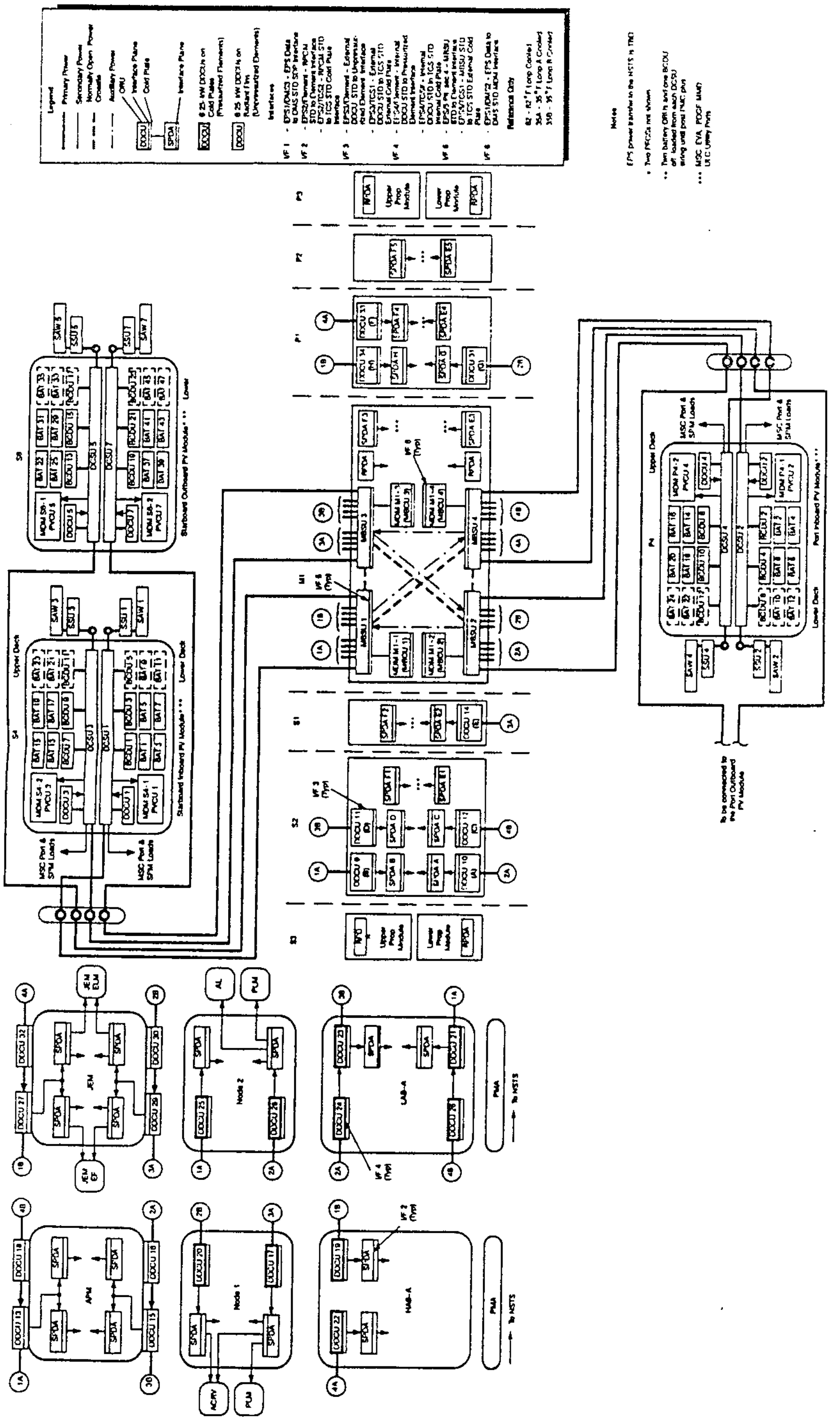

Figure 3-1
Space Station EPS Block Diagram.

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3.2 Battery Storage System Overview

The energy storage assembly consists of eight battery assembly ORUs at PMC that operate in conjunction with four dedicated BCDUs to meet the station power requirements during eclipse and loss of local or station-wide electric power. Two battery ORUs comprise one battery assembly. The energy storage assembly consists of 12 battery assembly ORUs (with 6 BCDUs) at post-PMC. The BCDUs condition the battery charge and discharge power based on commands received from the PV controller unit, which manages the charging and discharging processes. During eclipse or loss of solar array electric power, the BCDU provides voltage-regulated battery power to the DCSU for use as a dc source bus, and discharges stored energy to the dc power bus. Discharge is enabled automatically based on the bus voltage. Battery charge is enabled automatically based on the bus voltage, but controlled by the PC controller unit.

Charge Voltage	
Normal	**≤ 62.5 Vdc**
Off-loaded	**≤ 63 Vdc**
Discharge Voltage	**≥ 38.0 Vdc**
Nameplate Capacity	**≥ 81 Ah**
Depth of Discharge	
Nominal Orbit	**≤ 35%**
Contingency Orbit	**≤ 80%**
Output Energy	
Normal Orbit	**1.342 kWh**
Contingency Orbit	**0.997 kWh**
Heater Power per cell	**5.8 to 6.2 W (120 V)** **8.5 to 9 W (145 V)**
Efficiency	
0 to 5 yr	**≥ 80%**
5 to 6.5 yr	**≥ 76.9%**
Number of cells per ORU	**38**
Number of ORUs per assembly	**2**
Maximum Power Loss	
0-5 yr	**969 W**
> 5yr	**1.107 kW**
Temperature Range	
Normal Operation	**32 to 50 °F**
Contingency Operation	**23 to 50 °F**
Off-loaded Operation	**32 to 68 °F**
Design Life	**5 yrs**
MTBF	**75 years**

Table 3-1
Battery ORU Characteristics and Requirements.

Each battery has a nameplate capacity of 81 Ah and an average discharge voltage of 95 VDC. For the purpose of achieving a 6.5 year design life, a maximum of 35% of the rated capacity may be discharged during a normal eclipse. This equates to 2.7 kWh/battery for a reference orbit eclipse. During a contingency orbit, an additional 1.8 kWh may be discharged without exceeding 80% depth of discharge. Table 3-1 summarizes the battery ORU characteristics for the post-PMC station configuration.

The function of the BCDU is to control and condition battery charging and discharging, and provides monitoring and an interface to the battery ORU. It is a bidirectional power converter that is capable of parallel operation with up to tow other BCDUs. In the charge mode it accepts power from the voltage regulated primary power bus and outputs a regulated current to control the battery ORU charge rate. In discharge mode the BCDU outputs a regulated voltage to the primary power bus. The BCDU also provides protection for the primary power bus and dc control power bus. Table 3-2 summarizes the BCDU characteristics for the current EPS design.

Input Voltage	
Charge Mode	**130 to 180 Vdc**
Discharge Mode	**76 to 120 Vdc**
dc Control power bus	**70 to 130 Vdc**
Output Voltage	
Charge Mode	
Normal Operation	**76 to 126 Vdc**
Off-normal Operation	**1 to 76 Vdc**
Discharge Mode	**130 to 180 Vdc**
Dc control power bus	**75 to 130 Vdc**
Output Power	
Charge Mode	**8.4 kW**
Discharge Mode	
Normal Operation	**6.6 kW**
Off-normal Operation	**9.0 kW**
Nominal ORU Efficiency	
Charge Mode	**90%**
Discharge Mode	**90%**
Operating Setpoints	
Charge Current	**0 to 85 A**
Regulation	**10% or 3 A**
Charge Voltage Limit Setpoint	**72 to 130 Vdc**
Primary bus voltage	**130 to 180 Vdc**
Regulation	**±3%**
Temperature Range	
Nonoperating	**-65 to 180**
Mimimum Startup	**-65 °F**
Operating	**-11 to 104 °F**
Design Life	**15 years**
MTBF	**17.16 years**

Table 3-2
BCDU Characteristics and Requirements.

The battery storage system has a thermal control subsystem (TCS) that acquires and transports excess heat from the battery ORUs and BCDUs to dedicated EPS radiators for rejection to space. Each battery and electrical ORU baseplate is a structure that transfers heat from the heat generating components to the radiator heat exchanger. Heat is first removed from the batteries followed by that from the electrical equipment ORUs. The generated heat is then transported from the radiator heat exchanger to the coolant tubes within the IEA where it is carried away to the PV radiator and rejected to space. Table 3-3 summarizes the operating condition design points for the thermal control subsystem.

Parameter		Design-to Cases			Assessment Cases	
	LeRC-0001 Range	Case 1. Peaking at BOL+5 yr	Case 2. Peaking at BOL+15 yr	Case 3. Contingency at BOL	Case 4. MTC (For PV-1)	Case 5. PMC (For PV-1)
Orbit Altitude (nmi)	180-240	200	200	200	200	200
Beta Angle (deg)	0-52	27	27	27	27	27
Radiator Age (yr)	0-30	5	15	0	1	4
PV Array Age (yr)	0-15	5	15	0	1	4
Battery Age (yr)	0-6.5	5	5	0	1	6
Quantity Battery (ORU/IEA)	8-12	12	12	12	8	8
Electric Power Output (kW)						
Eclipse Power	16.75-18.75	18.75	16.75	-	18.75	17.1
Insolation Power		18.75	16.75	-	25	25
Peaking	23-25	25	23	-	-	-
Contingency	2.45	-	-	2.45	-	-
Solar Flux (W/m^2)	1,326-1,418	1,326	1,326	1,326	1,372	1,372
Radiator Pointing Error (deg)	0-4	4	4	0	4	4
Battery Temperature (°F)	32-68	32-50	32-50	32-50	32-68	32-68

Table 3-3
Thermal Control Subsystem Operating Conditions.

3.3 Comparison between Battery and Flywheel Storage Options

Utilizing the flywheel concept discussed in section 3, Rocketdyne performed a cursory study that compared the flywheel system against the NiH Space Station battery [Ref. 3-2]. There were three main conclusions from this study:

- The electromechanical battery subsystem mass is a factor of 2.4 less than the battery system, on a per IEA basis. The flywheel system weighs 2760 lbs versus 6,636 lbs for the battery system. These mass numbers are summarized in Table 3-4.

ELECTRO-CHEMICAL BATTERY SYSTEM

Total useable stored energy - 14.2 kiloWatt-hours

ORU Name	Quantity per IEA	Weight with factors for maturity		
		Pounds per ORU	Pounds per IEA	% of Total IEA weight
Electro-Chemical Battery	12	410	4920	24.60%
BCDU	6	286	1716	8.58%
TOTAL			6636	

ELECTRO-MECHANICAL BATTERY SYSTEM

Total useable stored energy - >18.2 kiloWatt-hours

ORU Name	Quantity per IEA	Weight with factors for maturity		
		Pounds per ORU	Pounds per IEA	% of Total IEA weight
Electro-Mechanical Battery	6	460	2760	13.80%
TOTAL			2760	

Table 3-4
Weight Comparison between the Station Battery Storage and Flywheel Storage Options.

- The higher flywheel efficiency results in lower waste heat from the energy storage subsystem. On an IEA basis, the battery energy storage system requires 7.4 kW of cooling capacity, compared to the flywheel storage system cooling requirement of 2.7 kW (Table 3-5).

ENERGY DISSIPATION IN ELECTRO-CHEMICAL BATTERY REQUIRES ELABORATE THERMAL CONTROL SYSTEM

Temperature control required to maintain +32F to +50F of all cells"

Peaking power at BOL + 5 years

ORU Name	Quantity per IEA	Dissipated Energy		
		Watts per ORU	Watts per IEA	% of Total per IEA
Electro-Chemical Battery	12	322	3864	52.28%
BCDU	6	399	2394	32.39%
DCSU	2	261	522	7.06%
DDCU	1	240	240	3.25%
PFCS	1	275	275	3.72%
PVCU	2	48	96	1.30%
Total			7391	

ENERGY DISSIPATION IN ELECTRO-MECHANICAL BATTERY MAY ALLOW PASSIVE COOLING

Thermal limits expected to be between -100F to +100F

Peaking power at BOL + 5 years

ORU Name	Quantity per IEA	Dissipated Energy		
		Watts per ORU	Watts per IEA	% of Total per IEA
Electro-Mechanical Battery	6	300	1800	24.35%
DCSU	2	261	522	7.06%
DDCU	1	240	240	3.25%
PVCU	2	48	96	1.30%
Total			2658	

Table 3-5
Energy Dissipation Comparison between the Station Battery Storage and Flywheel Storage Options.

- The higher charge/discharge efficiency of the flywheel system increases the overall energy storage capacity and system power capability during the insolation period by 1.85 kW and during the eclipse period by 2.74 kW. This increases the overall margin of the system, by reducing the PV array power requirement or by increasing the user power availability. The difference in energy flow from the PV to the storage subsystem is evident in Figs. 3-2 and 3-3 for the flywheel and battery system, respectively.

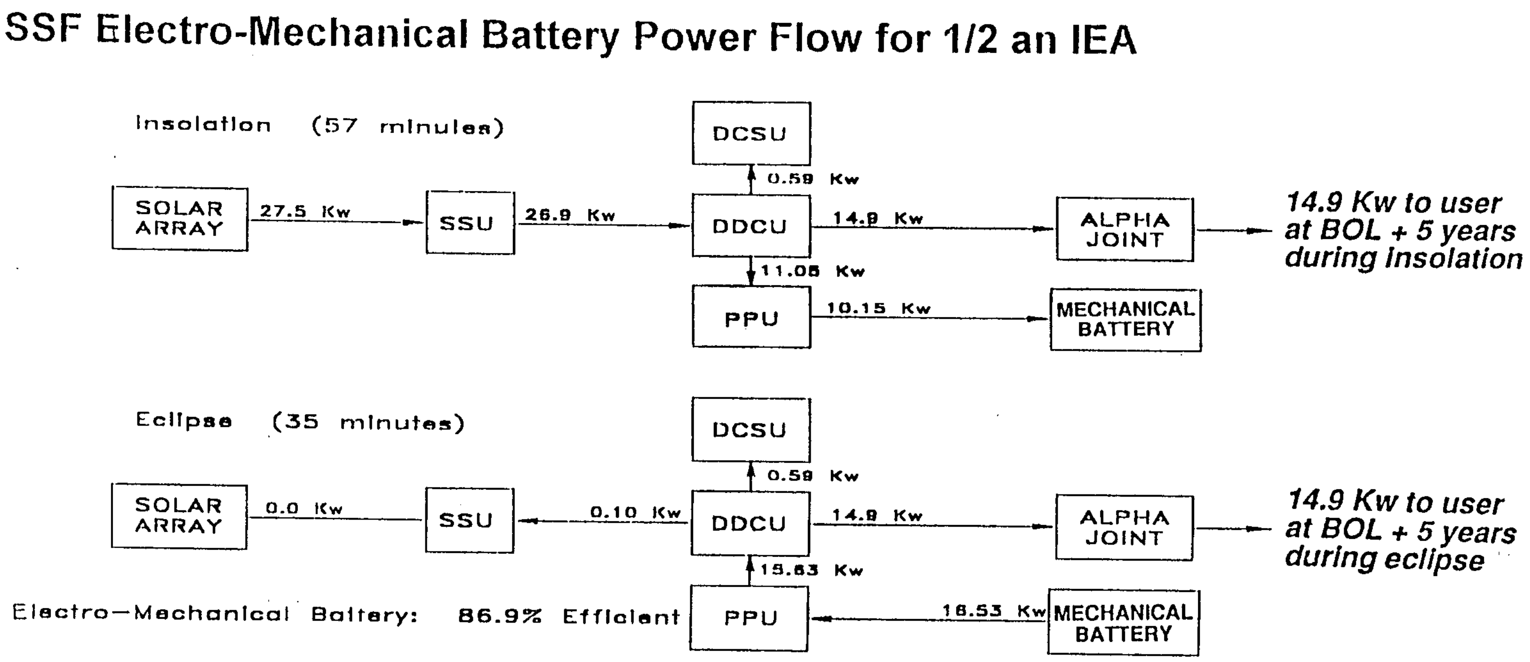


Figure 3-2
EPS Energy Flow for the Flywheel Storage Option.

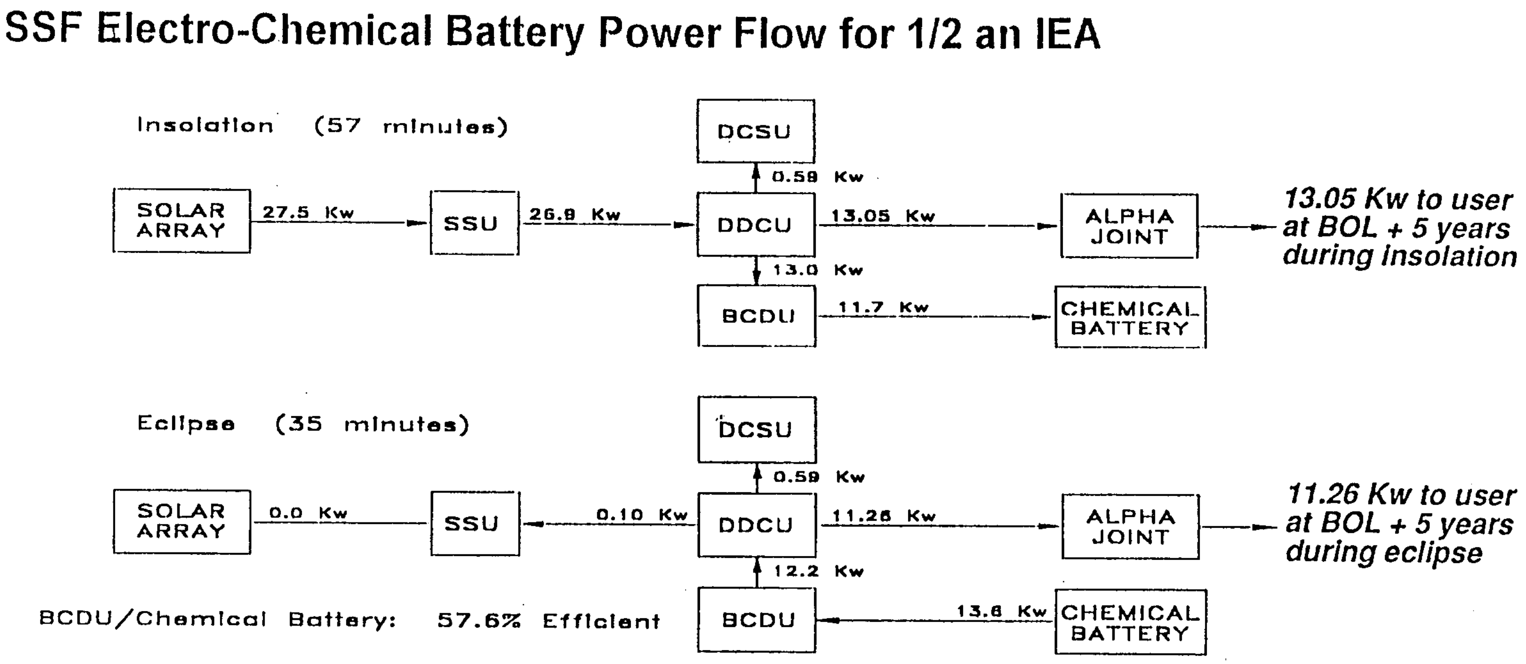


Figure 3-3
EPS Energy Flow for the Chemical Battery Storage Option.

4.0 Space Qualified Flywheel Motor/Generator Concept

This cursory study is based upon the Rocketdyne space-based flywheel concept that was originally proposed in Ref. 4-1 and initially developed in a subsequent Rocketdyne study [Ref. 4-2]. This section presents an overview of this concept from those two references.

4.1 Rocketdyne Flywheel Concept

A conceptual design of a flywheel electromechanical battery, as shown in Fig. 4-1, consists of a composite material rotor secured to a metal hub. The hub interfaces between the composite, the bearing and the motor/generator. The rotor is supported by the magnetic bearings during operation while the overload sleeve and bumper bearings offer support in case of an overload condition, bearing failure, or when the flywheel is inactivated. The rotor would be fixed during launch and requires to be unlocked prior to charging.

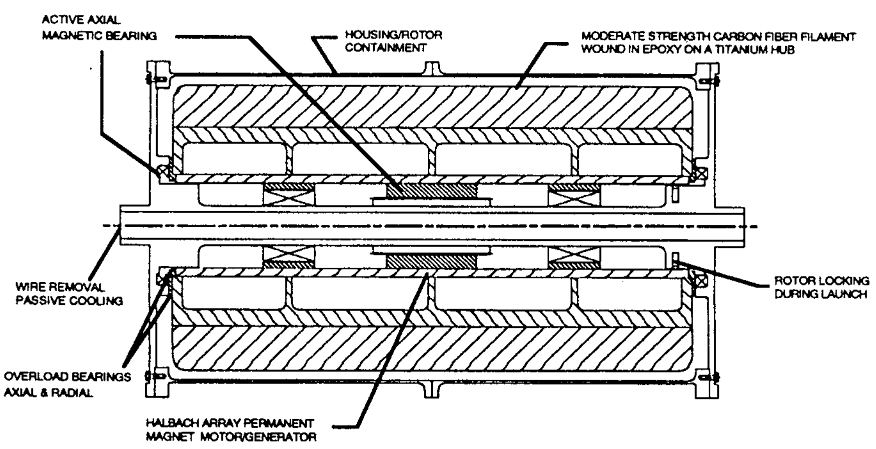


Figure 4-1. Conceptual Flywheel Design

The motor/generator takes electrical power from the power generating system and increases the speed of the flywheel storing energy in the form of kinetic energy. At the end of each insolation period, the flywheel will be fully charged and the motor/generator will start acting as a generator and produce electricity by discharging the flywheel. The flywheel will be fully discharged by the end of the eclipse period and the process will repeat itself during the next orbit.

The flywheel is contained within a lightweight containment vessel and requires a controller device for the magnetic bearings and the power processing unit for the motor/generator. The conceptual design of a complete flywheel energy storage unit containing two identical counter rotating flywheels is shown in Figure 4-2.

A comparison between performance characteristics of a flywheel energy storage system and a NiH_2 Battery is shown in Table 4-1. The flywheel system operates at efficiencies between 80 to 90 percent compared to 60 to 80 percent for the NiH_2 batteries. This results in more power output, smaller power generation system and less thermal load. Low heat generation coupled with large operating range could allow for a passively cooled system eliminating the need for complex thermal management system now envisioned for the electrochemical batteries. This feature also has a significant impact on the size of the power generation system in terms of both mass and, for PV systems, in the overall projected area. This area contributes to drag makeup requirements and, consequently, to the life cycle cost of the space station.

The life of the flywheel system is only limited by the electronics, which is estimated to be between 10 and 15 years. As a result, substantial cost savings can be realized by not having to replace the NiH_2 battery at the end of life, which is projected to be approximately five years.

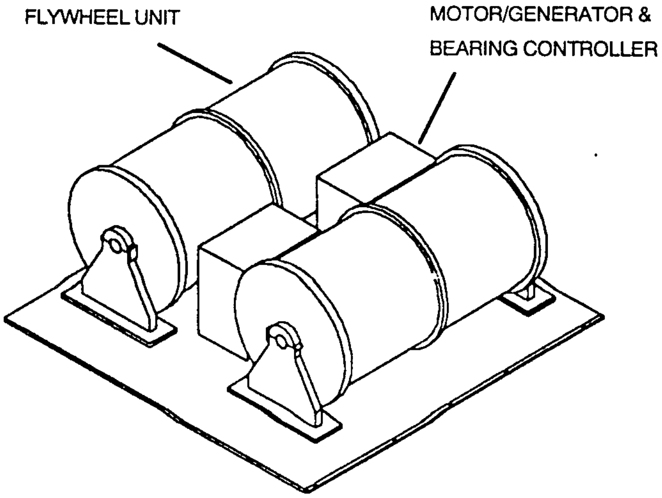


Figure 4-2. Flywheel Energy Storage System.

System Parameter	NiH_2 Battery	Flywheel EMB
Energy Density (W-hr/kg)	15 - 30	15 - 30
Round-trip Efficiency (%)	60 - 80	80 - 90
Expected Life (Years)	5 - 10	10 - 15

Table 4-1. Energy Storage System Performance Characteristics.

4.2 Halbach Array Motor/Generator

4.2.1 Summary Design Background

The Magnet Halbach Array Motor/Generator design has been proposed by a team headed by Dr. R. Post at the Lawrence Livermore National Laboratory for applications involving flywheel energy storage systems. The design has been characterized for having very high efficiency and power to weight ratio.

In the development of electromechanical batteries for commercial applications, such as electric powered vehicles, Rocketdyne investigated a number of motor/generator designs for such applications. The selection was narrowed down to two approaches, the Switch Reluctance and the Halbach Array designs. For aerospace applications the Halbach Array is the most promising because of its high efficiency and power to weight ratio. Although the Switched Reluctance design is also very promising, it was estimated that this approach would take longer time to develop. Currently, the General Electric Company is experimenting and has demonstrated the switch reluctance design as a starter/generator for aircraft engines. The higher manufacturing cost of the Halbach Array has made this design less attractive for electric vehicles; however for aerospace applications this design seems to be more suitable because of its unique characteristics, and no need for field excitation power when operating as a generator.

Rocketdyne conducted an independent analysis of the Halbach Array design. The results of the calculations were about 1 % apart from Dr. Posts's predicted values. In addition, a magneto 2D field analysis was conducted by Dexter Magnetics Co. to verify the uniformity and strength of the dipole field and the low external leakage estimated. The results of the analysis were very encouraging, showing high uniformity of the magnetic field in the central 2/3rds of the ID (central region) of the magnet Halbach Array. The values of the strength of the dipole field were also compared with the theoretical values. The values agreed within 2 percent of the value calculated by the code, using the actual B-H curve for Nd-Fe-B, thus giving added confidence in the use of the theoretical result for design calculations. The results of this analysis is attached in the Appendix of this report, Figures A-1, and A-2

Although limited test data is still available from experiments conducted by Dr. Post's team, it is believed that the approach has a lot of potential and should produce satisfactory results for aerospace applications. Preliminary testing at the Lawrence Livermore National Laboratory to evaluate the generator output signal, showed a high quality AC signal output with very little distortion (almost harmonic free), this test was conducted at approximately 10 kRPM, on a 1 KW prototype. Recently a larger unit, (10 KW) was tested under 20 kRPM, this a single phase prototype. This design is still being evaluated and a final report of the results expected by October 1994.

4.2.2 Halbach Array Motor/Generator Description

The motor/generator Magnet Halbach Array is relatively a very simple machine, similar to a permanent magnet DC motor/generator. It has a rotating magnetic field and a stationary stator. The stator has an "ironless" structure where the phase windings are located (see Figure 4 - 1.) The permanent-magnet assembly producing the field, has a group of high energy Nd-Fe-B individual linear magnets arranged as an outer ring and attached to the inner ring structure of the flywheel for support. When the flywheel rotates, the magnets produce a rotating field. The axes of magnetization of each individual linear magnet are calculated to produce a dipole magnetic field.

The stator of the motor/generator is made up of preferably a single-layer, 3-phase, windings assembled on the surface of a non magnetic cylinder. In the design the only substantive losses are the copper losses in the windings, since there are no hysteresis, windage, or bearing losses that need to be included. At high power levels the magnetic field produced by currents flowing in the windings will induce eddy current losses in the permanent magnet material, but an "upper limit" estimate has shown that this losses are negligible small (less than 10 watts.)

A total of 46 parameters have been identified for designing and obtaining performance data of this type of motor/generators. A computer program was developed to help optimize the designs. This program is attached in the Appendix of this report showing preliminary performance data for a specific design, (8.41 Design Number), in this case for the proposed demo unit (see Tables A-1 through A-6)

A summary design characteristics and performance data for the proposed motor/generator demo unit is depicted in Figure 4-3. For example, this design has a stator with single layer winding, each with 12 turns, 3-phase, 6.3 inches stator length, 1.93 inches stator diameter, 1.96 inches magnet ID, 2.94 inches magnet OD, 6.35 lbs. magnet weight. The plot in same figure depicts the operating performance of the motor/generator calculated as if the generator had a constant load of 5 ohms. The speed range considered was 50,000 RPM maximum and 25,000 RPM minimum. This two to one speed ratio is equivalent to as having the flywheel three-fourths discharged.

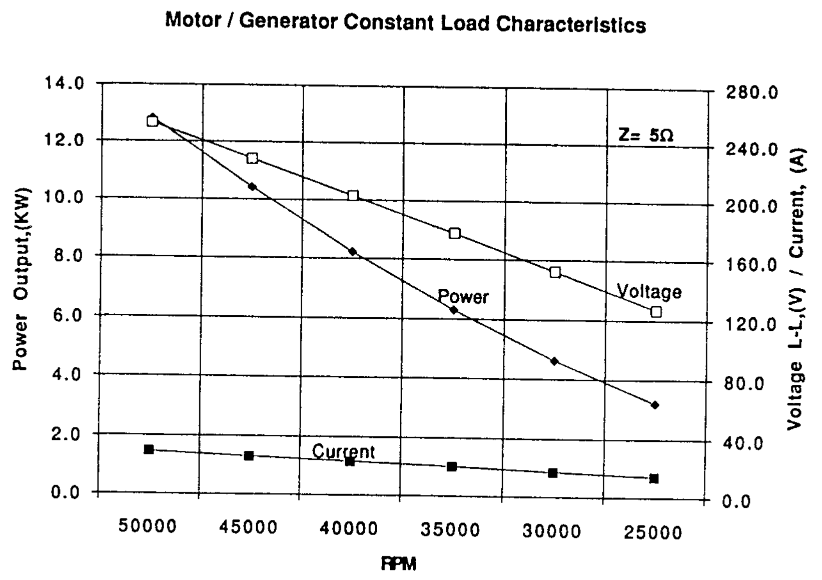


Figure 4-3
Motor/Generator Load Characteristics.

The power values depicted in Figure 4-3 are considered nominal under steady state conditions. More likely the peak power values could be two to four times larger for very short periods of time.

5.0 Space Station Battery/BCDU ORU Flywheel Replacement

The overall objective of this study was to determine the engineering feasibility of replacing the current Space Station Alpha Ni-H battery and battery charge/discharge unit (BCDU) with an electromechanical flywheel energy storage system ORU. Previous Rocketdyne work [Ref. 3-2] identified the savings in mass with the flywheel ORUs over the battery/BCDU units. This study examined the structural, electrical and thermal interface issues of replacing the battery units with flywheels in the current Space Station Alpha configuration, and the risk of failure and potential failure mechanisms of the flywheel ORUs. The second critical feasibility issue, cost of the flywheel ORU replacement program, is covered in detail in section 6. This section presents the top-level interface engineering issues germane to the flywheel ORU replacement of the battery/BCDU ORUs.

5.1 Overview

The Rocketdyne IR&D study concluded that it is possible to fit two flywheels (a flywheel pair) into the existing battery box ORU that was designed specifically for Space Station Alpha. The BCDU box is similarly utilized for the flywheel power processing unit (PPU) electronics. The basic design philosophy in fitting the flywheel system into the Station battery storage infrastructure is to utilize the existing design to the greatest extent possible with minimal design changes. There are two key advantages to this approach: First, there are minimal changes to the integrated equipment assembly (IEA) structure simply because it is designed to interface to the battery/BCDU ORUs and fits right in. Flywheel ORUs are inserted into the Station IEA as shown in Fig. 5-1. This translates into a more simple, less costly retrofit than performing costly redesign and EVA reconstruction of the IEA and Space Station structure. Secondly, utilizing existing equipment like the battery/BCDU ORUs reduces time and cost in designing a brand new flywheel ORU.

The objective of this subtask was to examine the feasibility of this flywheel/PPU deployment approach by focusing on the interface between the flywheel/PPU ORU and the Space Station IEA. Two key concerns that were not addressed prior to this work are the impact of the flywheel/PPU replacement ORU on the structural, electrical and thermal interfaces to the Space Station and the IEA in particular, and the operational risks and possible failure mechanisms of the flywheel/PPU ORU. The following assumptions and guidelines were used in this assessment:

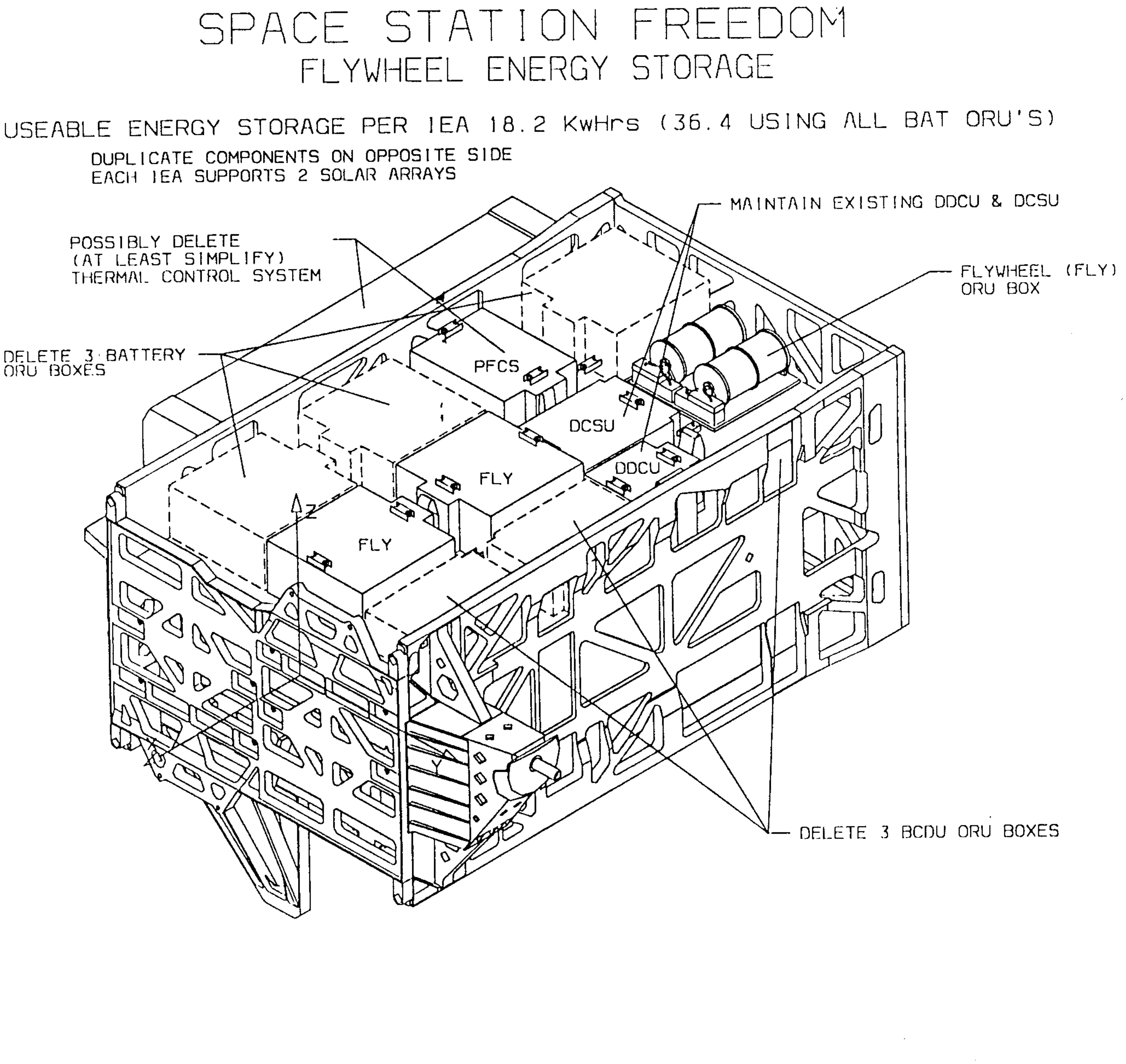


Figure 5-1
Flywheel/PPU ORUs placement in the Space Station IEA.

- The Space Station Alpha configuration as of February 1994 was established as the baseline platform. This includes the IEA and the battery/BCDU ORU designs as of that date. Reference 4-1 documents the standard EPS configuration that was used for this task.

- The Rocketdyne flywheel concept that was established in previous Rocketdyne work and consists of the flywheel pair, PPU, magnetic bearings and Halbach Array was assumed to be the generic flywheel unit. No new design work or enhancements to this design were done as part of this investigation.
- The flywheel/PPU system is deployed in the battery/BCDU boxes as discussed in Ref. 3-2.

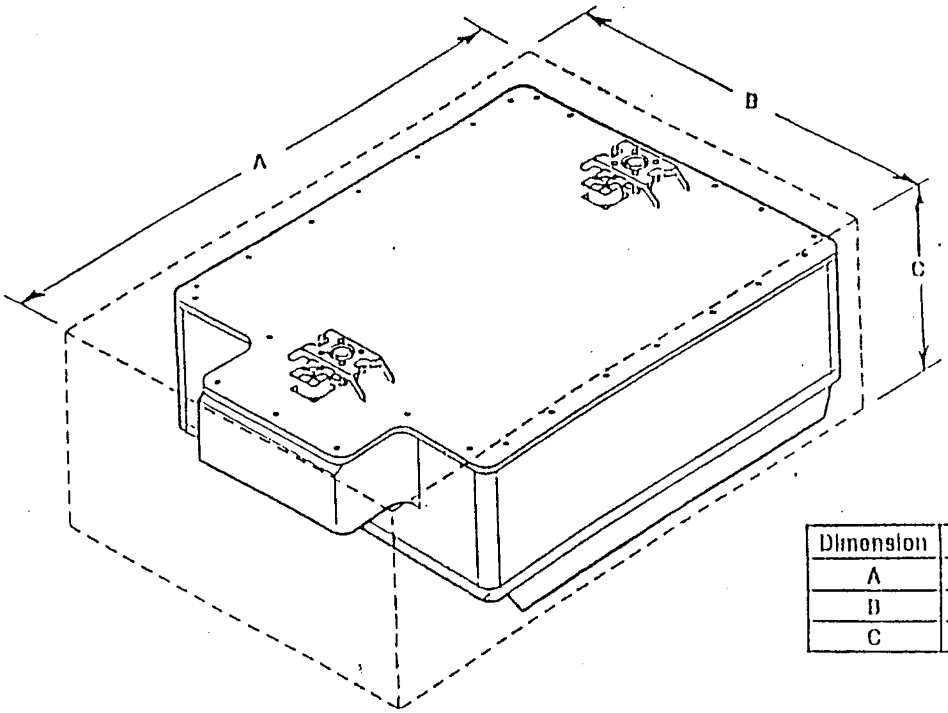
The interface between the flywheel/PPU ORUs and the Space Station were broken down into structural, electrical, and thermal components, and examined individually pursuant to the assumptions and configuration listed above.

5.2 Structural Interface

The structural interface between the flywheel system and the Space Station can be divided into two distinct members: the battery/BCDU ORUs and the placement and fastner/lock of the ORUs to the IEA. As shown in Fig. 5-1, the flywheel/PPU ORUs are locked into the same positions within the IEA that the battery/BCDU ORUs occupy. This eliminates the need to redesign the IEA to house the flywheels, and in fact, is the reason the original battery ORUs were selected to secure the flywheels and PPU. This particular structural interface issue is not addressed in this investigation because of this inherent design advantage. Two other structural issues of interest, the impact of flywheel deployment on the Space Station center of mass and Space Station response to flywheel dynamics are complex issues also outside the purview of this cursory work. Thus, the structural interface task was delegated to an examination of the existing battery/BCDU ORU enclosure to determine the changes, if any, are needed to house the flywheel and associated electronics.

The standard ORU box geometry is shown in Fig. 5-2. One of the key results from the previous study was that the flywheels can be housed within the battery box with no changes to its geometry. The placement of the flywheels (and magnetic bearing controllers) within the battery ORU box are shown in Figs. 5-3 and 5-4. The PPU electronics and power supply are placed in the BCDU ORU.

The flywheel power processing electronics and battery electronic packages have similar geometries and will be packaged in the BCDU ORU in a similar manner, adhering to the same specifications as the battery package. The PPU devices that are placed in the BCDU



Dimension	Standard	Battery	PFCS
A	41.0	41.0	41.0
B	29.0	37.0	29.0
C	13.5	18.6	17.5

Figure 5-2
Battery box ORU.

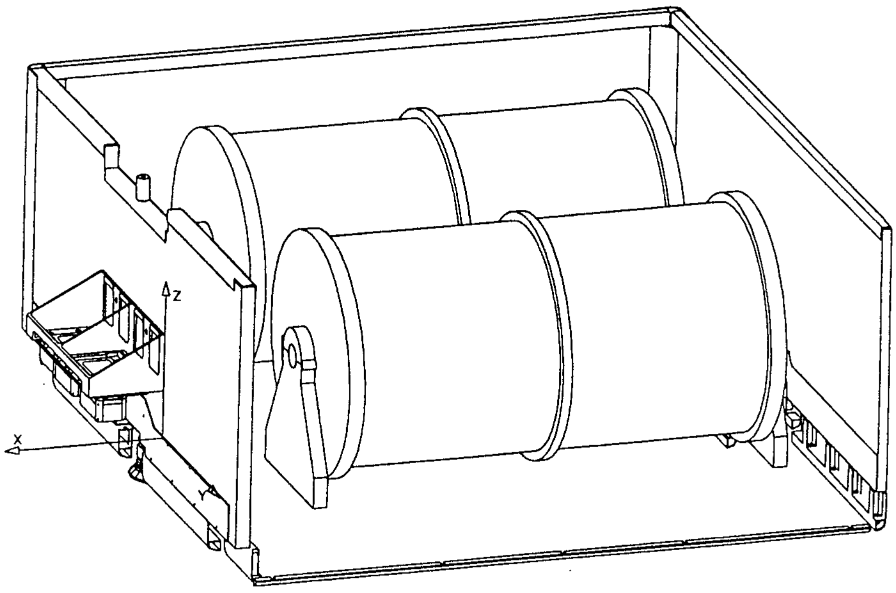


Figure 5-3
Flywheel pair placement in the battery box ORU.

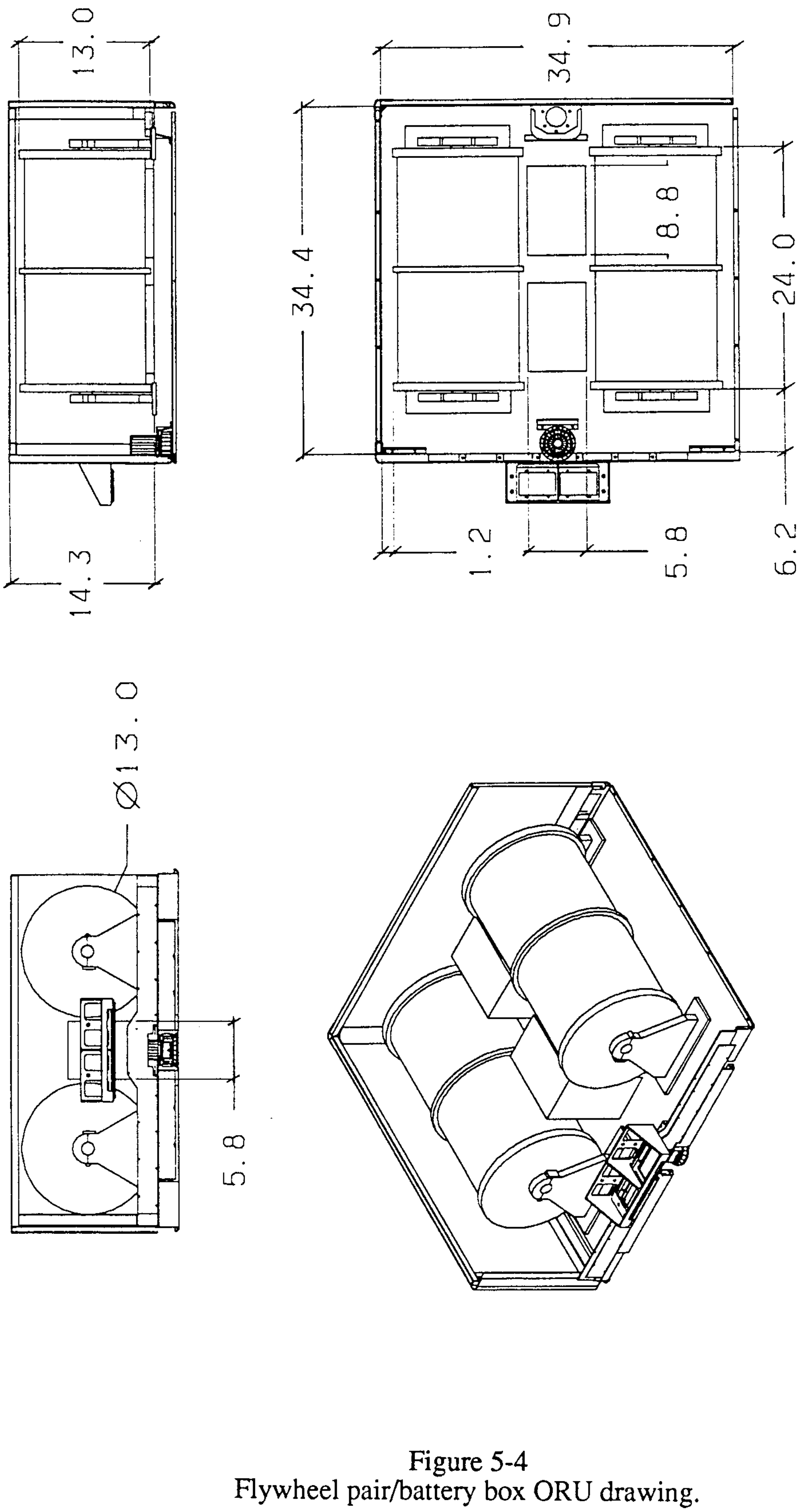


Figure 5-4
Flywheel pair/battery box ORU drawing.

and the interfaces to the flywheel ORU and Space Station are discussed in the next section. This similarity between the flywheel and battery electronics indicates there will be no changes to the BCDU geometry or internal support mechanisms for the circuitry. The only major change to the BCDU ORU is the addition of three phase AC power cables from the flywheel ORU (discussed in section 5.3).

Although the battery box ORU geometry remains the same for the flywheel application, its baseplate is designed specifically for batteries only. This is evident in Fig. 5-5, which shows the current baseplate design for the battery box. Each battery cell is fastened to the baseplate by a sleeve that is machined into the plate. The base plate has three rails that support the entire internal battery assembly. Heat rejection fins are machined on the exterior of the plate provide a heat-transfer path from the battery through the plate and fins and into the IEA thermal control system.

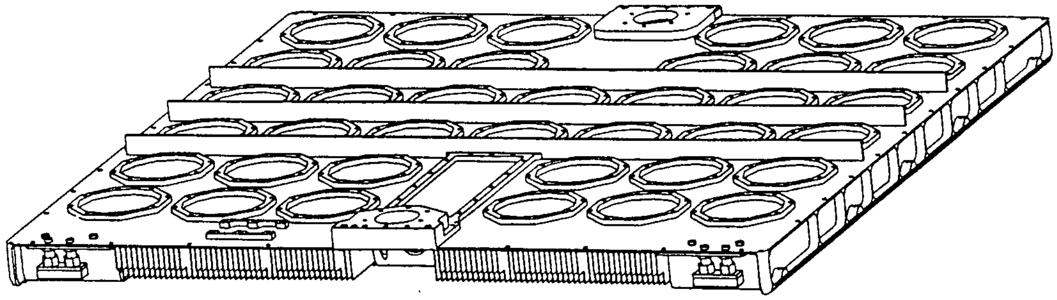


Figure 5-5
Existing Space Station battery box ORU base plate drawing.

This battery specific base plate design was modified to accommodate the flywheel pair and is shown in Fig. 5-6. The battery sleeves are no longer needed and are removed. Flywheel mounting hardware is added to the plate to adfix the flywheel to the ORU. The support rails are removed and the base plate thickness increased to provide additional support to the flywheels and associated equipment. The heat rejection fin assembly on the exterior-side of the plate is also removed because of the low heat rejection rate from the flywheels and magnetic bearing controllers. Thermal design considerations for the flywheel system, and the BCDU and flywheel ORUs are discussed in section 5.4.

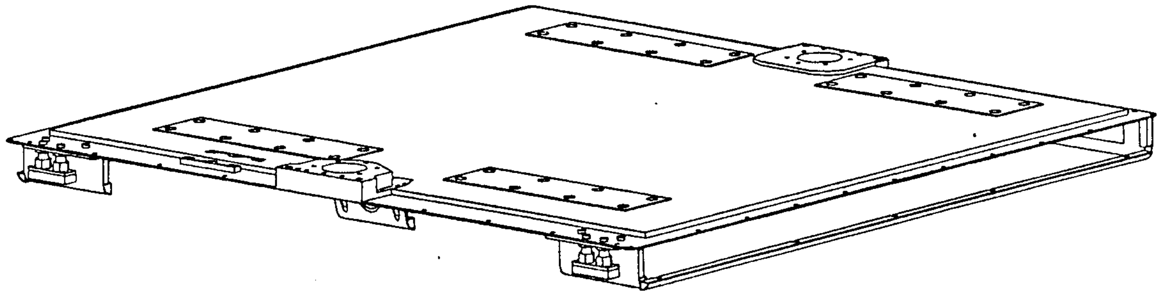


Figure 5-6
Redesigned battery box base plate for flywheel ORU.

5.3 Electrical Interface

A top level examination of the Space Station EPS was conducted to assess the feasibility of an experiment replacing the Ni H2 battery ORU box and BCDU, (Battery Charge Discharge Unit) for an EMB (electromechanical battery) ORU and a PPU (Power Processing Unit). This section discusses the results of this examination.

5.3.1 Major Subsystem Components

The present design in the Space Station EPS pertaining electrical power storage during insolation and electrical power supply during eclipse, consists of two elements, a Ni H2 battery ORU and a BCDU (Battery Charge Discharge Unit). The proposed Flywheel Energy Storage System system consists also of two elements, an Electromechanical Battery ORU and a PPU (Power Processing Unit). Basically the Battery ORU would be replaced by the electromechanical battery assembly and the BCDU by the PPU.

The electromechanical Battery ORU consists of four subassemblies (Table 5-1): 1) motor/generator, 2) rotor shaft position, 3) magnetic bearing, 4) magnetic bearing control system. The motor/generator design is a synchronous permanent magnet 3-phase variable voltage variable frequency machine capable to deliver 4 to 14 KW of nominal power. Although the magnetic bearing system has not been determined in this task order, a number of commercial designs are now available for future implementation. Advanced Controls

Technology Inc. from Northridge, CA has been working on a number of designs and have demonstrated their technology in a number of applications.

The PPU is the electronic control system with similar functions like the BCDU. The PPU is a bidirectional power converter and provides power to the motor from the DC bus and then when the motor works as a generator it converts generated AC power to DC power. The PPU has a Supervisory Control Monitor that controls the operation of the entire system and interfaces with the Space Station EPS computer power control. The bidirectional power converter in the PPU is a unipolar series resonant converter design

ELECTRO MECHANICAL POWER STORAGE SYSTEM

MAJOR SUBSYSTEM COMPONENTS

PRESENT DESIGN	ELECTRO MECHANICAL BATTERY (EMB) SUBSYSTEM DESIGN	EMB CHARACTERISTICS / OPERATION
NI H2 BATTERY ORU	EMB, ELECTROMECHANICAL BATTERY ORU: 1) MOTOR / GENERATOR ASSY 2) ROTOR SHAFT POSITION 3) MAGNETIC BEARING ASSY 4) MAGNETIC BEARING CONTROL SYSTEM	• 3Ø, VARIABLE VOLTAGE, VARIABLE FREQUENCY ELECTRICAL POWER GENERATED, 4 KW MIN POWER OUTPUT, 14 KW PEAK • SYNCHRONOUS MOTOR/GENERATOR, WITH PERMANENT MAGNET HALBACH ARRAY ROTOR DESIGN • IRONLESS STATOR, STATIONARY • MAGNETIC BEARING SYSTEM DESIGN TBD
BCDU BATTERY CHARGE DISCHARGE UNIT	PPU, POWER PROCESSING UNIT: 1) BIDIRECTIONAL POWER CONVERTER -MOTOR CONTROL SYSTEM -GENERATOR CONTROL SYSTEM 2) SUPERVISORY CONTROL MONITOR	• UNIPOLAR SERIES RESONANT POWER CONVERTER, BIDIRECTIONAL: 1) POWERS FLYWHEEL TO MAX SPEED, 2) CONVERTS GENERATED VARIABLE FREQ &VOLTAGE TO DC POWER. • SUPERVISORY CONTROL MONITOR INTERFACES PPU WITH ELECTRICAL POWER SYSTEM

Table 5-1
Major Subsystem Components of the EM Power Storage System.

5.3.2 Bidirectional Power Converter Controller

A top level electrical schematic for the motor/generator assembly an the BPCU (Bidirectional Power Converter Unit) interface is depicted in Fig. 5-7. The converter powers the motor from the DC bus and when the motor works as a generator then AC power is converted back to DC by the BPCU. The switching power functions of the converter are controlled by a digital control system that receives motor/generator rotor position information and control command signals from the supervisory control monitor of the PPU.

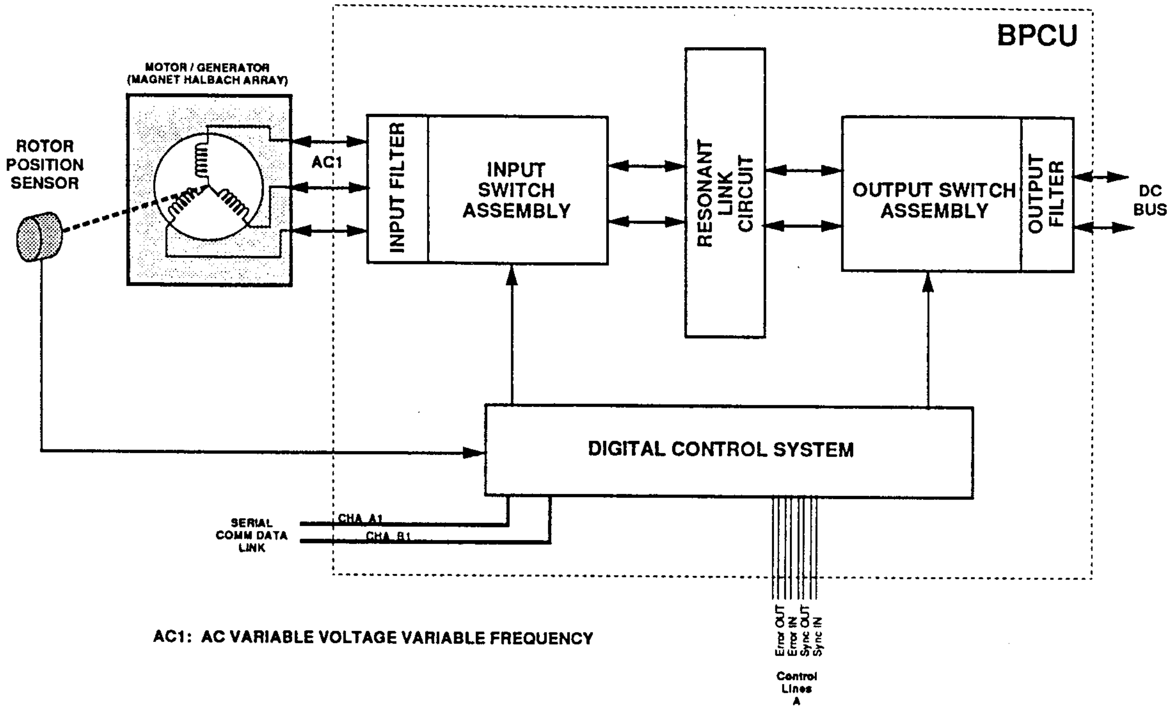


Figure 5-7
Bidirectional Power Controller Block Diagram.

5.3.3 4KW Power Converter

The unipolar series resonant converter depicted in Fig. 5-8 is a preliminary proposed design to interface the motor/generator with the DC bus operating in a bidirectional fashion. The MCT (MOS Controlled Thyristor) technology was considered for controlling the electrical power to the motor and from the generator to the DC bus. The MCT's are a new kind of power semiconductor devices that combine thyristor current and voltage capability with MOS gated turn-on and turn-off. This technology is characterized for providing minimum switching losses. The power circuit depicted consists of an input 3-phase bridge module connecting with the motor/generator, a resonant link module and an output bridge switch module. From generator output, the variable voltage variable frequency output signal is rectified and controlled by a resonant link circuit. The output of the resonant link circuit is then modulated to provide either a steady DC output or a variable DC output. In the opposite direction, from the DC bus, DC power is modulated by resonant link circuit. This signal then becomes the input to the input bridge module which controls power in a synchronous fashion to each phase of the motor.

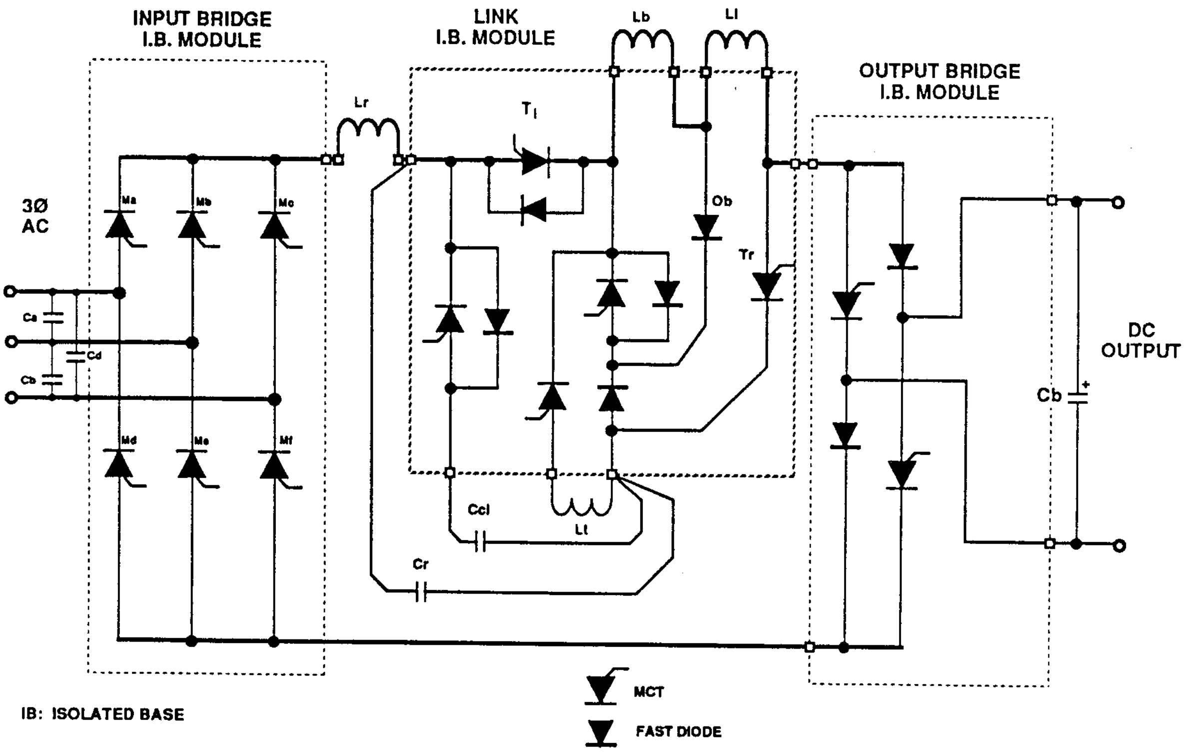


Figure 5-8
4 KW Power Converter Circuit Diagram.

5.3.4 Electromechanical Battery Power System

An overview of the electromechanical Battery design concept and its interface with the EPS (Electrical Power System) of the ISS is depicted in Fig. 5-9. The electrical power generated by solar array "charges" the flywheel during insolation. The DCSU (Direct Current Switching Unit) connects power to the PPU and distributes power to the loads. During eclipse the electromechanical Battery supplies power back to the DC bus. The DCSU isolates or connects the EMB system with the EPS.

The flywheel and the magnetic bearing control system are assembled in the EMB ORU. Because of the relatively large number of electrical connections expected between the magnetic bearing control system and the flywheel assembly, this hardware topology appears to be more suitable for maximum system reliability. Estimates that anywhere between 20 to 30 % of the circuit design may involve low voltage analog signals of which normally are susceptible to electrical noise and EMI.

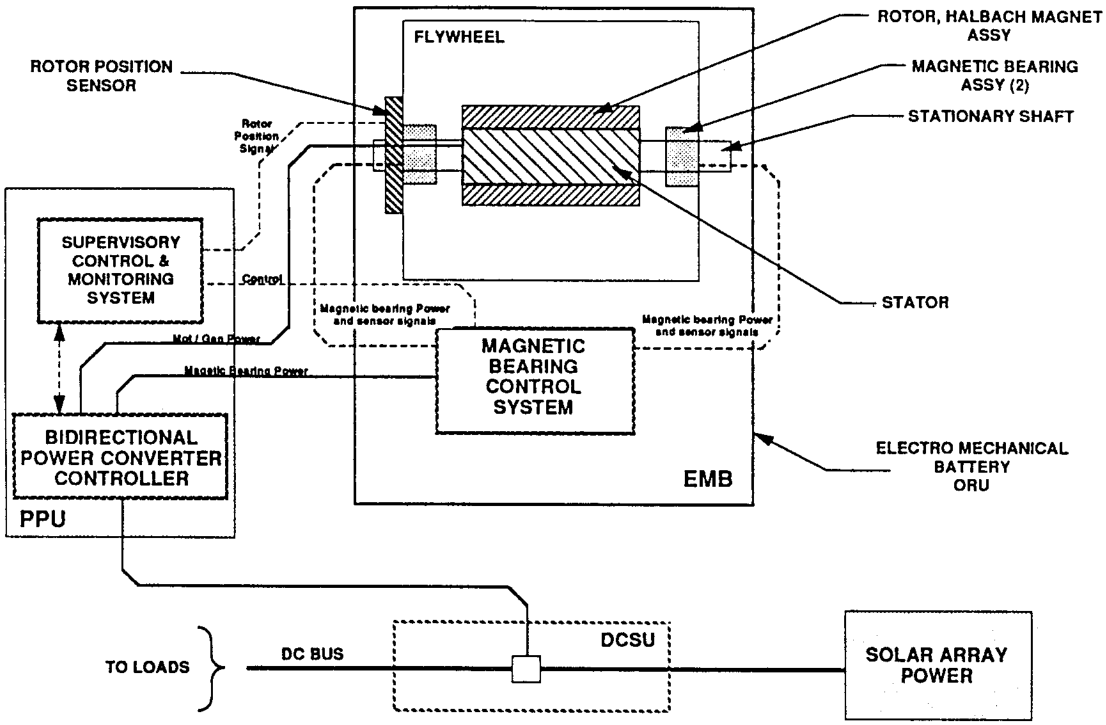


Figure 5-9
Flywheel System - EPS Interface.

5.3.5 Power Hookup Interface

A power hookup interface is depicted in Fig. 5-10 comparing the present space station design and the design involving electromechanical Batteries

In the electromechanical Battery approach, the PPU replaces the BCDU, and the Battery ORU is replaced By the EMB ORU. Each EMB ORU has a pair of Flywheels each rotating in opposite direction. The power hookups with the DCSU are unchanged. Existing connections between BCDU and Battery ORU may not be utilized in the replacement. As will be shown latter on, existing cable harnesses for subsystem control and EPS interface are utilized.

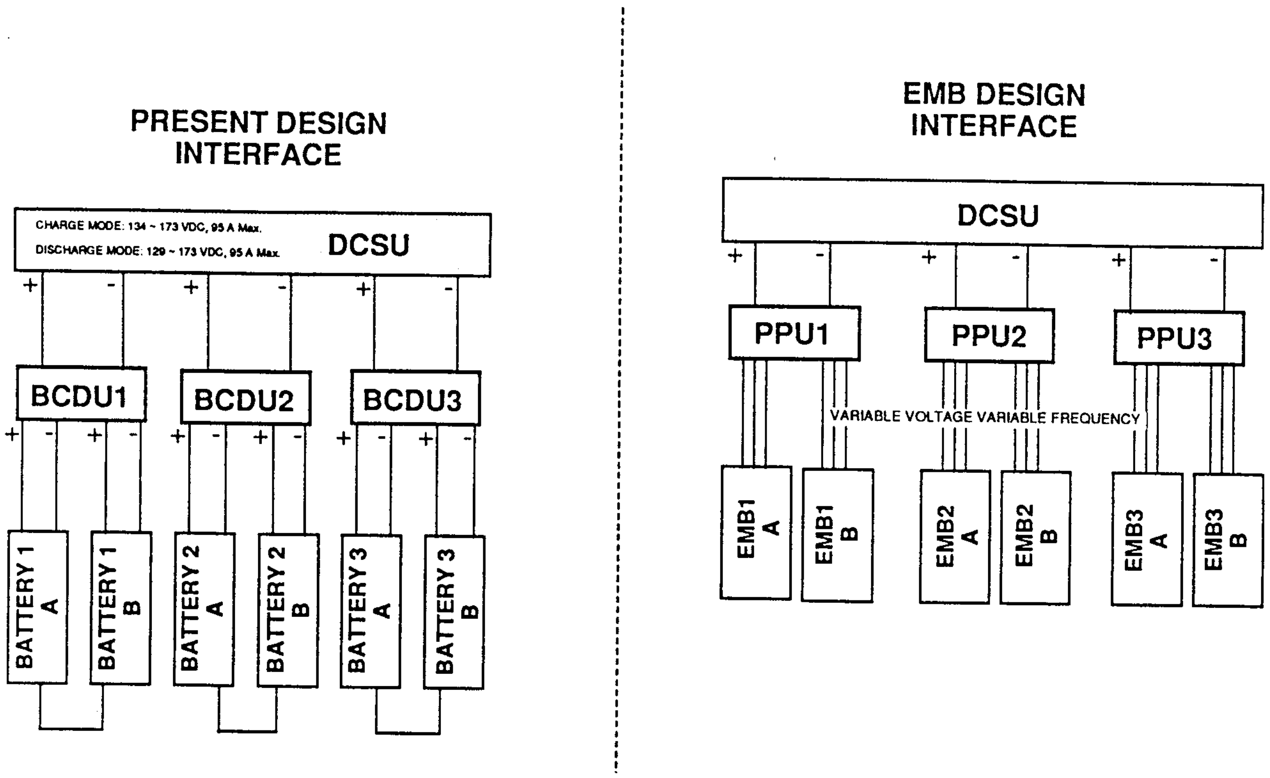


Figure 5-10
Comparison between Existing BCDU-DCSU Interface and Proposed EMB-DCSU Interface.

5.3.6 BCDU/PPU Interface Comparison

A more detailed comparison of the electrical interconnections between BCDU and PPU are depicted in Fig. 5-11 for the existing BCDU and Fig. 5-12 for the flywheel PPU. As can be observed except for the hookups between BCDU - Batteries and PPU - Flywheels, the rest are left unchanged. The LDI of the BCDU is substituted by the SCM, (Supervisory Control Monitor). The SCM performs a number of control and health monitoring functions such as the synchronous operation of the two flywheels during charging and discharging modes, magnetic bearings performance and control interface with the Space Station EPS.

BCDU

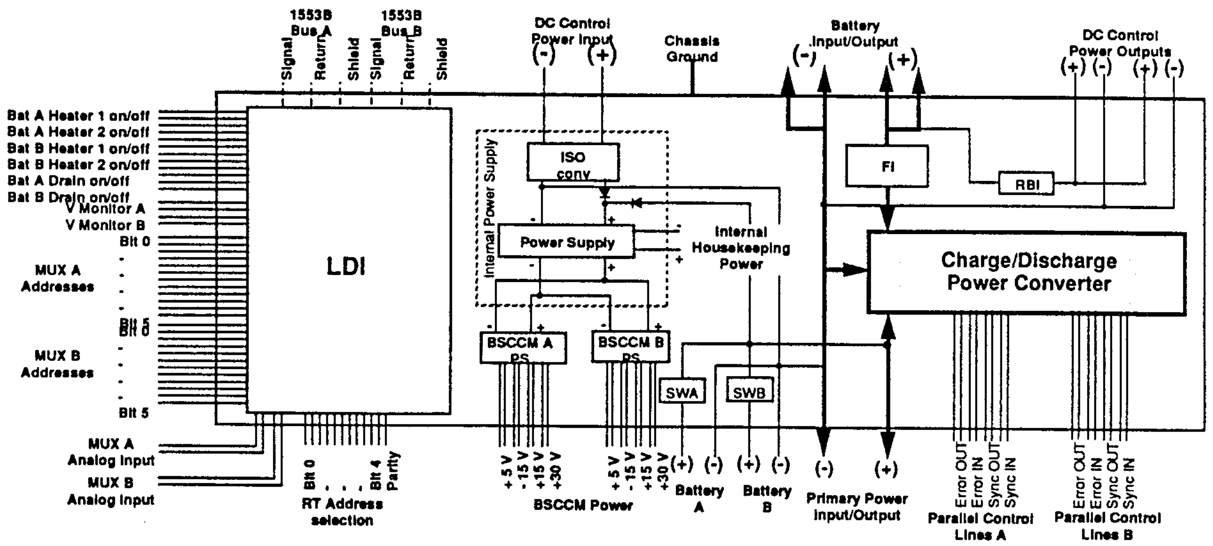


Figure 5-11
Current BCDU Interface Diagram.

PPU

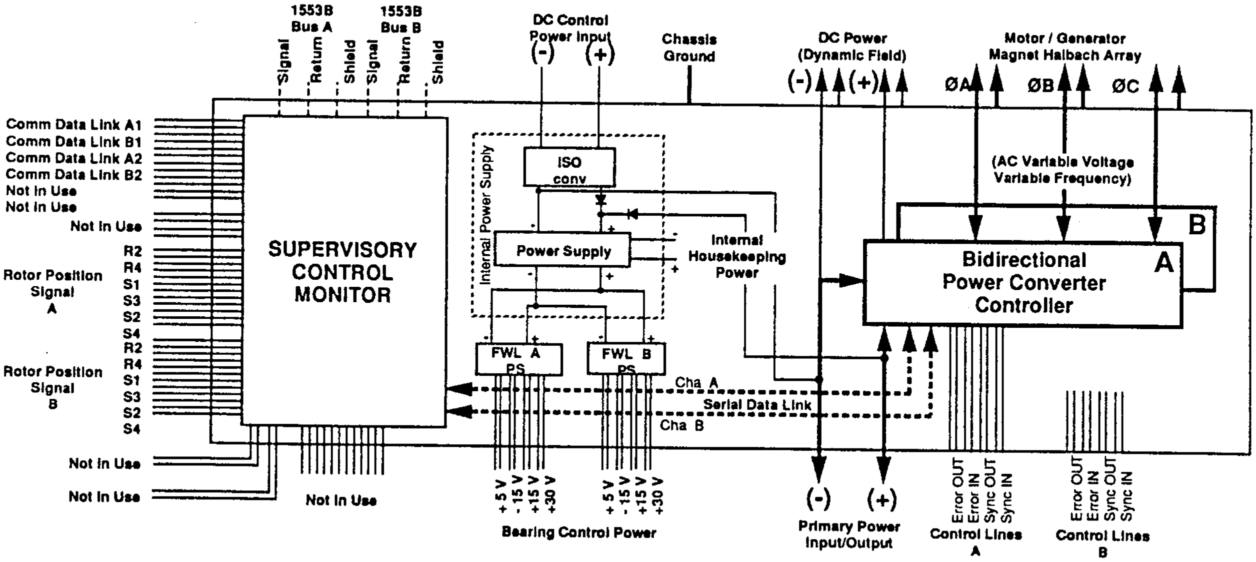


Figure 5-12
Proposed PPU Interface Diagram.

5.3.7 EMB ORU/PPU Electrical Interconnecting

A detailed overview of the electrical interconnecting between the EMB ORU and PPU is presented in Fig. 5-13. Except for the motor/generator electrical power hookups, the existing cable harnesses appear to be suitable to handle all signals required by the EMB system. In paragraph 5.4.4 it was briefly discussed the advantages for having the magnetic bearing controls assembled in the EMB ORU. The block diagram of the EMB ORU depicted in Fig. 5-13 shows the magnetic bearing system's components and interconnections.

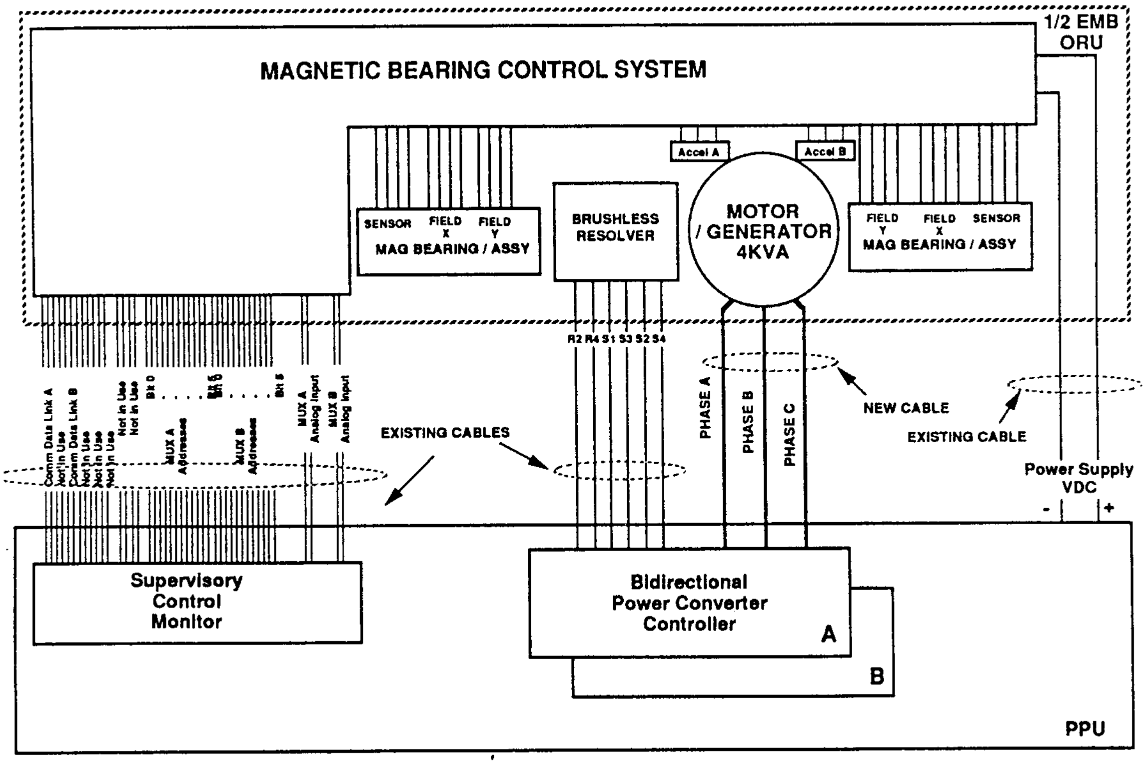


Figure 5-13
Flywheel ORU - PPU ORU Major Interfaces.

5.3.8 Retrofit Interface Requirements

A summary of retrofit interface requirements is listed in Table 5-2. The EMB ORU would require a total of two additional electrical power receptacles, and the PPU would require two power plugs. To interconnect the EMB ORU with PPU, two cable harnesses will be required. This is a new item that would have to be added in the retrofit.

COMPONENT	ELECTRICAL HARDWARE INTERFACE ISSUES
EMB ORU	TWO ADDITIONAL ELECTRICAL POWER RECEPTACLES REQUIRED, EACH, 4 PIN, AWG # 10 WIRE SIZE
PPU	TWO ADDITIONAL ELECTRICAL POWER, PLUGS REQUIRED, EACH 4 PIN, AWG # 10 WIRE SIZE
ELECTRICAL HARNESSES (NEW)	TWO CABLE HARNESSES, EACH, SHIELDED CABLE WITH 4 CONDUCTORS, AWG #10, STRANDED WIRE. EACH CABLE ENDED WITH RECEPTACLE AND PLUG CONNECTORS

Table 5-2
Flywheel Retrofit Interface Requirments.

5.4 Thermal Interface

One key advantage of the flywheel system is its higher inherent efficiency compared to the Space Station battery system. Based on Rocketdyne's previous flywheel study, the flywheel charge/discharge efficiency is:

(15.63 kW x 35 minutes discharge)/(11.05 kW x 57 minutes charge) = 86.9%.

This compares to predicted battery charge/discharge efficiency of:

(12.2 kW x 35 minutes discharge)/(13.0 kW x 57 minutes charge) = 57.6%.

The battery/BCDU system requires a thermal control subsystem (TCS) to remove battery/BCDU waste heat, and maintains the NiH batteries within their specified temperature operating range of 32 to 50 degrees F. A functional description and design specifications of the TCS are discussed in detail in Ref. 5-1. When the battery/BCDU ORUs are replaced by the flywheel/PPU ORUs, the IEA waste heat load drops from 7.5

kW/IEA to 2.7 kW/IEA. Thus, the existing TCS is sufficient to meet this lower heat load requirement for the flywheel system and no additional thermal capacity is required.

Power flows through the DC Switching Unit (DCSU), the PPU and the flywheel pair are shown in Fig. 5-14 for the Eclipse portion of the orbit (flywheel discharge) and in Fig. 5-15 for the Insolation portion of the orbit (flywheel charge). This computation assumed the PPU, flywheel, and Halbach Array power losses from Ref. 3-1 and computed component efficiencies based on the power flows. Thus, the flywheel/Halbach Array efficiencies are computed to be 98% and the PPU efficiency range to be 94 to 95.7%.

The total energy loss of the flywheel pair in the flywheel ORU amounts to approximately 70 watts/ORU. This low energy loss, together with the wider operating temperature range of the flywheel is the reason the exterior heat fin assembly is not required for the flywheel ORU. The PPU ORU remains actively cooled by the TCS because of the higher heat load (230 W) and tighter temperature range. Table 5-3 summarizes the waste heat loads and specified temperature ranges of the flywheel and PPU ORUs.

ORU	Nonoperating Temperature Range °F	Operating Temperature Range °F	Charge/Discharge Thermal Losses (W)
Flywheel	-150 to 150	-150 to 150	70
PPU	-65 to 180	-11 to 104	230

Table 5-3
On-Orbit Temperature Capabilities and Heat Load Requirements of Flywheel ORUs.

5.5 Failure Analysis and Risks

An analysis was conducted in the EMB ORU and PPU units to identify and evaluate the possible failure mechanisms, its consequences and to determine the necessary actions to minimize the risks that would be imposed on the Space Station Alpha in the event of a system malfunction.

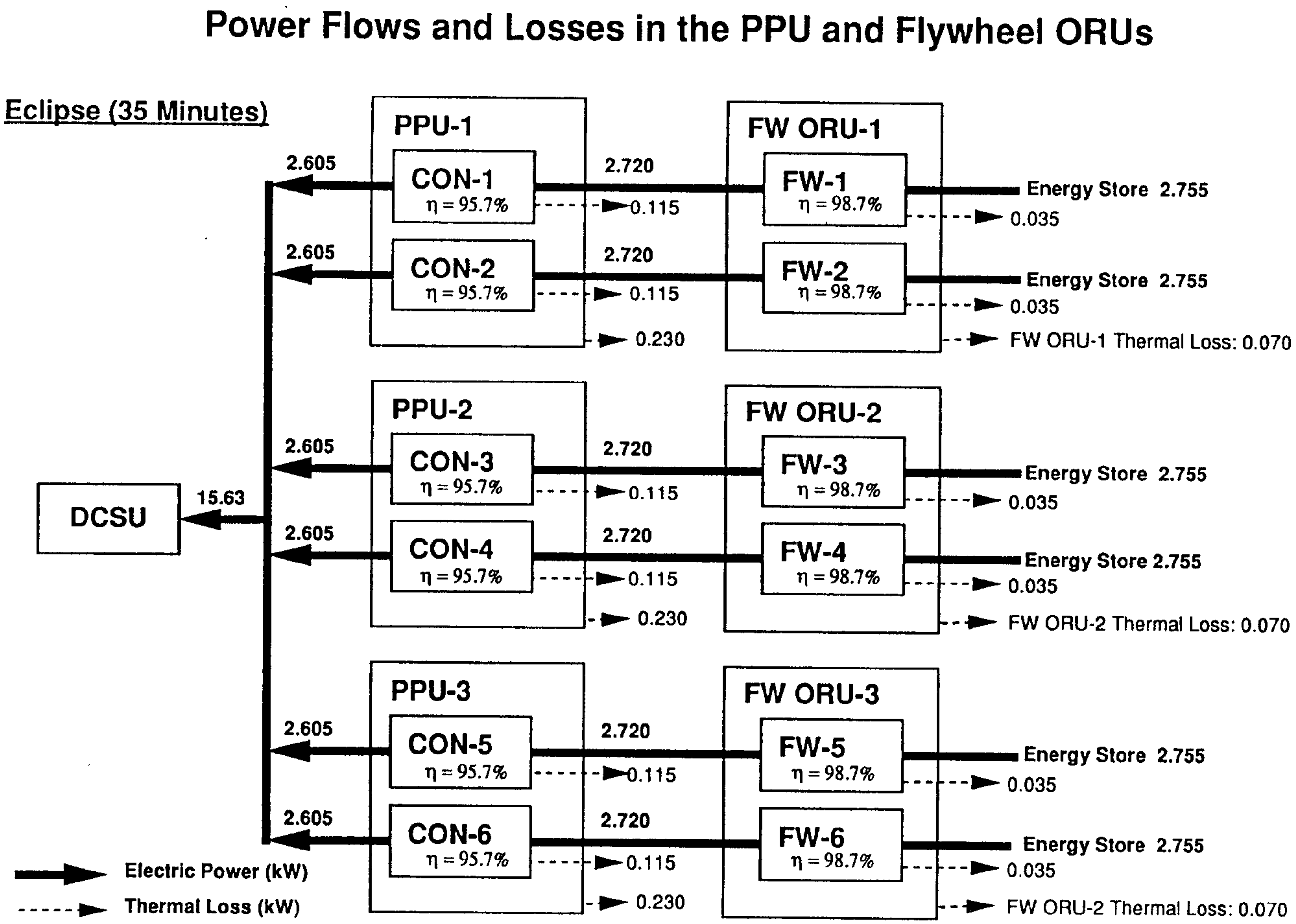


Figure 5-14
Power Flows and Losses in the PPU and Flywheel ORUs during Orbit Eclipse.

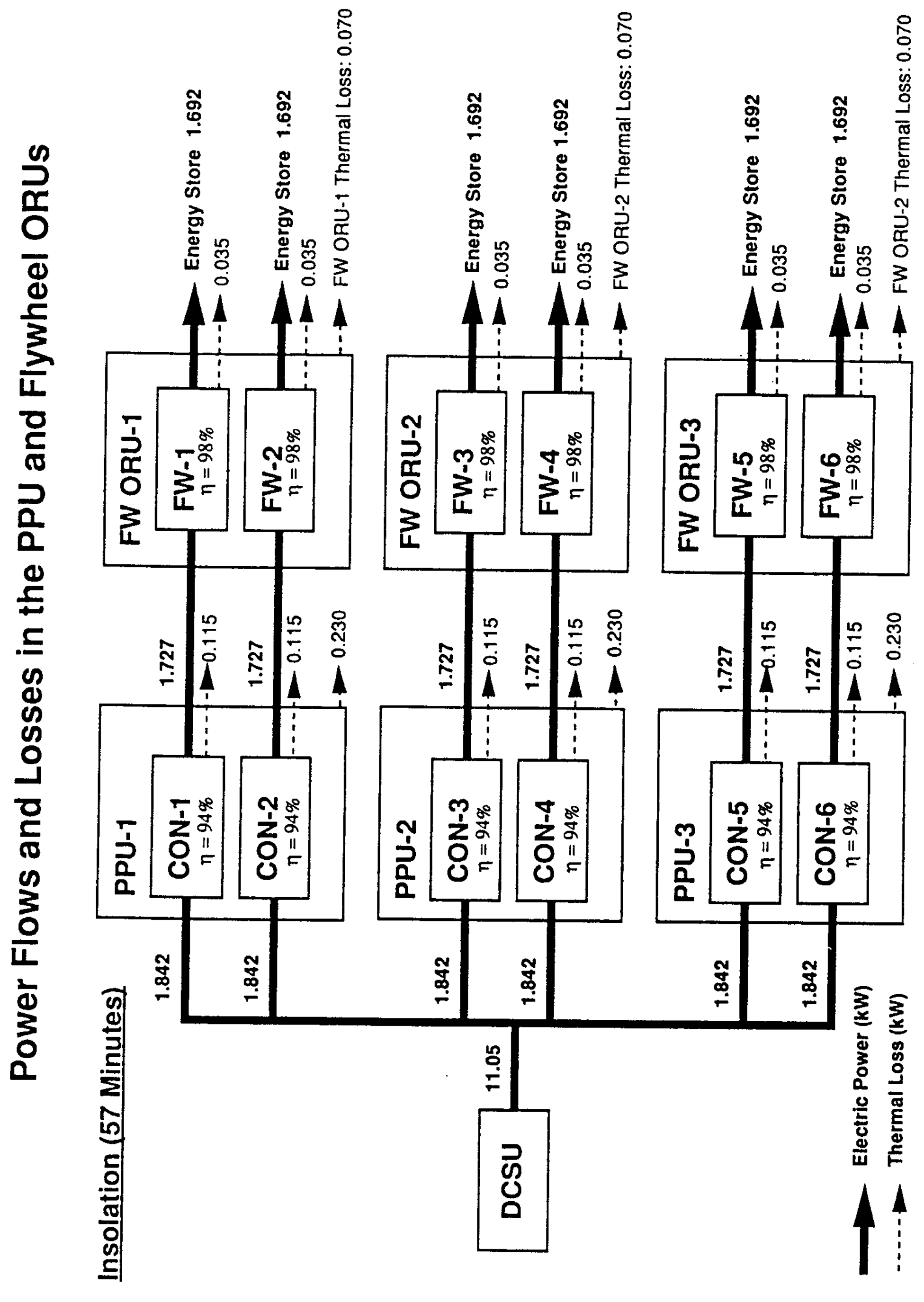


Figure 5-15
Power Flows and Losses in the PPU and Flywheel ORUs during Orbit Insolation.

5.5.1 Electrical Failure Analysis

During the preliminary design of the system, a number of options were investigated and weighed to minimize the risks and also to provide the best performance. These are summarized in Table 5-4.

	COMPONENT	FAILURE MECHANISMS	CONSEQUENCES	ACTION / IMPACT ON SYSTEM		
				EMB	PPU	SSEPS*
ELECTROMECHANICAL BATTERY ORU	MOTOR / GENERATOR	• PHASE, OPEN / SHORT • ROTOR PERMANENT MAGNET FATIGE	• OVERHEATING • UNBALANCE • FWL POWER LOSS	1) SHUTDOWN EMB 2) ISOLATE PPU 3) REPLACE EMB	NONE	• NO MAJOR RISKS ARE EXPECTED IF ONE EMB IS OUT OF ORDER. • IF TWO EMBs ARE OUT OF ORDER, THIS MAY REDUCE THE SPACE STATION TOTAL ELECTRICAL POWER OUTPUT • NOTE: AN ACCEPTABLE CRITERIA FOR DESIGNING THE SYSTEM WOULD BE ON THE ASSUMPTION OF DOUBLE EMB FAILURE AND FOR THE SYSTEM STILL CAPABLE TO DELIVER THE NOMINAL ELECTRICAL POWER OUTPUT REQUIRED
	ROTOR POSITION SENSOR	• OPEN / SHORT CIRCUIT • ROTOR FATIGE	• MOTOR / GENERATOR CONTROL LOSS	1) SHUTDOWN EMB 2) ISOLATE PPU 3) REPLACE EMB	NONE	
	MAGNETIC BEARINGS	• OPEN / SHORT CIRCUIT • SENSOR	• OVERHEATING • UNBALANCE • FWL POWER LOSS	1) SHUTDOWN EMB 2) ISOLATE PPU 3) REPLACE EMB	NONE	
	MAGNETIC BEARING CONTROLLER	• ELECTRONIC CONTROL HARDWARE • SENSOR INTERFACE • SYSTEM INTERFACE HARDWARE	• BEARING CONTROL LOSS • FWL POWER LOSS	1) SHUTDOWN EMB 2) ISOLATE PPU 3) REPLACE EMB	NONE	
POWER PROCESSING UNIT	BIDIRECTIONAL POWER CONVERTER CONTROLLER	• PHASE, OPEN / SHORT • ELECTRONIC CONTROL HARDWARE • INTERFACE ELECTRONIC HARDWARE	• MOTOR / GENERATOR CONTROL LOSS • HEALTH MONITORING SYSTEM LOSS • ELECTRICAL POWER OUTPUT MALFUNCTION	NONE	1) SHUTDOWN EMB 2) ISOLATE PPU 3) REPLACE PPU	
	SUPERVISORY CONTROL MONITOR	• 1553B BUS PORTS, (2) • INTERFACE ELECTRONIC HARDWARE	• PPU CONTROL LOSS • EMB CONTROL LOSS	NONE	1) SHUTDOWN EMB 2) ISOLATE PPU 3) REPLACE PPU	

SSEPS* : SPACE STATION ELECTRICAL POWER SYSTEM

Table 5-4
Flywheel ORU Failure Analysis Summary.

The Halbach Array Motor /Generator possible disintegration due to high centrifugal forces at high speeds is the worst mode of failure found. This type of failure would be detected on time by means of measuring the acceleration levels on the flywheel at more than one point. In the event of this kind of failure, an immediate EMB shutdown would have to take place, by means of totally or partially shorting out the phases on the stator by PPU and also controlling the speed of the remaining flywheel until stop.

Rotor position sensor, magnetic bearings, and magnetic bearing controller failures were also analyzed. The worst modes of failure for this components resulted in the eventual shutting down of the EMB without any catastrophic risks.

The failure mechanisms of the PPU resulted in motor/generator control loss or health monitoring loss or loss of control interface with Space Station EPS. In all these cases it was possible to shutdown the EMB and complete recommended system isolation.

5.5.2 Design Analysis & Issues

A list of design issues are summarized in Table 5-5. Two of the design issues that are important in the future development of flywheel energy storage systems deal with the fact that limited test data has been available for the motor/generator design. It is important that a Halbach Array motor/generator would be built and tested. Magnetic bearings at this point are not as necessary because still a preliminary evaluation of the design can be accomplished.

SUBSYSTEM	KEY ISSUES	PRELIMINARY RECOMMENDATIONS
EMB ORU	• LIMITED TEST DATA AVAILABLE FOR MOTOR/GENERATOR DESIGN • A MAGNETIC BEARING CONTROL SYSTEM NEEDS TO BE IDENTIFIED • PPU INTERFACE SOFTWARE NEEDS DEVELOPMENT	• BUILD, TEST AND VERIFY DESIGN DATA OF A FULL SIZE MOTOR GENERATOR • DESIGN & BUILD BREADBOARD OF MAGNETIC BEARING CONTROL SYSTEM • INTEGRATE & TEST MOTOR / GENERATOR, FLYWHEEL & MAGNETIC BEARING ASSY
PPU	• BIDIRECTIONAL OPERATION OF VF / DC POWER CONVERTER • PARALLEL OPERATION BETWEEN VF / DC POWER CONVERTERS • PPU / EPS INTERFACE SOFTWARE NEEDS DEVELOPMENT	• BUILD AND TEST A VF / DC POWER CONVERTER • DESIGN & BUILD BREADBOARD OF MAGNETIC BEARING CONTROL SYSTEM • INTEGRATE & TEST MOTOR / GENERATOR, FLYWHEEL & MAGNETIC BEARING ASSY • TEST AND EVALUATE PARALLEL OPERATION

Table 5-5
Flywheel ORU Design Issues.

6.0 Flywheel Demonstrator Experiment

The flywheel demonstrator experiment is a flight-qualified Space Station Alpha experimental payload designed to investigate the practical deployment of a Space Station sized (but generic) flywheel pair/PPU ORU in a space environment. This section presents an initial specification of the experiment, its objectives, the experimental package deployment location on the Space Station, a description of the flywheel and PPU interfaces, possible failure mechanisms, and a test manifest and testing schedule.

6.1 Overview

Dynamic power generation and energy storage techniques historically have not been selected nor utilized for manned/robotic missions because of technical immaturity and perceived difficulties and incompatibilities germane to the dynamics of the machine. Static power generation and storage devices such as fuel cells, photovoltaic arrays, RTGs, and batteries have traditionally been deployed for most missions to date. For dynamic cycle devices, the key issue is the resolution of these technical issues that obstruct their present-day and future deployment.

The demonstrator experiment is a necessary first step to resolve these technical uncertainties for flywheel technology. Before dynamic devices are accepted as a legitimate power generation/storage alternative to the standard static devices, all technical doubts and questions must be satisfactorily resolved. Many of these technical issues can be answered in the laboratory. Ultimately, a space-based experiment will be needed to realistically measure machine-payload compatibility and quantify machine-environment interactions under actual space conditions. Space Station Alpha is the perfect space-based, man-tended, power-rich platform to perform such tests. In the case of the flywheel, an experimental package consisting of a flywheel pair and associated power conversion and control electronics is proposed for Space Station deployment to demonstrate the technology in a space environment.

This task consisted of crafting the objectives of the flywheel experiment and specifying the basic requirements of the total package. The experimental hardware consists of the flywheels, motor/generators, control electronics, power processing electronics, enclosure and interface to Space Station Alpha. Although the Space Station is an excellent platform to perform this test, the energy storage capability of the flywheel demonstrator creates unique interface requirements to the Station. The overall experimental objectives also impact the Space Station deployment location. This task also delineated failure mechanisms and possible safety risks to the Space Station and personnel during flywheel demonstrator operation. The approach taken to investigate the concept of a space-based flywheel demonstration experiment was:

- Define technical objectives.
- Specify Demonstrator electrical, structural and thermal requirements.
- Specify location (on Space Station) of experimental package.
- Examine interface between Demonstrator and Space Station.
- Examine Demonstrator safety risks and possible failure modes.

6.2 Demonstrator Experiment Objectives and Specifications

Flywheel pair energy storage has never been utilized on a space-based platform. Hence, this experiment represents the first flywheel pair deployment in space and is a key milestone to eventual acceptance of EM energy storage devices for space missions. There are two possible approaches to the flywheel demonstrator experiment. The first is to consider the total experimental package to be Space Station specific only. That is, tailor the device specifications and hookup location on the Space Station to closely simulate an actual hookup of a flywheel/PPU ORU within an IEA. This would involve a direct interface with the primary EPS bus. In this case, the demonstrator objectives are oriented specifically at future Space Station deployment only.

The second option is to consider the demonstrator experiment in a generic sense, designed for no particular mission. There are many possible missions for flywheel energy storage devices; LEO satellites, deep-space probes, surface planetary manned/robotic loads, and Space Station Alpha. In this case, Space Station hookup location is not an issue and the experiment focuses on the key flywheel technical issues. After consultation with Space Station personnel and flywheel experts at Rocketdyne and NASA LeRC, this latter approach was selected. Space Station hookup location considerations that entered into this deliberation are discussed in the next section.

Note that an underlying assumption is that the demonstrator package will be deployed on Space Station Alpha, as opposed to the Russian Mir station, as a space shuttle payload, or on a dedicated LEO platform. In the event the flywheel demonstrator experiment cannot be tested on Space Station Alpha, it can be appropriately scaled and tested on an alternative platform.

In keeping with this generic flywheel philosophy, the key objective of the flywheel demonstrator experiment is to resolve all flywheel technology issues by demonstrating space operation of all critical flywheel technologies. In so doing, it is hoped this demonstration will show that flywheel energy storage techniques are a viable alternative to conventional energy storage devices such as fuel cells or batteries.

This overall objective can be divided into two sets of subobjectives, each with its own specific demonstrator objectives as shown in Table 6-1. The first subobjective is to demonstrate that the flywheel pair system meets all designated design performance technical goals. These include demonstrating total system efficiency, transient response and steady-state operation at various power levels, charge/discharge characteristics and efficiency, stability (electric and rotational), system autonomy, adaptability at different power levels and charge/discharge cycles, and that the total system does not catastrophically fail and works successfully during the entire test period.

<table>
<tr><th colspan="2">Resolve flywheel technology issues by demonstrating space operation</th></tr>
<tr><th>Performance</th><th>External Impacts</th></tr>
<tr><td>• Efficiency
• Transient/Steady-State
• Design/Offdesign
• Startup/Shutdown
• Autonomy
• Life
• Robustness</td><td>• Space Environment
  • Zero-g
  • Vacuum
  • Radiation
  • Thermal
• Space Station
  • Electrical
  • Structural
  • Thermal
  • Dynamics</td></tr>
</table>

Table 6-1
Heirarchy of Flywheel Demonstrator Objectives.

The second set of objectives is to understand and clarify the impacts and interface issues between the flywheel system, the Space Station, and the space environment. Thus, the effect of the space environment upon the flywheel demonstrator materials and operation, the measurement and impact of flywheel dynamic disturbances upon the Space Station, and the impact of adverse Space Station conditions (current spikes, energy availability, EVA requirements, etc.) are key technical measures of the robustness or viability of the flywheel energy storage device to the overall mission, platform, and operation environment.

Primary flywheel experiment specifications include:

1) The demonstrator will consist of two flywheel motor/generator units rated at 2.14 kW-hrs total energy storage and 1.61 kW-hrs useable energy storage per flywheel. The total demonstrator energy storage capability is 3.22 kW-hrs. The operational flywheel speed will be 26 - 52 kRPM and is capable of 78 kRPM. Note that this energy storage capability is the same as the proposed Station flywheel replacement ORU. This similarity in size was selected to minimize design and development tasks as the overall program moved from the demonstrator phase to the ORU replacement program (discussed in section 7.0).

2) The flywheel input voltage will be 120 - 126 VDC, which is the specified Station secondary side voltage of the DDCU. Note that this is different from the BCDU input voltage range of 134-173 VDC, which would also be the input voltage for the flywheel replacement ORU. It is not an objective of the flywheel demonstrator experiment to test the wider voltage range of the primary side station EPS because that can be adequately tested on the ground.

3) The flywheel pair will be placed in the battery ORU box (similar to the replacement ORU) and the associated power converter electronics will be packaged in the BCDU ORU. Both boxes are mounted on support pallet that provides the direct interface to the Space Station.

4) Special thermal requirements of the demonstrator will be met by Space Station resources.

5) The flywheel demonstrator will be hooked external to the Station EPS on the secondary power side using the external utility ports. This location offers enhanced safety

and operational stability and minimizes Station structure scars. The next section discusses the rationale behind this selection.

6) The demonstrator will be capable of space-based operation of one year duration, subjected to a rigorous test program (discussed in section 6.7).

Other more specific requirements such as special ground equipment, prelaunch storage and checkout, shuttle launch considerations, cargo bay concerns, etc. were not considered in this task.

6.3 Demonstrator Hookup Location Evaluation

Space Station Alpha is an excellent platform to test energy sources, power generation and energy storage technologies in a zero-g, vacuum, space environment. The station will be mantended after August 1997 with permanent six man on-orbit presence established in CY2002. Although experimental payload autonomy is a crucial payload requirement that minimizes EVA and operational time, human operational and maintenance capabilities are invaluable, as proven by the Hubble Space Telescope service mission, STS-61. The station also provides a stable dynamic platform that will allow precise measurement of dynamic disturbances by the power device operation. One unique advantage the Space Station enjoys over all other space-based platforms is its power generation capabilities that are critical (and necessary) to the testing of energy storage devices. The Space Station also has additional thermal maintenance resources that could be interfaced to potential experiments with high heat rejection needs or tight temperature range requirements.

Table 6-2 summarizes the five demonstrator deployment strategies that were considered in this task. Each has its own set of advantages and disadvantages, discussed below.

Demonstrator Deployment Scenario	Space Station Interface		
	Power	Load	Structure
1. Battery/BCDU Replacement	yes	yes	yes
2. Empty Battery/BCDU Slot	yes	yes	yes
3. Station Supplied Power and Load	yes	yes	no
4. Autonomous Power and Load	no	no	no
5. Station Power/ Autonomous Load	yes	no	no

Table 6-2
Summary of Flywheel Demonstrator Station Hookup Configurations.

1. Battery Box/BCDU Replacement

Replace an operational battery/BCDU ORU within the IEA with the demonstration package. The power and load are provided by the Station (Fig. 6-1).

This scenario is schedule independent and requires minimal Station hardware changes to implement. The schedule independence and minimal Station changes implies a lower cost (compared to the other alternative scenarios). Operational risk increases if the excess energy stored by the demonstration unit is needed by the Station load. Rigorous, independent testing of the flywheel/PPU ORU is not possible for this configuration. The flywheel ORU is directly interfaced with the EPS primary bus. Electrical stability of the total system is an issue and dependent on the eventual flywheel/PPU design.

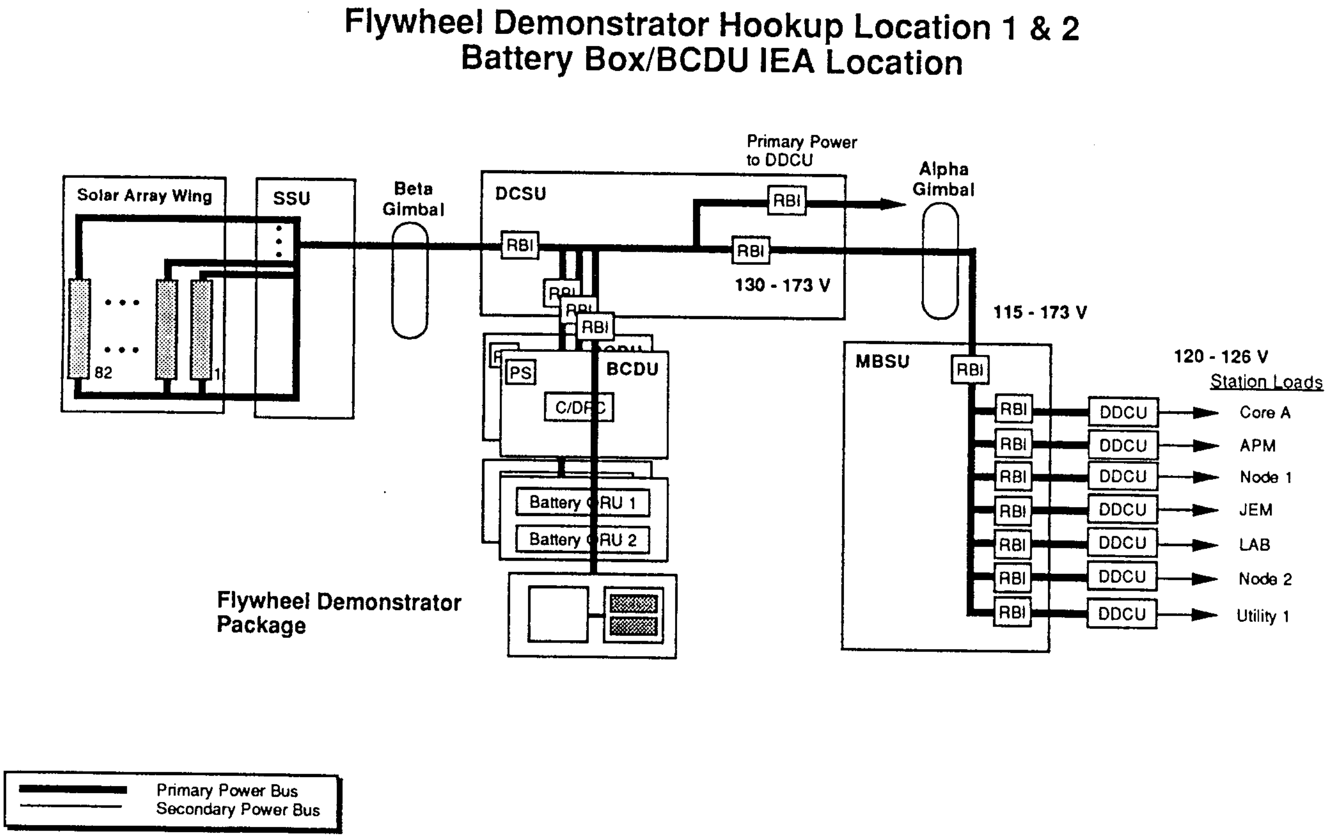

Flywheel Demonstrator Hookup Location 1 & 2
Battery Box/BCDU IEA Location

Figure 6-1
Flywheel Demonstrator Hookup Locations 1 & 2; Battery Box/BCDU IEA Location.

2. Empty Battery/BCDU Slot Insertion

Place the demonstration package in an empty IEA battery ORU/BCDU slot during station construction during October 1999 through December 2000. The power and load are provided by the Station (Fig. 6-1).

There is a higher schedule risk due to the early deployment of the demonstration package and limited window of opportunity to do so, but a lower risk to normal station operations. As in the first scenario, there are minimal changes to the Station hardware since the IEA is the experimental platform. Independent testing of the flywheel/PPU ORU is not possible for this configuration. The flywheel/PPU ORU is directly interfaced with the EPS primary bus. Electrical stability of the total system is an issue, dependent on the eventual flywheel/PPU design.

3. Station Supplied Power and Load

Place the demonstration package exterior to the IEA with the power and load provided by the station (Fig. 6-2).

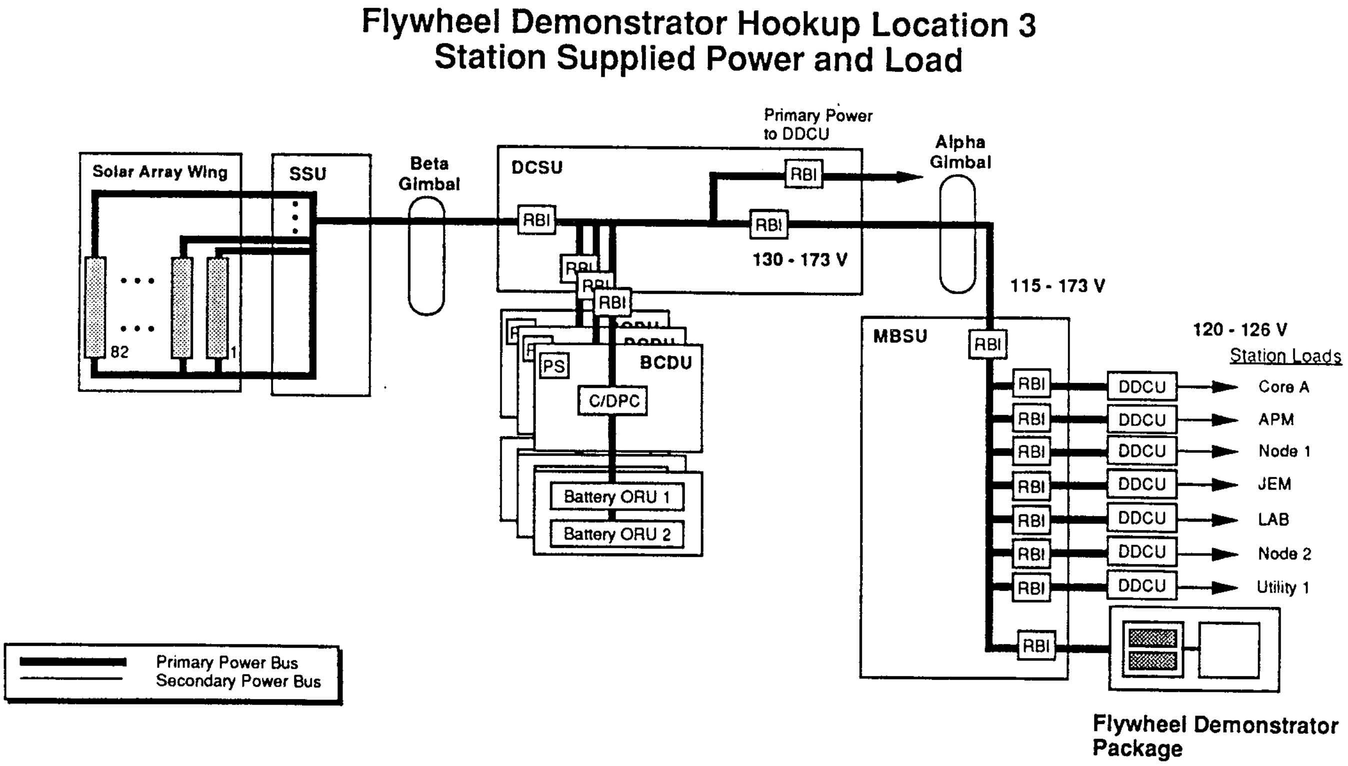

Flywheel Demonstrator Hookup Location 3
Station Supplied Power and Load

Figure 6-2
Flywheel Demonstrator Hookup Locations 3; External to IEA with Station Power and Load.

There is lower inherent risk to station operations in this scenario since the station load is not dependent upon the demonstrator excess energy storage. It is also schedule independent but can incur extra cost by additional Station hardware modifications (control and power lines). The demonstrator is interfaced to the EPS primary bus through the Main Bus Switching Unit (MBSU). Since the Space Station provides the load, independent testing of the flywheel experiment is limited. Electrical stability may be an issue when the demonstrator is interfaced directly on the primary power bus.

4. Autonomous Power and Load

Place the demonstration package exterior to the IEA with the power and load provided by autonomous systems (Fig. 6-3).

Flywheel Demonstrator Hookup Location 4
Autonomous Power/Load

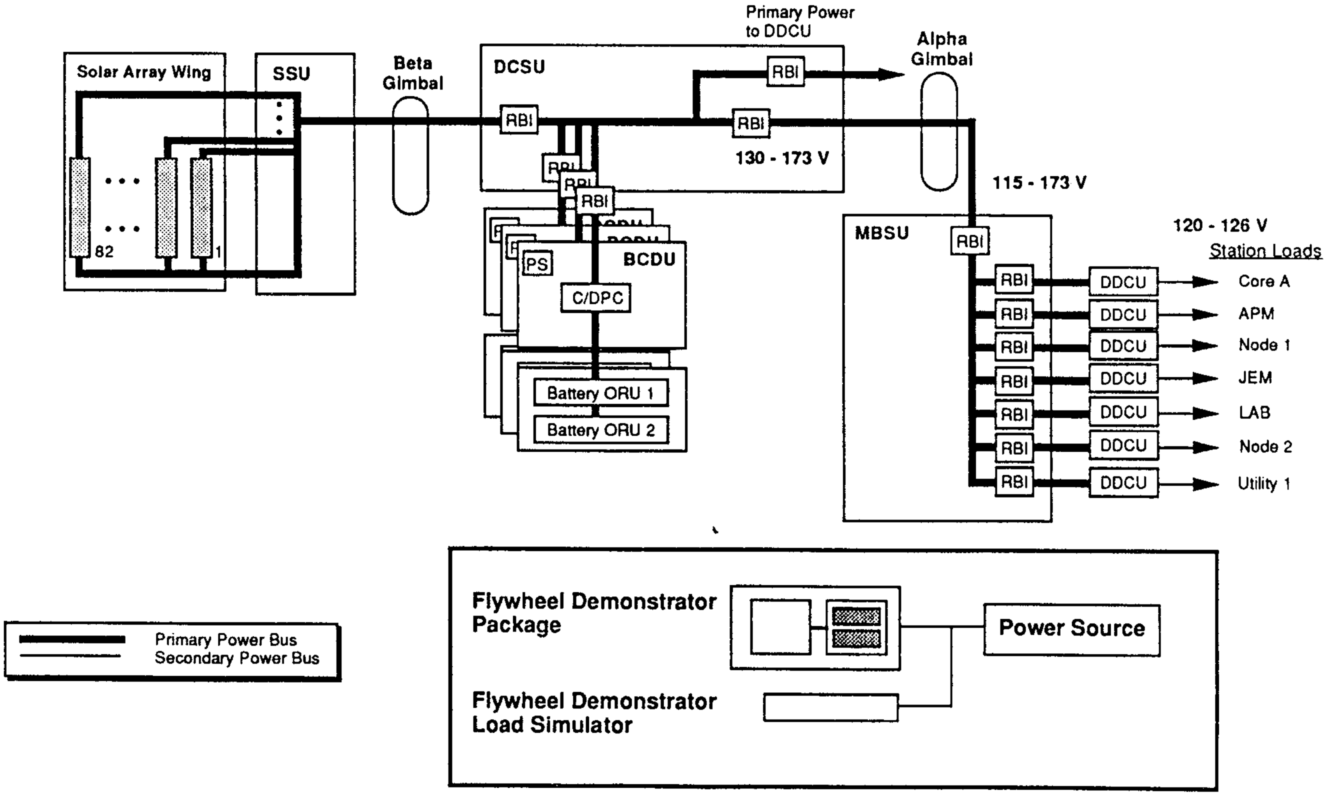


Figure 6-3
Flywheel Demonstrator Hookup Location 4; Autonomous Power/Load.

This case is similar to number 3 above except the power and load is independent of Station capabilities. This minimizes risk to Station operations but requires additional hardware for the power source and load. The simulated load provides a better opportunity to exercise the flywheel demonstrator capabilities with a rigorous and independent test program. This configuration does not take advantage of the Space Station power capacity. Electrical stability is not an issue since the demonstrator/power package is totally separate from the Station EPS.

5. Station Power/Autonomous Load

Place the demonstration package exterior to the IEA with power provided by the Station and the load simulated (Fig. 6-4).

This scenario is similar to number 4 except power is provided by the Station EPS. Station hardware modifications may be necessary to route power and control lines to the flywheel demonstrator. The simulated load enables a rigorous flywheel/PPU test program independent of Space Station loading. Electrical stability is not an issue when the demonstrator is interfaced on the secondary power side.

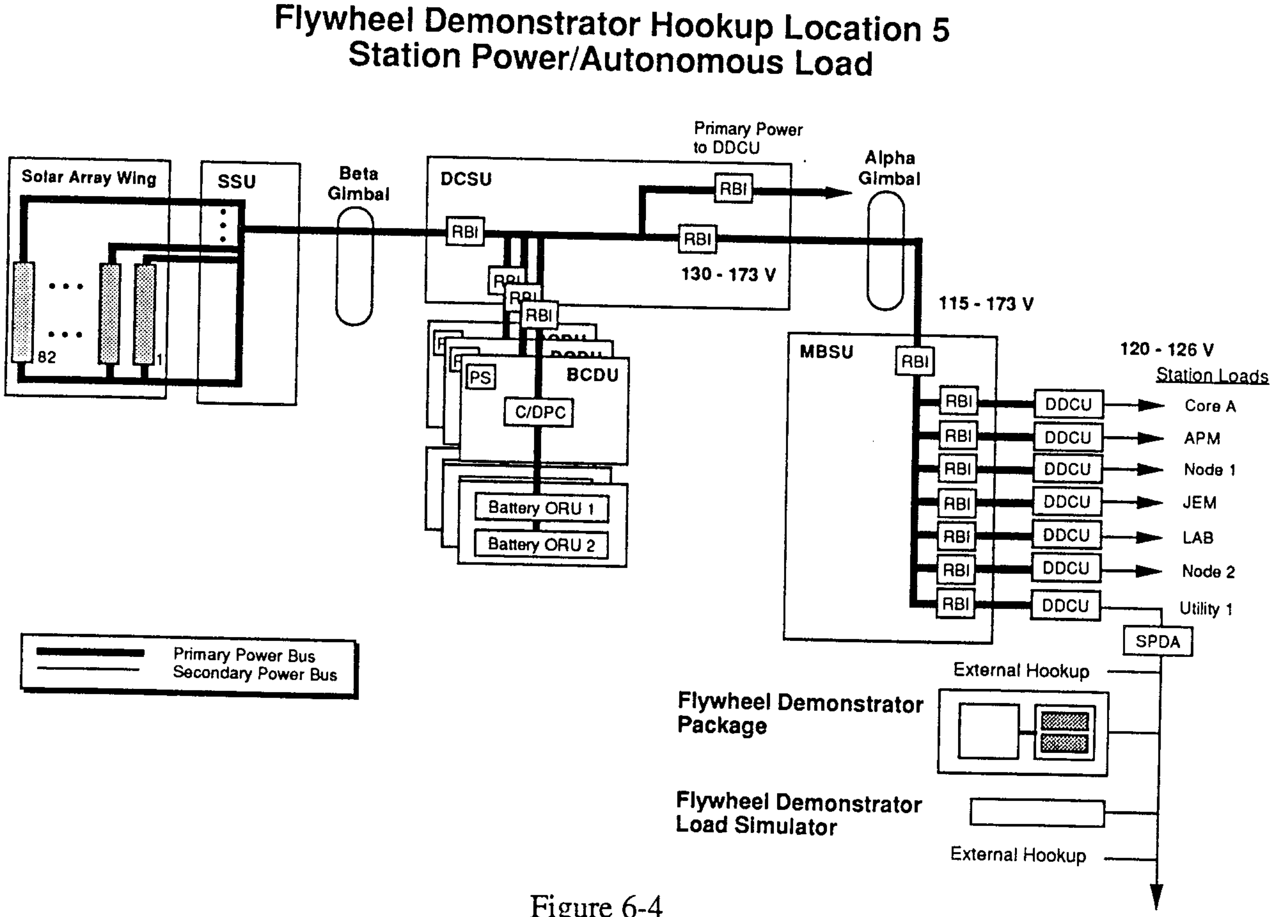


Figure 6-4
Flywheel Demonstrator Hookup Location 5; Station Power/Autonomous Load.

Scenario 5, Station Power/Autonomous Load was selected as the flywheel demonstrator configuration for the following reasons:

- Takes full advantage of Station excess power.
- Minimizes Station operation risk and possible EPS electrical instability by interfacing on the secondary power side.
- Not dependent on Station loads to discharge stored energy.
- Allows multiple charge/discharge cycles independent of Station orbit.
- Not dependent on IEA slot.
- Minimizes dependency on Space Station schedule.
- Minimal Station hooks and scars.

6.4 Demonstrator Electrical Interface

Several hookup options to demonstrate the application of flywheel energy storage systems were considered. The study was based on the Space Station Alpha design configuration as of April of 1994. The criteria for selecting the hookup was to obtain no risk to the operation of the Space Station Alpha.

6.4.1 EMB Demonstration Unit Hookup And Facts

Two potential hookup locations were identified for Option 5, (Table 6-3) both branched out from the MBSU (Main Bus Switching Unit). The best hookup with the least impact to the operation of the Space Station Alpha and also having the best access was at utility port 4A in the secondary power distribution assembly. The electrical rating of this outlet is nominal 6.25 KW of power at 100 to 115 VDC.

The demo preliminary design is estimated to deliver 2.75 KW of power at the lowest operating speed.

Power to charge demo will be provided by MBSU. Discharge of the demo will be accomplished through an impedance load bank which will be supplied with the demo unit

- HOOKUP LOCATIONS IDENTIFIED
- HOOKUP OPTION 5 IDENTIFIED AS HAVING THE BEST ACCESS FOR INTERCONNECTION AND NO IMPACT ON OPERATION OF SPACE STATION ALPHA
- HOOKUP AT UTILITY 4A CONNECTING POINT IN SPACE STATION ALPHA
- 6.25 KW OF POWER AT 100~115 VDC AVAILABLE FROM DDCU / SPDA
- MOTOR/GENERATOR DESIGNED TO DELIVER 2.75 KW AT FLYWHEEL LOWEST OPERATING SPEED
- IMPEDANCE LOAD BANK UTILIZED TO DISCHARGE EMB

Table 6-3
EMB Demonstration Unit Hookup and Facts.

6.4.2 EMB Demonstration Unit Hookup Options

The two best options found for the demo hookup are illustrated in Fig. 6-5. The option 1 hookup has the advantage of supplying a wider voltage range to the demo, thus similar to the power provided by DCSU to the BCDU's and batteries. This option had the disadvantage of having a more difficult access and also that the hookup would be directly to a vital power source Bus without an external electrical isolation means. The option 2 hookup appeared to be more suitable not only from the safety point of view but also has better access. The electrical rating of this hookup is nominal 6.25 KW of power at 113 to 126 VDC

6.4.3 EMB System Demo Nominal Power Capability

A nominal power flow diagram examining the two option hookups is depicted in Fig. 6-6. Hookup option 1 is characterized for having more power available for a larger demo system, however as indicated in paragraph 6.4.2, this option is less suitable because of its higher risk estimated for the demonstration. The preferred option 2 hookup is characterized for delivering a little less than half the power provided by option 1. 6.25 KW of power is available at the DDCU output. The efficiency of the power processing unit calculated is at least 93 %, therefore the available power to the flywheels would be 6.8 KW. In the discharge cycle considering the efficiencies and the duration of the eclipse, the total nominal power available is estimated to be about 6 KW.

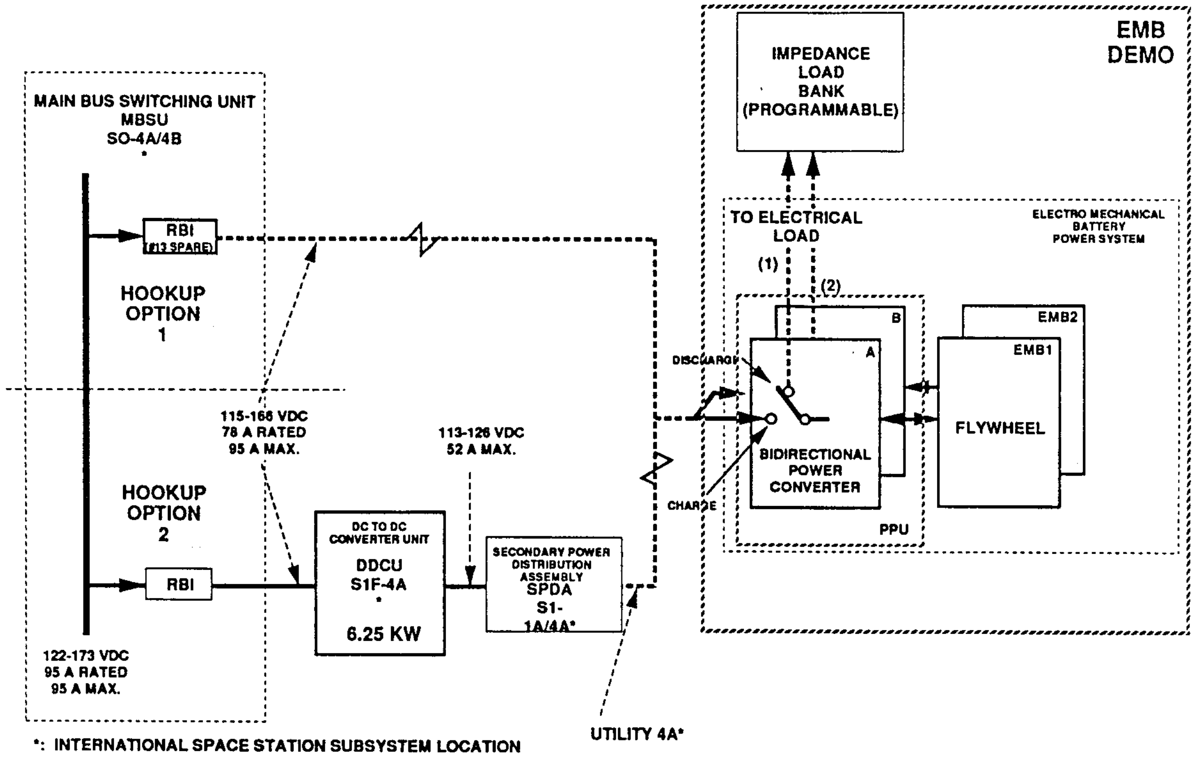


Figure 6-5
Flywheel Demonstration Unit MBSU Hookup Options.

6.4.4 Charge/Discharge Sequence

The charge/discharge sequence operation of the demo was analyzed and the results are summarized in Table 6-5. The preliminary demo design assumes that a programmable impedance load bank is integrated to the demo and used to consume the energy stored by the EMB. This approach makes the design more independent, instead of using existing loads in the ISS. The load bank should also facilitate static and dynamic test loading of the EMB. Currently the EMB's are designed to deliver 5.5 KW, operating in a 2:1 speed ratio to a maximum of 50,000 RPM. Consequently 75 % of the total energy stored would be dissipated by the load bank.

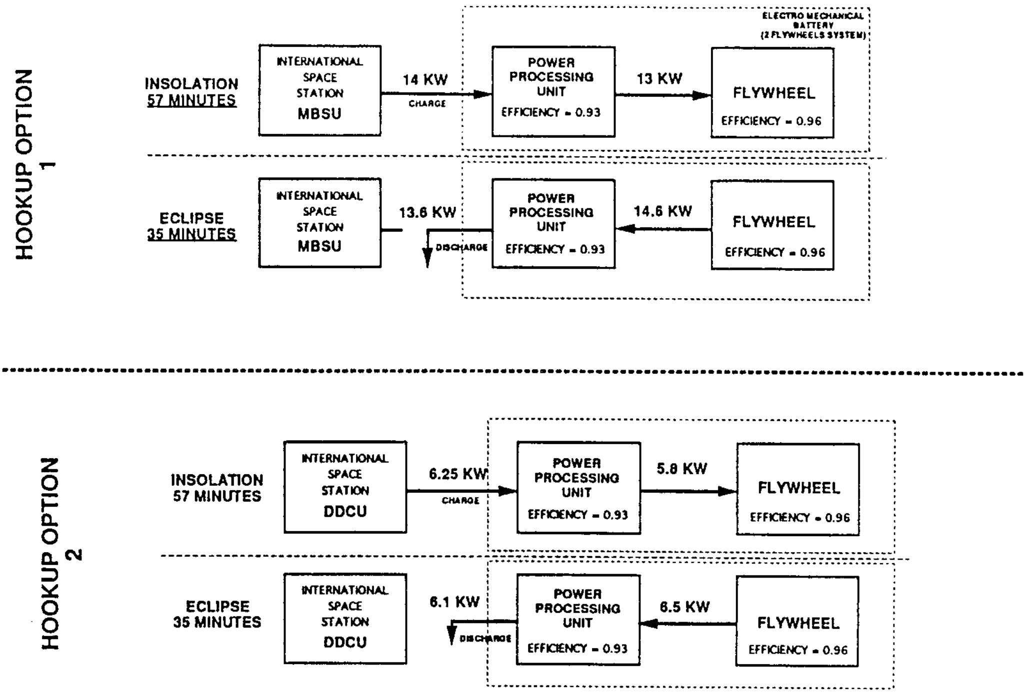


Figure 6-6
Flywheel Demonstration Unit Nominal Power Capacity.

- PRELIMINARY DESIGN DEMO ASSUMES AN IMPEDANCE LOAD BANK FOR DISCHARGING EMB.
- ELECTRICAL POWER FOR EMB CONTROLS PROVIDED THROUGH MAIN ELECTRICAL HOOKUP REGARDLESS OF LINE CONTACTOR POSITION

CHARGE	DISCHARGE
1) LINE CONTACTOR CLOSES, ISSEPS SUPPLIES POWER TO EMB IN INSOLATION	1) LINE CONTACTOR DISCONNECTS EMB FROM ISSEPS AT ECLIPSE POINT
2) PPU STARTS SPINNING FWL	2) EMB CONTROL POWER IS SWITCHED FROM ISSEPS TO EMB POWER
3) LINE CONTACTOR DISCONNECTS EMB FROM ISSEPS AT ECLIPSE POINT	3) EMB DISCHARGE TESTING BEGINS
4) ISSEPS POWERS EMB CONTROLS DURING INSOLATION / ECLIPSE TRANSITION	4) EMB CONTROL POWER SWITCHES FROM EMB TO ISSEPS POWER DURING ECLIPSE / INSOLATION TRANSITION
5) EMB POWERS IMPEDANCE BANK LOAD AND ITSELF, (CONTROLS)	5) EMB DISCHARGE ENDS
6) EMB MAY DISCHARGE UP TO 75% OF ITS ENERGY (MAXIMUM) DURING ECLIPSE	6) LINE CONTACTOR CLOSES, ISSEPS SUPPLIES POWER TO EMB IN INSOLATION

Table 6-4
Flywheel Demonstration Unit Charge/Discharge Sequence.

6.5 Demonstrator Structural Interface

The Flywheel Demonstrator consists of several components that are integrated on the ground prior to on-orbit delivery by the Shuttle. These components include the flywheel ORU, PPU ORU, load impedance simulator, load simulator thermal management subsystem, and radiator. All components are mounted to the demonstrator test skid, which supports all components and is the main structural interface to the Space Station.

6.5.1 Flywheel ORU

The flywheel pair is placed in a modified battery ORU similar to the Station replacement ORU discussed in section 4.0. Thermal management of the flywheel ORU is not performed because of the low waster heat rate and wider operating range of the flywheels. Despite the fact the flywheel demonstrator is designed to be a generic experiment, the battery ORU was selected as the enclosure for the flywheels because it decreases overall cost of the experimental package, is an "off-the-shelf" item, and is easily modified for the flywheel integration.

As discussed in the previous section, the electrical power interface to the demonstrator is through the secondary side EPS utility port. This port is located on the long spacer assembly between segments S4 and S6 (on the starboard side). This site, shown in Fig. 6-7, is where the demonstrator is integrated to the Space Station truss.

6.5.2 PPU ORU

The PPU is placed in a modified BCDU ORU and interfaces with the flywheel ORU in a similar manner to the replacement ORU discussed in section 4.0. This ORU is actively cooled (and heated if necessary) by the demonstrator thermal management system because of its higher heat load and tighter temperature range (Table 4-3). The PPU ORU is the main electrical interface to the flywheel demonstrator skid, which provides a conduit for power and control lines from the demonstrator to the Space Station. Like the Flywheel ORU, the BCDU ORU box was selected as the demonstrator PPU enclosure because it is cheaper and available.

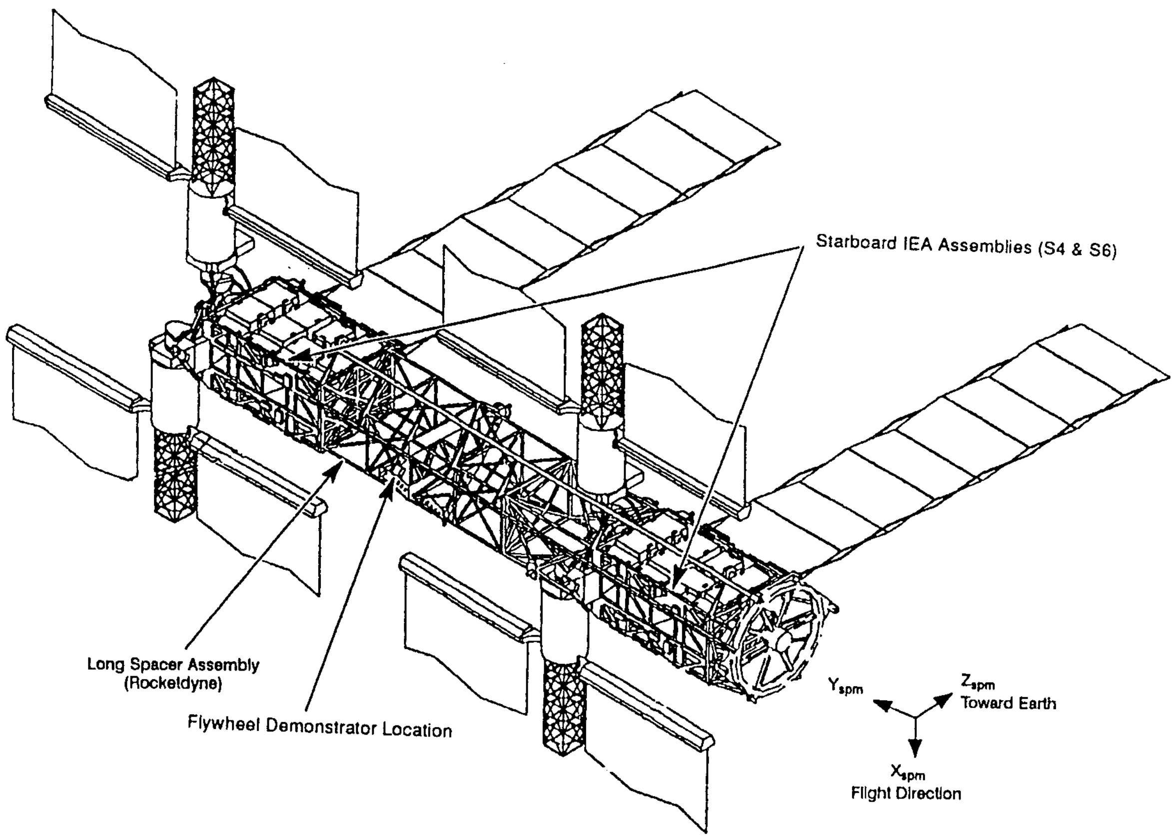


Figure 6-7
Flywheel Demonstration Location on Long Spacer Assembly.

6.5.3 Load Impedance Simulator

The function of the Load Impedance Simulator is to present a controlled, programmable, electrical load to the flywheel demonstrator unit. The Simulator is programmable to simulate any number of postulated load scenarios, ranging from steady-state, transient, or cyclic load profiles. This permits a wider range of flywheel tests that can duplicate any postulated mission scenario. The Simulator is sized for a maximum of 6.25 kw of electrical energy dissipation, which is the maximum input power from the DDCU. Waste heat generated by the Simulator is removed by the thermal management subsystem.

6.5.4 Demonstrator Thermal Management Subsystem

The Flywheel Demonstrator has a thermal management system independent of the Space Station TMS that removes the waste heat generated by the Load Impedance Simulator and PPU ORU. The Demonstrator Thermal Management subsystem is modeled after the IEA

TMS, which has similar operating characteristics and specifications (Ref. 4-1). This system consists of a convective cooling loop that circulates coolant through the Load Simulator and PPU ORU base plate, transfering waste heat from these devices to the coolant. The coolant flows to the radiator where the excess energy is radiated to space.

6.5.5 Flywheel Demonstrator Test Skid

The two primary functions of the test skid is to provide structural support for all Demonstrator components and to act as the primary interface from the Demonstrator to the Space Station. Fig. 6-8 presents a cursory configuration of the key Demonstrator components on the test skid and gives a rough estimate of its size (45 x 110 x 12 inches). One key advantage of deploying the Demonstrator components together in one package is the reduction of EVA installation time required to mount and interface the Demonstrator on the Station truss structure and connect the electrical and control lines. The actual skid design is highly dependent on the final Station truss configuration.

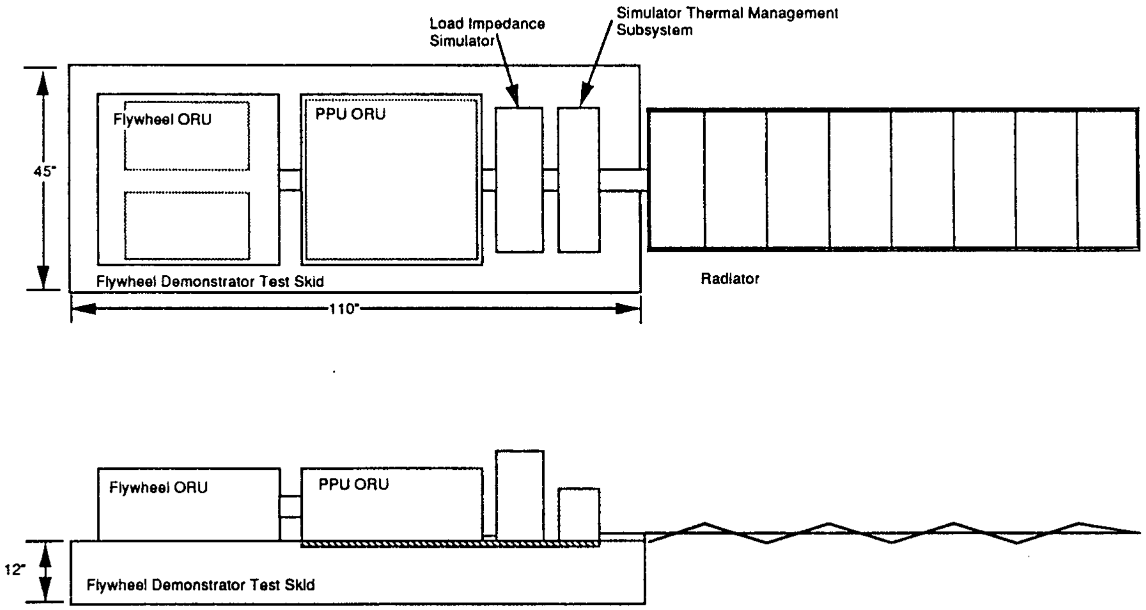
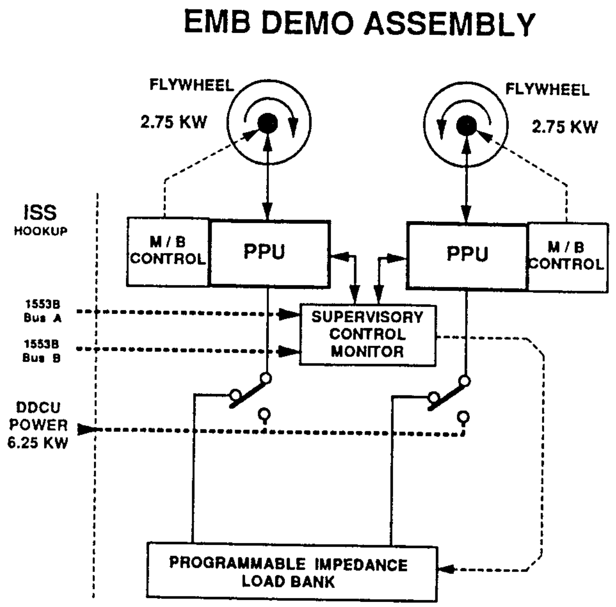


Figure 6-8
Flywheel Demonstrator Component Locations on Test Skid.

6.6 Demonstrator Test Manifest

A preliminary test plan was developed to evaluate the performance of the 5.5 KW flywheel demo system. The plan identifies four sequential steps as depicted in Fig. 6-9.



OPERATING TEST SEQUENCE

1) PARTIAL CHARGE / DISCHARGE
  •TEST AND EVALUATION:
    -Vibration, Temperature levels
    -Insolation / eclipse power transition
    -Steady electric loading operation

2) MEDIUM RANGE CHARGE / DISCHARGE
  •TEST AND EVALUATION:
    -Vibration, Temperature levels
    -Insolation / eclipse power transition
    -Steady and dynamic electric loading operation, step loading
    -Startup cycling

3) NORMAL CHARGE / DISCHARGE
  •TEST AND EVALUATION:
    -Nominal discharge,50000 to 25000 RPM, (75% total energy stored) testing

4) SINGLE FLYWHEEL LOSS SIMULATION
    -Shutdown sequence at different charge levels

Figure 6-9
Preliminary Demonstrator Test Plan.

In the first step of the testing, the system is operated at low power levels, derived from low speed conditions, moderately charging and discharging the EMB's to insure that the mechanical system is working properly and that the electronics respond to all commands. Levels of vibration and temperature rise in critical zones will be measured and assessed. The tests in this first step should be conducted in steady electric loading conditions. Also the transition from insolation to eclipse will be evaluated. This test is critical because the power to control the electronics of the demo switches from the Space Station Alpha to the demo's own power. During eclipse the flywheel supplies its own power for controls

In the second step of the testing, the EMB's are operated at medium level of power, also implying medium speeds. During the testing, dynamic electric loading should be accomplished to evaluate the dynamic response of the demo. Startup cycling should also be carried out to evaluate the safety mechanisms and electrical control interface with the DDCU.

In step three normal charge and discharge cycling will be evaluated. This will help to complete the evaluation of the system's performance.

In the last step a single flywheel loss simulation should be attempted to verify the shutdown sequence of the demo unit. This should be experimented at different power levels alternating the flywheels. This test requires that the alternate flywheel is also shutdown in a synchronous fashion to minimize mechanical torque on the ISS structure.

6.7 Failure Analysis and Risks

The electrical failure analysis conducted for the demo system was based on single failure mode scenarios. The risks associated with the failures were found to be minimum without severe consequences for the Space Station.

6.7.1 EMB Demo Electrical Failure Analysis

An electrical failure analysis was conducted for the EMB ORU and PPU unit. The failure mechanisms, consequences and the actions to take place and impact to the Space Station Alpha are depicted in Table 6-5.

The possible electrical failures identified in the EMB ORU, are such that it may produce overheating in the system, flywheel unbalance and power loss and the loss of motor/ generator control. In all the failure situations identified the action to take should be to disconnect demo from the Space Station Alpha grid and to shut down the EMB. No major risks were found

Failures in the electronic control hardware of the PPU were also analyzed. The consequences identified were loss of bearing control, flywheel power, motor/generator control, health monitoring system, PPU control, and EMB control. In all cases the action to take was to proceed to shutdown the EMB and isolate the PPU. No major risks were found for the Space Station Alpha.

	COMPONENT	FAILURE MECHANISMS	CONSEQUENCES	ACTION / IMPACT ON SYSTEM	
				EMB	ISSEPS*
ELECTROMECHANICAL BATTERY ORU	MOTOR / GENERATOR	• PHASE, OPEN / SHORT • ROTOR PERMANENT MAGNET FATIGE	• OVERHEATING • UNBALANCE • FWL POWER LOSS	1) DISCONNECT FROM ISSEPS 2) SHUTDOWN EMB	• NO MAJOR RISKS ARE EXPECTED FOR FAILURES ANALYZED
	ROTOR POSITION SENSOR	• OPEN / SHORT CIRCUIT • ROTOR FATIGE	• MOTOR / GENERATOR CONTROL LOSS		
	MAGNETIC BEARINGS	• OPEN / SHORT CIRCUIT • SENSOR	• OVERHEATING • UNBALANCE • FWL POWER LOSS		
POWER PROCESSING UNIT	MAGNETIC BEARING CONTROLLER	• ELECTRONIC HARDWARE • POSITION SENSOR • INTERCONNECTING HARDWARE	• BEARING CONTROL LOSS • FWL POWER LOSS	1) DISCONNECT FROM ISSEPS (DEMO DISCONNECTS FROM ISSEPS IF PARTIAL LOSS OF POWER OCCURS) 2) SECOND FLYWHEEL TRACKS SPEED OF FAILED FWL PREPARING FOR SHUTDOWN.	
	BIDIRECTIONAL POWER CONVERTER CONTROLLER	• SINGLE PHASE, OPEN / SHORT • THREE PHASE CONTROL LOSS • CONTROL HARDWARE • INTERCONNECTING HARDWARE	• MOTOR / GENERATOR CONTROL LOSS • HEALTH MONITORING SYSTEM LOSS • ELECTRICAL POWER OUTPUT MALFUNCTION		
	SUPERVISORY CONTROL MONITOR	• 1553B BUS PORTS, (2) • INTERFACE ELECTRONIC HARDWARE	• LOSS OF ISSEPS CONTROL		

ISSEPS* : INTERNATIONAL SPACE STATION ELECTRICAL POWER SYSTEM

Table 6-5
Flywheel Demonstration Failure Risks.

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7.0 Flywheel ORU Life Cycle Cost Analysis

Trade studies were made to compare the life-cycle cost (LCC) of flywheels versus batteries/BCDUs (battery charge/discharge unit) for the Space Station energy storage subsystem (ESS) of the electrical power system (EPS). It is believed that flywheels can provide a lower cost alternative to batteries/BCDUs because they cost less and weigh less (so the launch cost is lower). However, the flywheels must be developed, and that development cost penalty must be traded against their cost advantages to see if there is a net LCC savings.

The results of the flywheels-versus-batteries comparison depend on a number of things that have uncertainty at this time, such as launch cost, Space Station life, flywheel life, and flywheel costs. Therefore, the trade studies were made for a range of values applied to these items. Table 7-1 shows the trade study variations that were considered.

Trade Parameter	***Variation***		
Launch Cost ($/lb)	2000		4000
Space Station Life (years)	10	15	20
Flywheel Life (years)	5	7.5	10
Flywheel Costs (1994$M)	**High Estimate**	**Best Estimate**	**Low Estimate**
Development	120	90	86
Unit Production (initial)	3.26	1.58	1.41
Unit Production (replacement) (1.3 times initial)	4.24	2.05	1.83

Table 7-1
Life Cycle Cost Trade Study Variations.

For the scenario that is somewhat in the middle of these uncertainty ranges (e.g., $3000/lb launch cost, 15-year station, 7.5-year flywheel, and the best estimate flywheel costs), the flywheels will save approximately $100M in LCC. The savings could be as high as $272M (for a 20-year station, $4000/lb launch cost, 10-year flywheel, and the lowest flywheel costs).

On the other hand, a station with only a 10-year life would have no cost savings with flywheels. For the 15 and 20-year stations, the crossover point where the flywheel savings start to be realized is about five to six years after PMC (permanently manned configuration).

7.1 Method of Analysis

A spread sheet model was constructed to perform the trade studies. The life-cycle cost (development + production + operations) of flywheels was compared to that of batteries in order to determine which kind of energy storage would be the most cost effective over the life of the Space Station. It was assumed that initially the station will use batteries/BCDUs for the first five years of operation. After that time, the batteries/BCDUs may be replaced by flywheels. Since the initial shipset of batteries/BCDUs will already be on the station, the cost of developing the batteries and BCDUs and the production cost of the first shipset of ORUs (orbital replacement unit) are assumed to be a sunk cost and are not included in the trade studies. Thus, the batteries/BCDUs LCC includes only the operations cost which is the cost for replacement ORUs and the cost to launch them. On the other hand, the flywheels LCC includes all the costs to develop, produce and launch the flywheel ORUs (including replacements).

In general (and for the flywheels):

LCC = DEVELOPMENT COST
+ INITIAL HARDWARE PRODUCTION COST
+ INITIAL HARDWARE LAUNCH COST
+ REPLACEMENT HARDWARE PRODUCTION COST
+ REPLACEMENT HARDWARE LAUNCH COST

For the batteries/BCDUs:

LCC = 0
+ 0
+ 0
+ REPLACEMENT HARDWARE PRODUCTION COST
+ REPLACEMENT HARDWARE LAUNCH COST

Other groundrules and assumptions are:

1. All costs are in constant 1994$.
2. Launch costs include a factor of 1.2 for flight support equipment.
3. The Space Station has 3 IEAs (integrated equipment assemblies).

4. Vendor G&A and profit are 26% (applied to the PRICE model cost estimates for purchased flywheel components).
5. Rocketdyne material procurement expenses and other related expenses are 29% (applied to the PRICE model cost estimates for purchased flywheel components).
6. Rocketdyne G&A and profit are 20% (applied to the PRICE model cost estimates for all costs).

The battery and BCDU unit production costs were obtained from the Space Station spares cost list. Their weights were the "shall not exceed" weights given in the Space Station specifications (RC1804 for the battery and RC1807 for the BCDU). The requirements for MTBF (including the effect of limited-life items) were also given in the specifications.

The PRICE H model (Martin Marietta PRICE Systems) was run to estimate the flywheel ORU costs. The cost breakdown structure that was used for the flywheel ORU is given in Figure 7-1. The PRICE H model is based on weight, engineering complexity, and manufacturing complexity. The weights of the components were fixed during the trade studies, but the complexities were varied in order to determine the sensitivity of the results to the complexities.

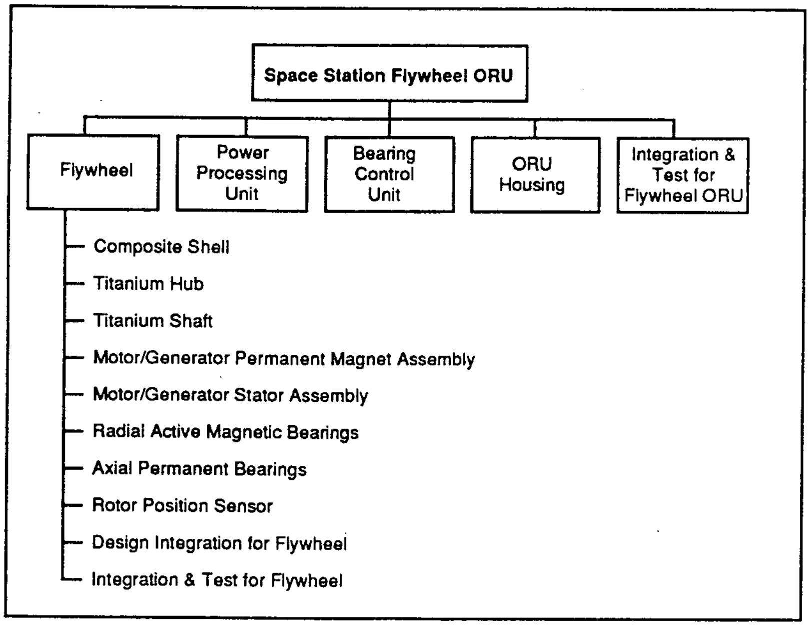


Figure 7-1
Cost Breakdown Structure for PRICE H Parametric Computations.

Three variations were made in the complexities. Initially, both the engineering complexity (designated ECMPLX in the PRICE model) and manufacturing complexity (designated MCPLXS) for several of the components in the flywheel were estimated to be very high by the Rocketdyne flywheel engineers. As the engineers gathered more information about the flywheel design and component suppliers, they revised the complexities downward to a low level. A final review brought the manufacturing complexities up a little to what is believed to be the best values based on what is currently known. Thus, three PRICE runs were made, one for the "high" complexities one for the "low" complexities, and one for the "best" complexities. The results of the trade studies show the effects of these three variations in flywheel costs. The "low" and "best" results are relatively close together because the engineering complexities are the same for both cases (only some of the manufacturing complexities are different).

A typical printout from the PRICE model for one of the flywheel components is shown in Table 7-2. It shows the development and production costs that were calculated by the model. It also lists the values that were input to the code for the different variables (e.g., weight, complexity, and quantities of hardware). Printouts similar to this were obtained for each of the items in the cost breakdown structure.

The PRICE model output for the "best" costs are summarized in Table 7-3. This spreadsheet applies the wrap factors to each of the items and gives the total development cost and the unit production cost for the flywheel ORU. Since the PRICE model does not include G&A (general and administrative) or profit in its calculations, these are entered in the spreadsheet as multipliers (or wraps). for Rocketdyne "make" items, this wrap factor is assumed to be 1.20. For "buy" items the PRICE model output is wrapped with a factor of 1.26 (assumed for the vendor G&A and profit), another factor of 1.29 (estimated for material procurement and related expenses), and a final factor of 1.20 for Rocketdyne G&A and profit. Table 7-3 also summarizes all the inputs to the PRICE runs for the "best" costs including the rationale used to generate the manufacturing complexity factors (MCPLXS).

Two values from the spreadsheet shown in Table 7-3 are then input to the spreadsheet shown in Table 7-4 which inputs all the other variables and performs the trade study analyses. The two values taken from Table 7-3 are the total development cost ($90,063K converted to $90M for Table 7-4) and the amortized UPC ($1,584.80K converted to $1.58M for Figure 7-5).

The other inputs to the trade studies are summarized in Table 7-5. Launch costs were varied from $2,000/lb (similar to the Proton launch cost) to $4,000/lb (similar to Ariane V and Shuttle launch costs).

```
                         PRICE HARDWARE MODEL                      Page 1 of 1
                           Mechanical Item
                Project Name: C:\DATA\PRICE\SSFW13.HPR
                    Tue June 21 1994 3:22 PM (1.21)
Composite Shell
                       Costs in ($1000 Constant 194)
Global Title: PRICE H Preset Acquisition Global Table (1993)
Escalation Title: PRICE H Preset Escalation Table (1993)
Program Cost                   Development      Production        Total Cost
Engineering
  Drafting                          1168.1            12.1            1180.2
  Design                            4447.2            39.8            4487.0
  Systems                           1634.4               -            1634.4
  Project Mgmt                      1438.9           125.3            1564.3
  Data                               687.6           129.9             817.5
   SubTotal(ENG)                    9376.2           307.1            9683.3
Manufacturing
  Production                             -          1369.0            1369.0
  Prototype                          707.3               -             707.3
  Tool Test Eq                        71.7           190.1             261.9
    SubTotal(MFG)                    779.1          1559.2            2338.2
      Total Cost                   10155.3          1866.3           12021.6

Schedule Start                Apr 94 [  20]   Apr 96 [  10]
First Item                    Nov 95*[   8]   Jan 97*[   6]
Finish                        Jul 96*[  29]   Jul 97*[  15]

  Unit Production Cost                                 38.03
  Production Rate                                       6.06

 Prototype Quantity             6.000   Production Quantity              36
 Unit Weight                  100.000   Unit Volume                  10.000
 Quantity/Next Higher Assy          1

Design Factors                       MECHANICAL Product Descriptors
 Weight                                100.000 Engineering Complexity  1.900
 Density                                10.000* Prototype Support       1.000
 MFG. Complexity                         6.331 Proto Schedule Factor   0.250*
 New Design                              1.000
 Design Repeat                           0.000 Platform                2.500
 Engineering Changes                     0.010* Year of Technology      1994
                                               Reliability Factor      1.000
 Integration Level                       0.500 MTBF (Field)            39998*

Supplemental Information                       Tooling & Process Factors
                                                Development Tooling     1.000*
 Amortized Unit Cost            51.842*         Production Tooling      1.000*
 T-1 Cost                       55.624*         Rate Tooling            0.000
 Dev Cost Multiplier             1.000*         Prod Cost Multiplier    1.000*
 PRICE Improvement Factor        0.924*         Unit Learning Curve     0.904*
```

Table 7-2
PRICE Hardware Model Flywheel Composite Shell Data Sheet.

7.2 Flywheel ORU Life Cycle Cost Results

The results of the flywheels-versus-batteries comparison depend on the assumptions that are made for a number of variables that have uncertain values at this time. Therefore, instead of arriving at a single result, the trade studies show a range of results based on the range of the input variables.

A limited selection of the results are shown in this section. More detailed results for all of the sensitivity analyses are included in Appendix B.

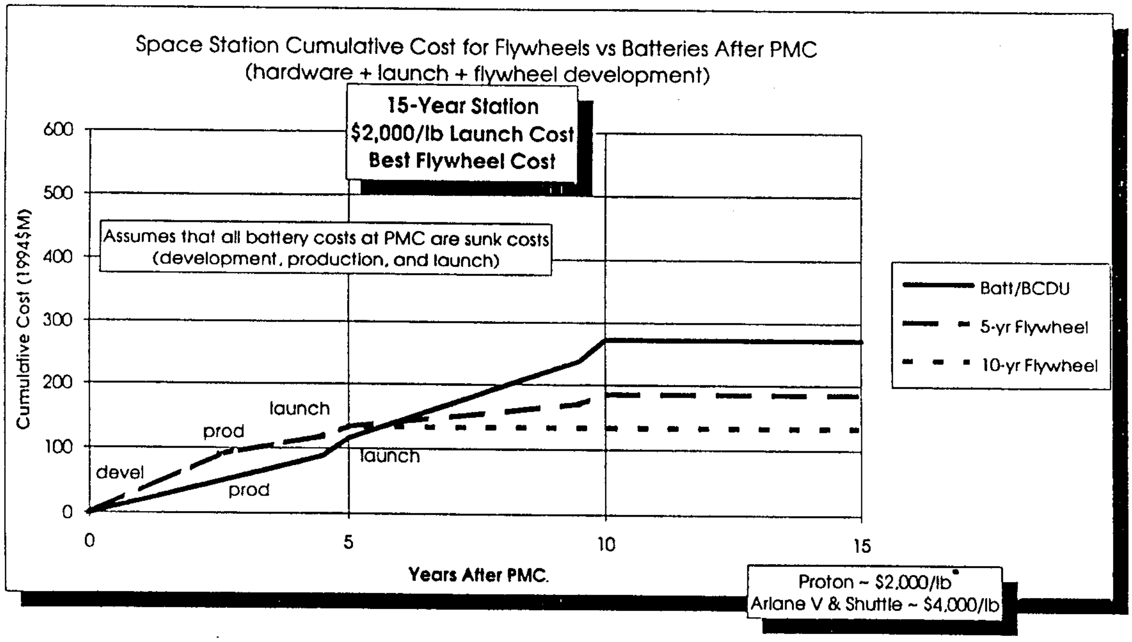
Figure 7-2 shows how the cumulative cost for batteries compares to that for flywheels during the life of a 15-year station. Although the cumulative cost of batteries starts out lower than the cost of flywheels, it becomes higher about six years after PMC. Thus, by replacing batteries with flywheels after five years of operation, the net cost savings for the 15-year station is between

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	file	SSFW13E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW13 & SSFW13B										
2	date	6/27/94		**PRICE Model Cost Estimate for Flywheels**							**BEST ESTIMATE**									
3	time	9.37 AM		**(cost to the government, 1994$M)**																
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel								
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18								
7	initial ORU cost (1993$M)				1.82		1.38													
8	1.042	1993-->1994 escalation factor																		
9	initial ORU cost (1994$M)				1.90		1.44			1.58		1.58								
10	1.3	replacement ORU cost factor																		
11	replacement ORU cost (1994$M)				2.47		1.87			2.05		2.05								
12	weight per ORU (lb)				375		196			411		411								
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00								
15	development cost (1994$M)				0	sunk	0	sunk		90		90								
16	initial HW cost/SS (1994$M)				0	sunk	0	sunk		28		28								
17	replacement HW cost/SS (1994$M)				89		34			37		37								
65								**15-Year Station**												
66	$2,000	/lb launch cost (with FSE factor of 1.2)																		
67	launch cost/SS (1994$M)				27		7			15		15								
68									Battery											
69					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			**ssfw13e3** chart				flywheel savings	
70	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDU	5-yr Flywh	10-yr Flyw	5-yr Flywh	10-yr Flyw
71	0				0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
72	2 5	flywheel devel		batt prod (	49	49	0	0	49	90	90	90	90		3	49	90	90	-41	41
73	4 5	prod		batt prod (	39	89	0	0	89	28	118	28	118		5	89	118	118	-30	-30
74	5	launch			27	116	0	0	116	15	133	15	133		5	116	133	133	-17	-17
75	9 5	prod			89	205	34	34	238	37	170	0	133		10	238	170	133	68	105
76	10	launch			27	232	7	41	272	15	185	0	133		10	272	185	133	87	139
77	15				0	232	0	41	272	0	185	0	133		15	272	185	133	87	139
78																				
79																				
80								**15-Year Station**												
81	$2,000	/lb launch cost (with FSE factor of 1.2)																		
82	launch cost/SS (1994$M)				27		7			15		15								
83									Battery											
84					Battery		BCDU		+BCDU	5-yr Flywheel		7.5-yr Flywheel			**ssfw13e3** chart •				flywheel savings	
85	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	7.5-yr Flywheel		years	Batt/BCDU	5-yr Flywh	7.5-yr Flyw	5-yr Flywh	7.5-yr Flyw
86	0				0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
87	2.5	flywheel devel		batt prod (	49	49	0	0	49	90	90	90	90		3	49	90	90	-41	-41
88	4 5	prod	b & fw	att prod (	39	89	0	0	89	28	118	28	118		5	89	118	118	-30	-30
89	5	launch	b & fw		27	116	0	0	116	15	133	15	133		5	116	133	133	-17	-17
90	9.5	prod	b & BCDU		89	205	34	34	238	37	170	0	133		10	238	170	133	68	105
91	10	launch	b & BCDU		27	232	7	41	272	15	185	0	133		10	272	185	133	87	139
92	12	prod	fw			232		41	272		185	0	133		12	272	185	170	87	102
93	12.5	launch	fw			232		41	272		185	37	170		13	272	185	185	87	87
94	15				0	232	0	41	272	0	185	15	185		15	272	185	185	87	87
95												0	185							
96																				

Table 7-4
PRICE Flywheel System Trade Study Analysis Spreadsheet.

ORU DATA	Battery	BCDU	Flywheel		
			High Estimate	Best Estimate	Low Estimate
Development Cost ($M)	0	0	120	90	86
Initial Cost per ORU ($M)	0	0	3.26	1.58	1.41
Replacement Cost per ORU ($M) (1.3 times initial ORU cost)	2.47	1.87	4.24	2.05	1.83
Weight per ORU (lb)	375	196	411		
Replacement Interval (years) (for life or MTBF)	5	10	5, 7.5, 10		
Quantity of ORUs on station (in 3 IEAs)	36	18	18		
Space Station Life (years):		10, 15, 20			
Launch costs ($/lb):		2000, 4000			

Table 7-5
LCC Trade Study Inputs Summary.


Space Station Cumulative Cost for Flywheels vs Batteries After PMC
(hardware + launch + flywheel development)

15-Year Station
$2,000/lb Launch Cost
Best Flywheel Cost

Assumes that all battery costs at PMC are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb*
Ariane V & Shuttle ~ $4,000/lb

Figure 7-2
Cumulative Cost Comparison between the Battery/BCDU, 5-year Flywheel System, and 10-year Flywheel System for a 15-year Station.

$87M (for a 5-year flywheel) and $139M (for a 10-year flywheel). The assumptions for this case were: 15-year station, $2000/lb launch cost, and best flywheel cost.

The maximum cost savings obtained using the best flywheel cost are shown in Figure 7-3. Here the cost savings are between $195M and $261M for the 5-year and 10-year flywheel, respectively. In this case, the assumptions were: 20-year station life, $4000/lb launch cost, and best flywheel cost.

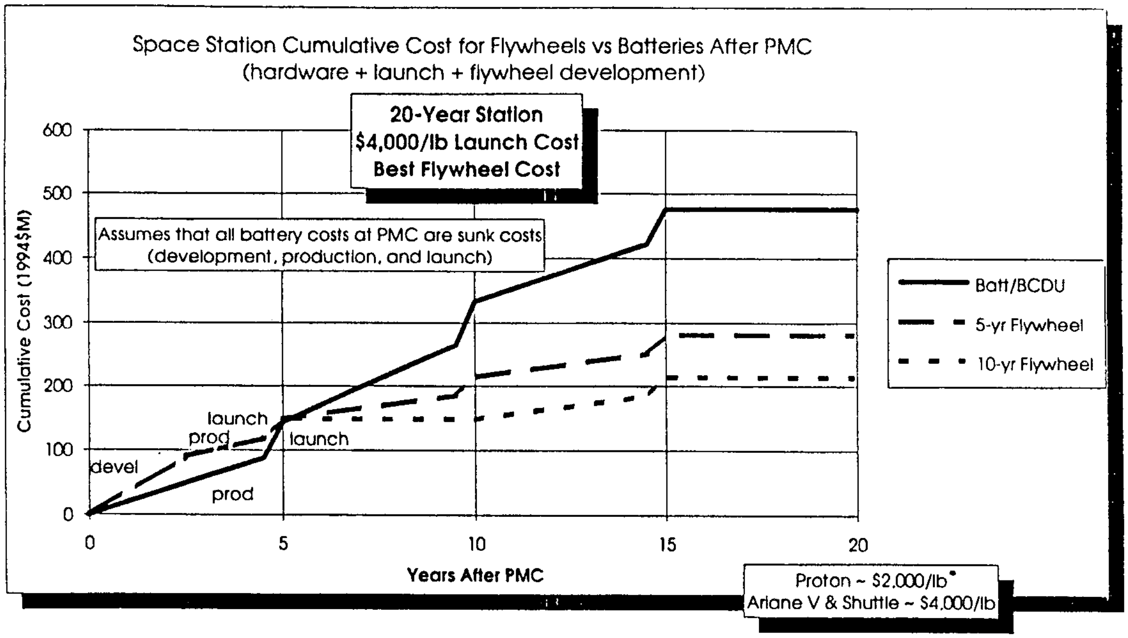


Figure 7-3
Cumulative Cost Comparison between the Battery/BCDU, 5-year Flywheel System, and 10-year Flywheel System for a 20-year Station.

There are no cost savings for flywheels on a 10-year station. Flywheel development costs are too high to be recovered during operations in that short a time.

The results for all the variations considered are given in Table 7-6. It shows both the total cumulative cost for batteries and flywheels as well as the total cost savings realized by replacing batteries with flywheels.

The values in Table 7-5 can be used to show sensitivities to the different variables. For instance, Figure 7-4 shows how the cost savings increase with launch costs for the 15-year station. Figure 7-5 shows how the cost savings decrease as station life decreases, and there are no savings with a 10-year station.

Space Station Flywheels Versus Batteries Trade Studies Summary

(All costs are in constant 1994$M)

	Total Cumulative Cost				Cost Savings With Flywheels		
	Battery	10 Yr FW	7.5-Yr FW	5-Yr FW	10-Yr FW	7.5-Yr FW	5-Yr FW
Low Flywheel Cost							
20-Year Station							
$4,000/lb Launch Cost	476	204	204	266	272	272	210
$2,000/lb Launch Cost	388	174	174	222	214	214	166
15-Year Station							
$4,000/lb Launch Cost	333	141	204	204	192	129	129
$2,000/lb Launch Cost	272	126	174	174	146	98	98
10-Year Station							
$4,000/lb Launch Cost	143	141	141	141	2	2	2
$2,000/lb Launch Cost	116	126	126	126	-10	-10	-10
Best Flywheel Cost							
20-Year Station							
$4,000/lb Launch Cost	476	215	215	281	261	261	195
$2,000/lb Launch Cost	388	185	185	237	203	203	151
15-Year Station							
$4,000/lb Launch Cost	333	148	215	215	185	118	118
$2,000/lb Launch Cost	272	133	185	185	139	87	87
10-Year Station							
$4,000/lb Launch Cost	143	148	148	148	-5	-5	-5
$2,000/lb Launch Cost	116	133	133	133	-17	-17	-17
High Flywheel Cost							
20-Year Station							
$4,000/lb Launch Cost	476	314	314	420	162	162	56
$2,000/lb Launch Cost	388	285	285	376	103	103	12
15-Year Station							
$4,000/lb Launch Cost	333	208	314	314	125	19	19
$2,000/lb Launch Cost	272	193	285	285	79	-13	-13
10-Year Station							
$4,000/lb Launch Cost	143	208	208	208	-65	-65	-65
$2,000/lb Launch Cost	116	193	193	193	-77	-77	-77

Table 7-6
Space Station Flywheels versus Batteries Trade Studies Summary.

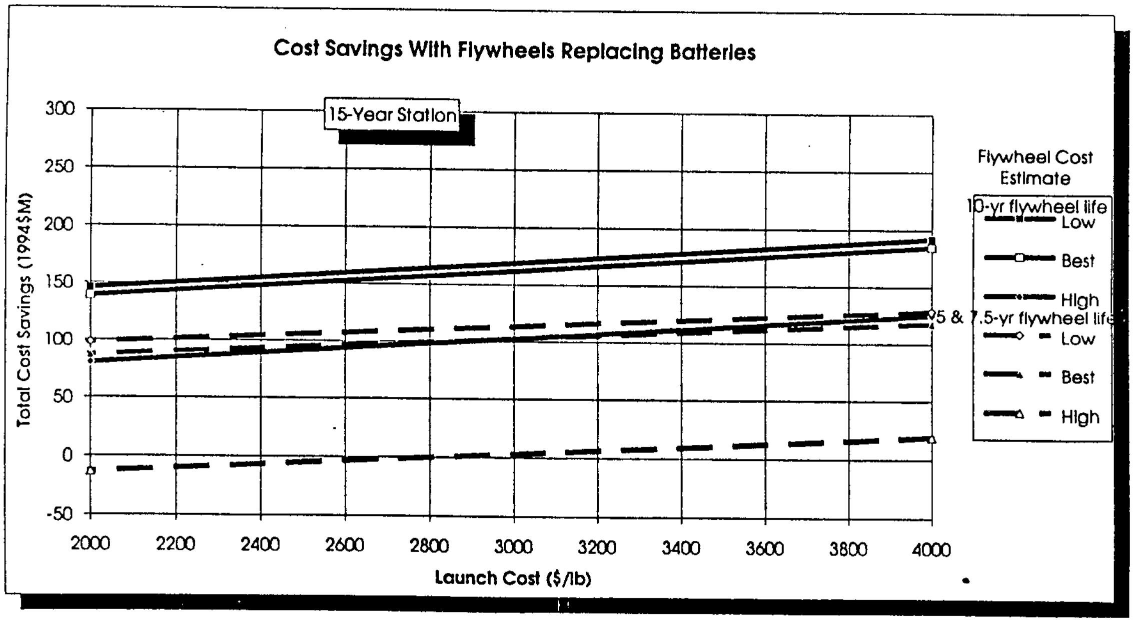


Figure 7-4
Cost Savings of Flywheels Replacing Station Batteries as a Function of Launch Cost.

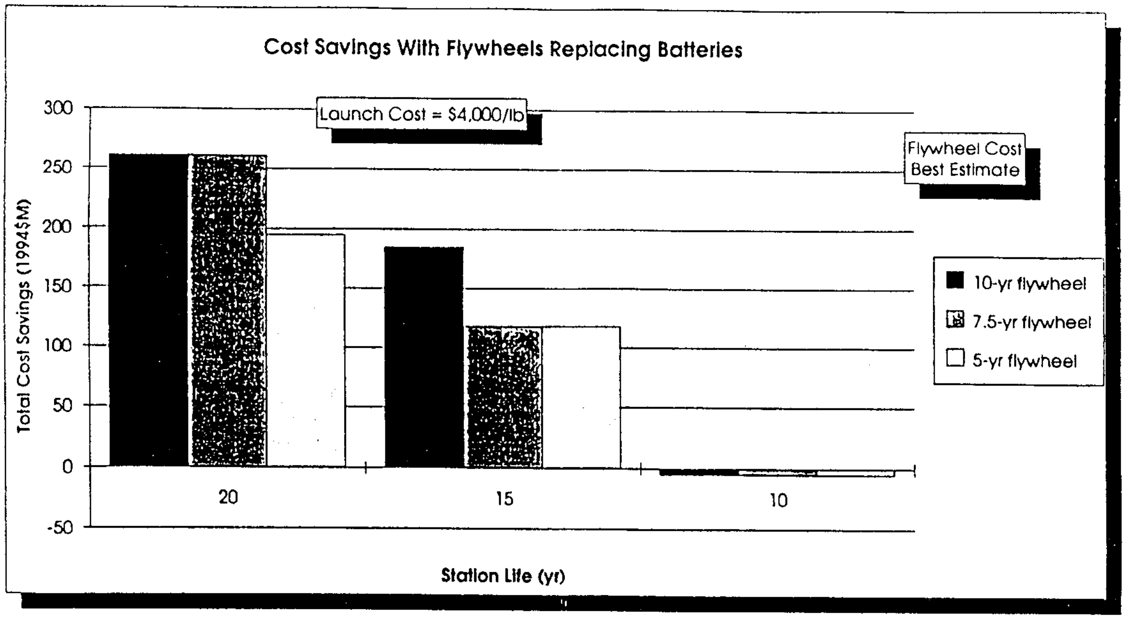


Figure 7-5
Cost Savings of Flywheels Replacing Station Batteries as a Function of Station Life.

Figure 7-5 also shows that with a 15-year station, a 7.5-year flywheel has no cost advantage over a 5-year flywheel, but a 10-year flywheel has a greater cost savings. On the other hand, with a 20-year station, the 7.5-year flywheel has a greater cost savings than the 5-year flywheel, but there is no further advantage for a 10-year flywheel.

In these trade studies, it was assumed that development costs were independent of flywheel life (based on the judgment of the flywheel engineers). If, instead, development costs increase significantly with flywheel life, these trade study conclusions could change.

7.3 Flywheel ORU Life Cycle Cost Conclusions

Trade studies that were performed one to two years ago on flywheels versus batteries for the Space Station energy storage subsystem showed very large cost savings (some more than $1B) if flywheels are used. However, for the current trade studies, the groundrules and assumptions have changed considerably, and the cost savings using flywheels are much smaller (or even zero with some assumptions). The changes that have had a major impact on the results are summarized in Table 7-7.

Parameters	Previous Studies	Current Studies
Station Life (yr)	30	10-20
Battery Life (yr)	3.13	5
Flywheel Life (yr)	9.38	5-10
Launch Cost ($/lb)	4,500	2,000-4,000
Battery/BCDU initial Cost ($M/shipset)	5.23	0
Flywheel Initial Cost ($M/shipset)	2.52	1.41-3.26
Battery/BCDU Development Cost ($M)	0	0
Flywheel Development Cost ($M)	0	86-120

Table 7-7
Parameter Comparison Between Current Study and Previous Work.

Most of these changes reduced the cost savings attributed to using flywheels, and a 10-year station shows no cost savings for flywheels in the current trade studies. The maximum cost savings shown in the current studies is $272M (for a 20-year station, $4000/lb launch cost, 10-year flywheel, and the lowest flywheel cost). A nominal case will have a flywheel cost savings of about $100M (15-year station, $3000/lb launch cost, 7.5-year flywheel, and best flywheel cost). The crossover point where the flywheel savings start to be realized is about five to six years after PMC.

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8.0 Flywheel Development Plan

This section presents the top-level development plan for the flywheel technology demonstration unit and the flywheel ORU flight hardware. Technology development programs for the four critical flywheel technologies, composite flywheel, magnetic bearings, PPU and Halbach Array, are proposed as well. The evolution and maturing of the space-based mechanical energy storage system from the initial technology programs through the demonstration unit and eventual space station deployment is graphically presented in schedules. Major program milestones are shown on each schedule for each program and discussed.

8.1 Flywheel Development Plan Summary

An overview of the preliminary program plan for moving flywheel technology out of the laboratory and onto the Space Station as a battery/BCDU replacement is presented in this section. Although this plan is cursory, its objectives, schedule, and milestones are based on the Space Station Battery/BCDU development plan that was initially proposed in 1987 and actually implemented over the succeeding years at Rocketdyne in Work Package 4. This program will result in flywheel technology demonstrations by CY1997 and design, development, fabrication, test, delivery, and operational support of the flywheel demonstrator unit in CY2000 and eventual replacement of all Space Station battery/BCDU ORUs by CY2006.

There are three major flywheel/PPU program objectives:

- Demonstrating the four critical flywheel technologies.
- Space Station ORU Demonstration Unit test.
- Battery/BCDU replacement.

The tasks required to meet these objectives are sequentially ordered as shown in Fig. 8-1. It is logical to assume that flywheel technology must be proven prior to the ORU demonstration flight and that the flywheel ORU demonstration must be successful prior to replacement of the Space Station battery/BCDU ORUs by flywheel/PPU ORUs. As such, the overall flywheel development plan is divided into three distinct programs that address each major flywheel development objective. These programs are individually scheduled and implemented in logical sequential order. The initial technology demonstration program is relatively independent of the Space Station program. The two other flywheel programs, however, are dependent on actual Space Station Alpha milestones and schedule.

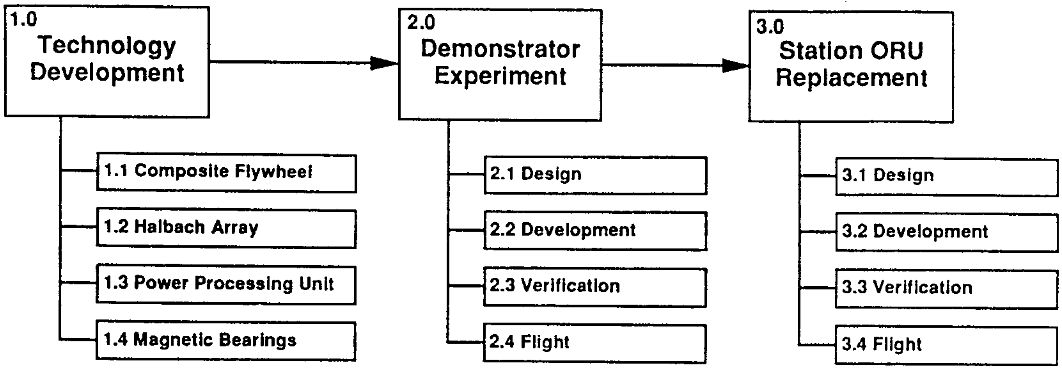


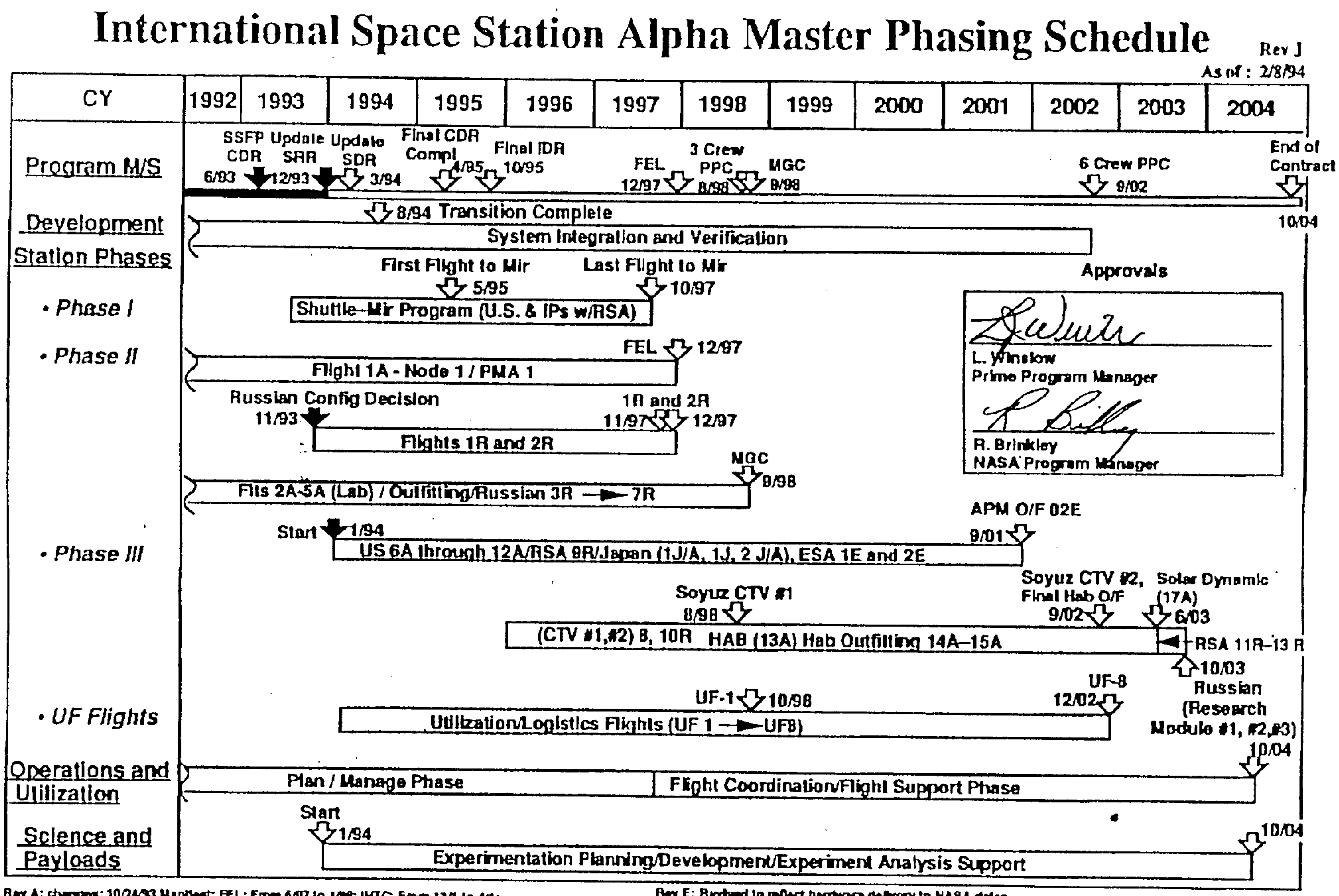
Figure 8-1
The Flywheel Development Program is Divided into Three Basic Tasks in Sequential Order.

For purposes of this study we are assuming the Alpha station program will be implemented as proposed in Ref. 8-1 and that all milestones will be completed on schedule. Thus, the proposed flywheel program schedule is based on the amended Alpha Station program, effective February 10, 1994 and shown in Fig. 8-2. Significant Alpha program milestones that impact flywheel development activities include:

- Final Alpha PDR date (10/95).
- First Station assembly launch, flight number 01R (10/97).
- Battery/BCDU ORUs delivered and installed (10/99 - 12/00).
- U.S. assembly complete, 6-person permanent on-orbit presence (9/02).

The overall flywheel development program schedule is shown in Fig.8-3. Flywheel development begins in CY1995 with the technology development program. This program is split into four subtasks that target the four key flywheel technologies; flywheel, PPU, magnetic bearings, and Halbach Array. These tasks are conducted simultaneously for 36 months. After all key flywheel technologies have been demonstrated, the requirements and specifications for the flywheel demonstrator experiment will be specified. The flywheel demonstrator ORU program starts in CY1997 and lasts 48 months until the postflight checkout of the demonstrator unit. At that point in the program a decision to replace the existing battery/BCDU ORUs is made, and the production flywheel program commences in CY2001. This program lasts 70 months until all flywheel ORUs are operational by the middle of CY2006.

An overview of the total program logic that connects all three phases of the flywheel development program is presented in Fig. 8-4. Each program phase begins with an initial requirements review



Rev A: changes: 10/24/93 Manifest; FEL: From 6/97 to 1/98; IHTC: From 11/1 to 4/1;
PHC: From TBD to 5/98
Rev B: 11/1/93 Addendum to Program Implementation Plan, Renumbered Russian Flight
Final Russian Launch attached to PHC Rather than IHTC
Rev C: Manifest Date 11/9/93
Rev D: Manifest Date 11/12/93 (Attached to Revision A of the JPD)
Rev E: Revised to reflect hardware delivery to NASA dates
Rev F: Added Build-up phases, removed TBDs & PHC M/Ss
Rev G: Added Mir-Shuttle phase and revised phases, added 6 month to launch dates,
corrected SSFP CDR data, renamed to Master Phasing Schedule
Rev H: Added (2) American/(1) Russian flights and updated to manifest dated 1/14/94,
PPC= Permanent Presence Capability,
(Note: Phase 1 flights are tentative)
Rev I: Revised to reflect 1 month adjustment to Prelim. 1-14-94 manifest
Rev J: Revised to reflect 2-3-94 SDR manifest baseline

GR013/28B/GRFX/S. Loncy/2-7-94

Figure 8-2
Space Station Alpha Program and System Phasing Schedule, Effective February 1994.

Overall Program

Flywheel Development Plan 1994 - 2006

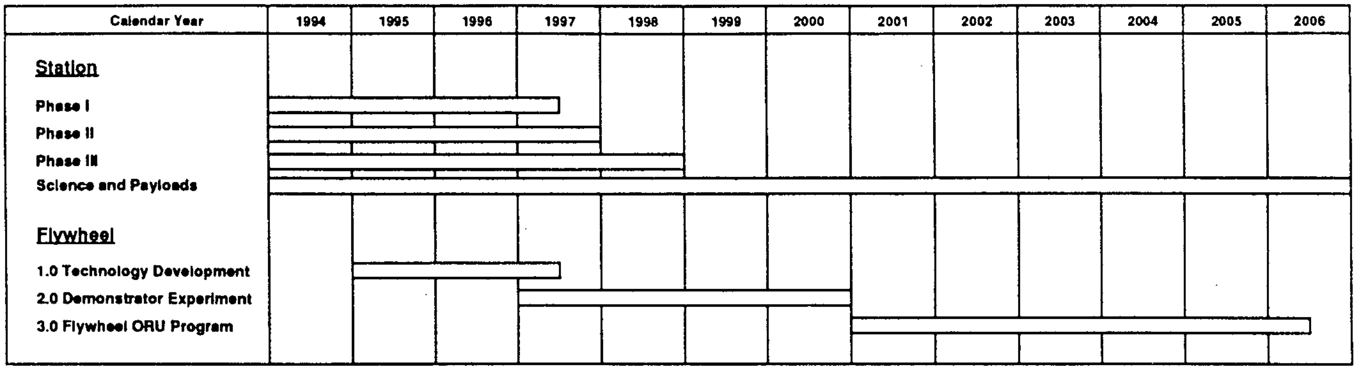


Figure 8-3
Flywheel Development Program, CY1995 - CY2006.

that defines the technical specifications of each task. Key inputs into the flywheel technology program include an assessment of the current technical status of each key flywheel component and a definition of the space-based flywheel requirements. These two evaluations will define the technical goals for each key flywheel component and shape the programs over the following 24 month period.

The technical status of the four critical flywheel technologies will be evaluated at end of the technology programs, and a decision made to initiate the flywheel demonstrator program. If the flywheel technology programs have made insufficient progress by this point, additional technology development time or reevaluation of the initial set of technical goals may be necessary. A demonstrator requirements review and flywheel technology review are the two key inputs into the demonstrator design task. After demonstrator design, engineering, qualification, and demonstrator fabrication tasks result in a flight unit. An assessment of station power availability, site considerations, and overall station status determines the actual demonstrator flight, installation and operational schedule. After completing the three month test period, the demonstrator will be removed and examined.

The decision to eventually replace all battery/BCDU units on station Alpha is a total evaluation of the status of flywheel technology at that time, a status review of station Alpha, and consideration of the flywheel demonstrator performance. Once the decision to replace the battery/BCDU ORUS is made, these inputs are used to define the final flywheel/PPU ORU specification. This specification initiates the ORU design task and subsequent engineering, QA, acceptance and ORU production

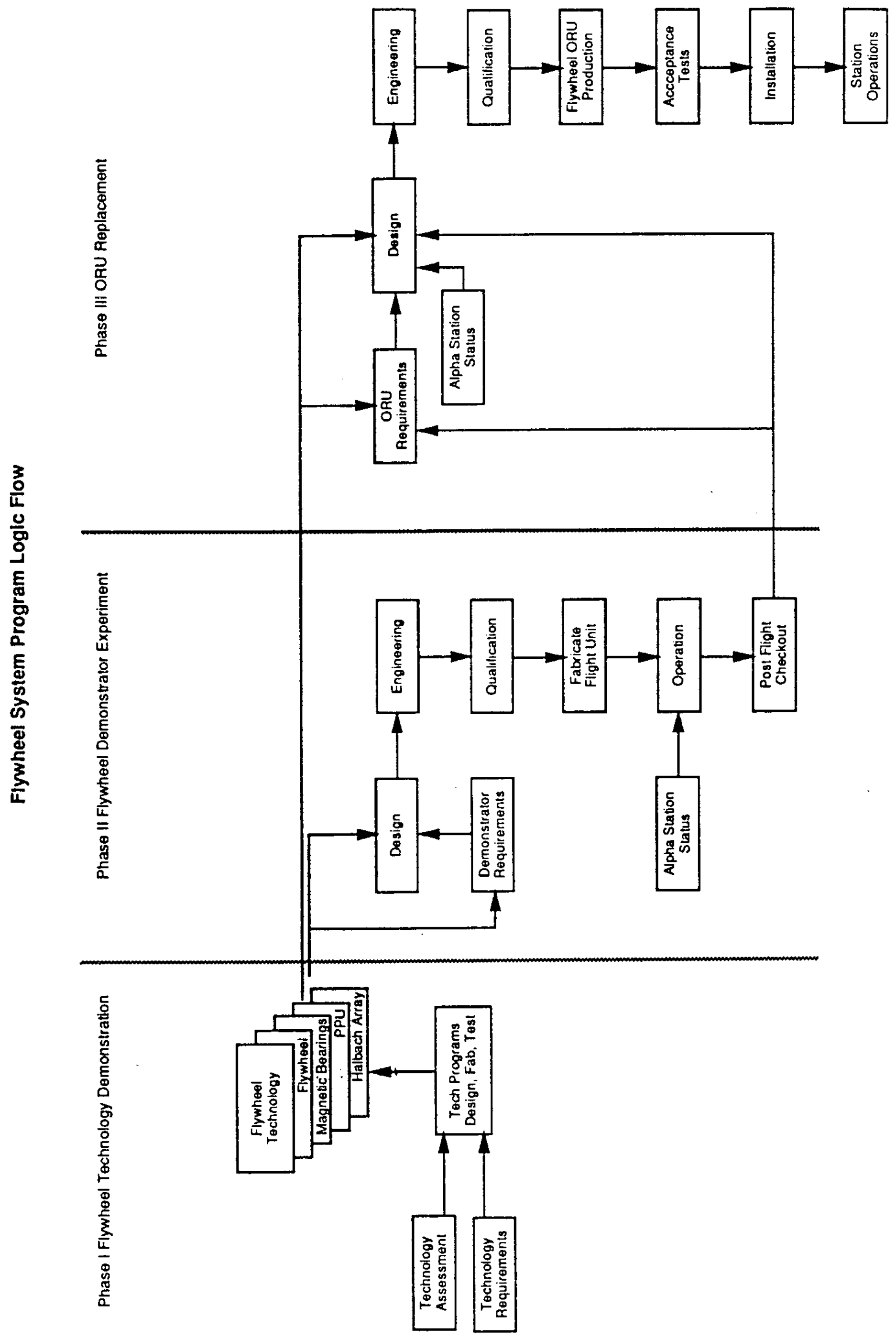


Figure 8-4
Overview of Flywheel Development Program Logic Encompassing the Three Basic Flywheel Programs.

tasks. Battery/BCDU replacement is performed individually for each IEA at a time, over an 18 month period beginning with the S4 IEA unit. The overall program ends in 2006 with the replacement of the battery/BCDU units with flywheel/PPU ORUs in the P4 IEA.

The key flywheel development task that enables all subsequent tasks throughout this proposed program is the maturation and demonstration of the four key flywheel technologies; the flywheel, PPU, magnetic bearings and Halbach Array. Once these technologies have been demonstrated both the flywheel demonstrator and ORU replacement programs can proceed.

8.2 Flywheel Technology Development Plan

This section discusses the technology development program for the four key flywheel components: the flywheel, PPU, magnetic bearings, and Halbach Array. Overall technical objectives, program logic and a cursory schedule for each component is presented. Realistic technical milestones for each component are proposed.

An assessment of the existing technology readiness level (TRL) of the flywheel, Halbach Array, magnetic bearings, and PPU is summarized in Table 8-1. The overall objective of the flywheel technology development program is to improve these technology readiness levels to a minimum TRL 5 before advancing into the flywheel demonstrator development program. Technology goals (summarized in Table 8-2) for each component will be determined at the start of each program by a requirements flowdown from the flywheel ORU specifications. The uneven TRL status of the four flywheel components suggests program resources be allocated appropriately to meet the TRL 5 objective. In this case individual technology programs for each key flywheel component are defined that account for these TRL differences.

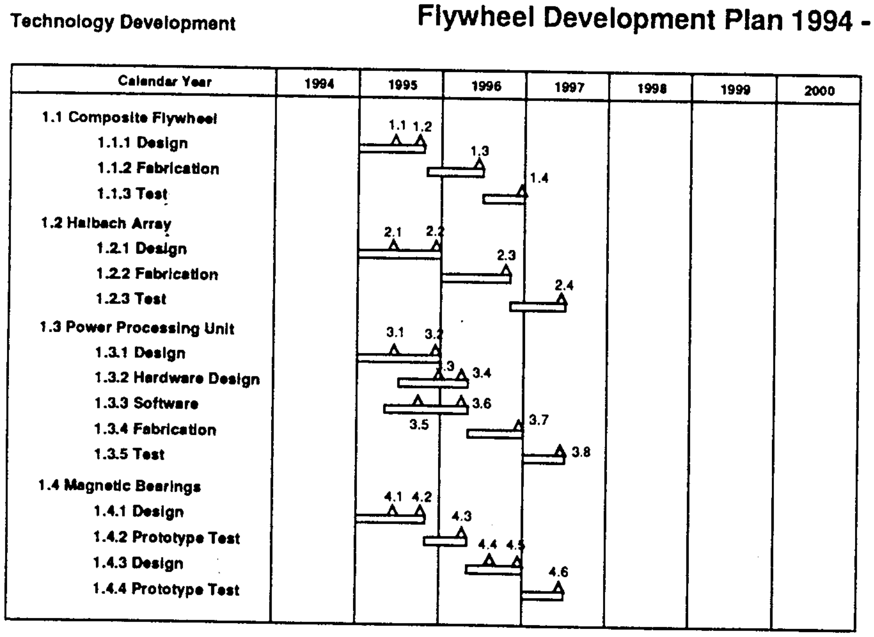
Flywheel Component	TRL	Comments
Composite Flywheel	2	Conceptual design exists
Halbach Array	3	Concept tested in laboratory
Magnetic Bearings	4	Well known and tested; tailor to flywheel specifications
Power Processing Unit	4	Tailor to flywheel specifications

Table 8-1
Technology Readiness Level Assessment for Critical Flywheel Components.

Flywheel Component	Technical Issues
Composite Flywheel	Structural integrity, performance, mass
Halbach Array	Efficiency and mass
Magnetic Bearings	Stability, performance, and mass
Power Processing Unit	Efficiency and mass

Table 8-2
List of Flywheel Component Technical Issues.

All technology programs will be conducted simultaneously over a thirty month period. Figure 8-5 presents a tentative schedule of all four technology program subtasks. Although each subtask will be tailored specifically for each key technology, all are divided into design, laboratory fabrication and test phases. Milestones for each subtask are defined at each critical point in each program. The logistics of performing each task are also similar in structure but different in content, as shown in Figure 8-6.



Milestone List

Number	Description
1.1	Flywheel PDR
1.2	Flywheel CDR
1.3	Flywheel Fabrication Completed
1.4	Flywheel Concept Proven
2.1	M/G PDR
2.2	M/G CDR
2.3	M/G Fabrication Completed
2.4	M/G Concept Proven
3.1	PPU PDR
3.2	PPU CDR
3.3	PPU Hardware Design PDR
3.4	PPU Hardware Design CDR
3.5	Software PDR
3.6	Software CDR
3.7	PPU Fabrication COmpleted
3.8	PPU Concept Proven
4.1	Magnetic Bearing PDR
4.2	Magnetic Bearing CDR
4.3	Magnetic Bearing Fab & Test
4.4	Magnetic Bearing PDR
4.5	Magnetic Bearing CDR
4.6	Magnetic Bearing Conept Proven

Figure 8-5
Thirty Month Flywheel Technology Development Plan Schedule.

The first two critical steps in the technology program are the assessment of the existing technology base and a requirements flowdown from a realistic design evaluation of the flywheel ORU/PPU replacement. The technology assessment for each component will be conducted by the experts in each field. The technology requirements of the replacement flywheel ORU unit will be determined by evaluating the Space Station Alpha battery/BCDU specifications and the replacement ORU conceptual design. These two inputs will determine realistic technology goals and construct an individual technology program for each flywheel component technology to meet those goals. The goals and milestones presented in this study represents an initial consideration of many of these technology issues.

The remainder of the technology development program for all flywheel components consists of a design, fabrication or laboratory mockup, and a test phase. The design phase consists of preliminary and comprehensive design milestones. A laboratory prototype is subsequently constructed and tested. Should the laboratory component not meet the technical objectives set forth earlier in the program, additional design, fabrication and testing may be required to meet the TRL 5 goal. The TRL 2 and 3 articles, the composite flywheel and Halbach Array, require two series of tests to graduate to a TRL 5 rating. The preliminary tests examine the device functionality relative to the desired specification. For example, a key requirement for the flywheel disc is to maintain structural integrity not only within its speed range of 26 - 52 kpm, but also up to 78 kpm in the event of overspeed conditions. The first test series will examine the integrity issue within the 26 - 52 kpm range. Once this requirement is met in the preliminary tests and TRL 4 is achieved, a second series of environmental tests is conducted to examine performance up to the 78 kpm range. In addition, the flywheel will be subjected to vacuum, temperature, and other dynamic loading tests in a space environment to achieve the final TRL 5 rating.

The end result for all technology programs are flywheel components at TRL 5 that can be integrated into either the demonstrator experiment or the flywheel replacement ORU. At this point in the program the critical deployment issues evolve from technical uncertainties to engineering and cost issues.

8.3 Flywheel Demonstrator Development Plan

The program plan of the flywheel demonstrator experiment is designed to meet the overall demonstrator objective: develop a generic flywheel experiment for the Space Station Alpha consisting of all four key flywheel components integrated together in a single package that demonstrates (and qualifies) EM energy storage in a space environment over an extended period of time. In doing so, the technology readiness level of EM energy storage increases from TRL 5 to TRL 7. The end result is that once EM energy storage is flight qualified and a multitude of manned and robotic missions are consequently enabled. One such mission is the Space Station Alpha

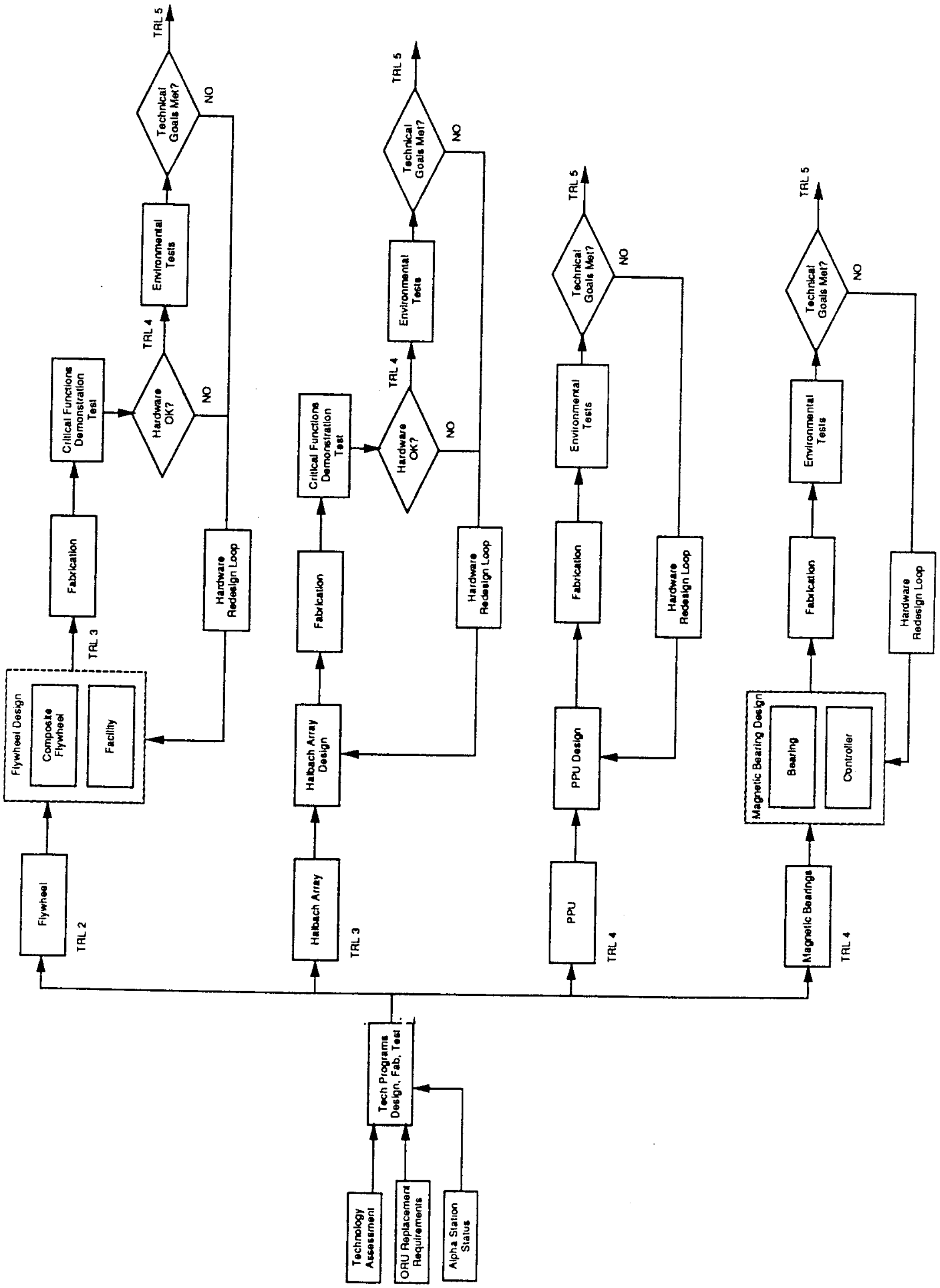


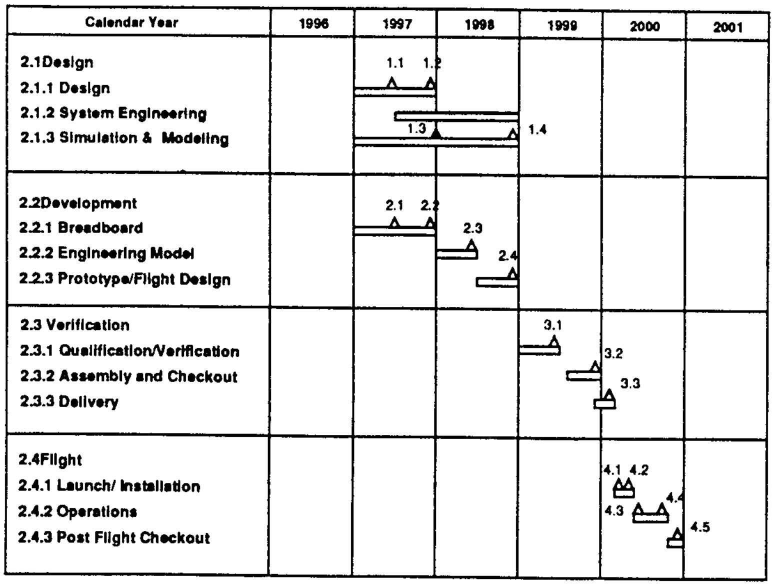
Figure 8-6
Flywheel Technology Development Plan Program Logic.

battery/BCDU replacement program discussed in the next section. Other orbital, deep-space, planetary, manned/robotic missions can also implement tailored EM energy storage technology over traditional battery storage methods as well, once EM technology is flight qualified.

The flywheel demonstrator experiment program schedule, shown in Fig. 8-7, commences in CY1997 and concludes in CY2000 for a total length of four years. Since the flywheel demonstrator experiment will be deployed on Space Station Alpha, the complete installation of all battery/BCDU units by the end of CY2000 is a key requirement to this program. Indeed, the flywheel demonstrator program schedule was tailored to fit the Space Station Alpha schedule and assumes that the actual construction and deployment of Station hardware will occur as currently planned. It is assumed that excess power will be available for demonstrator operational testing because of total power overcapacity. This is dependent upon the eventual Station loading, which is unknown at this time. As shown in Fig. 8-7, installation and operation of the demonstrator experiment occurs early in the Space Station life (CY2000). This early date was chosen so the results of the demonstrator experiment can be fully utilized for the flywheel replacement ORU design task.

Demonstrator Experiment

Flywheel Development Plan 1996 - 2001



Milestone List

Number	Description
1.1	Demonstrator PDR
1.2	Demonstrator CDR
1.3	System Model Complete
1.4	DemonstratorSimulation Complete
2.1	Breadboard Fabrication Complete
2.2	Breadboard Tests Complete
2.3	Engineering Model Tests Complete
2.4	Flight Design Complete
3.1	Flight Unit Qualified
3.2	Final Assembly Complete
3.3	Delivered for Launch
4.1	Launch
4.2	Station Installation Complete
4.3	Demonstrator Checkout Complete
4.4	Demonstrator Tests Complete
4.5	Post Flight Checkout Complete

Figure 8-7
Forty eight Month Flywheel Demonstrator Development Plan Schedule.

There are four overall subtasks defined in the demonstrator program; demonstrator design, development, verification, and flight operations. These program elements are logically connected as shown in Fig. 8-8. The two key inputs into the design subtask are an assessment of the four key flywheel technologies and the demonstrator experiment specifications. PDR and CDR milestones are established during the one year design subtask schedule. System engineering of the total demonstrator package commences after the preliminary design is completed and extends for approximately 18 months until the demonstrator engineering model is complete. The system engineering task is responsible for resolving both internal and external (to Space Station Alpha) interface issues. Moreover, this subtask is responsible for total system engineering of the flight unit that is developed and qualified. Simulation and modeling of the demonstrator experiment has several objectives:

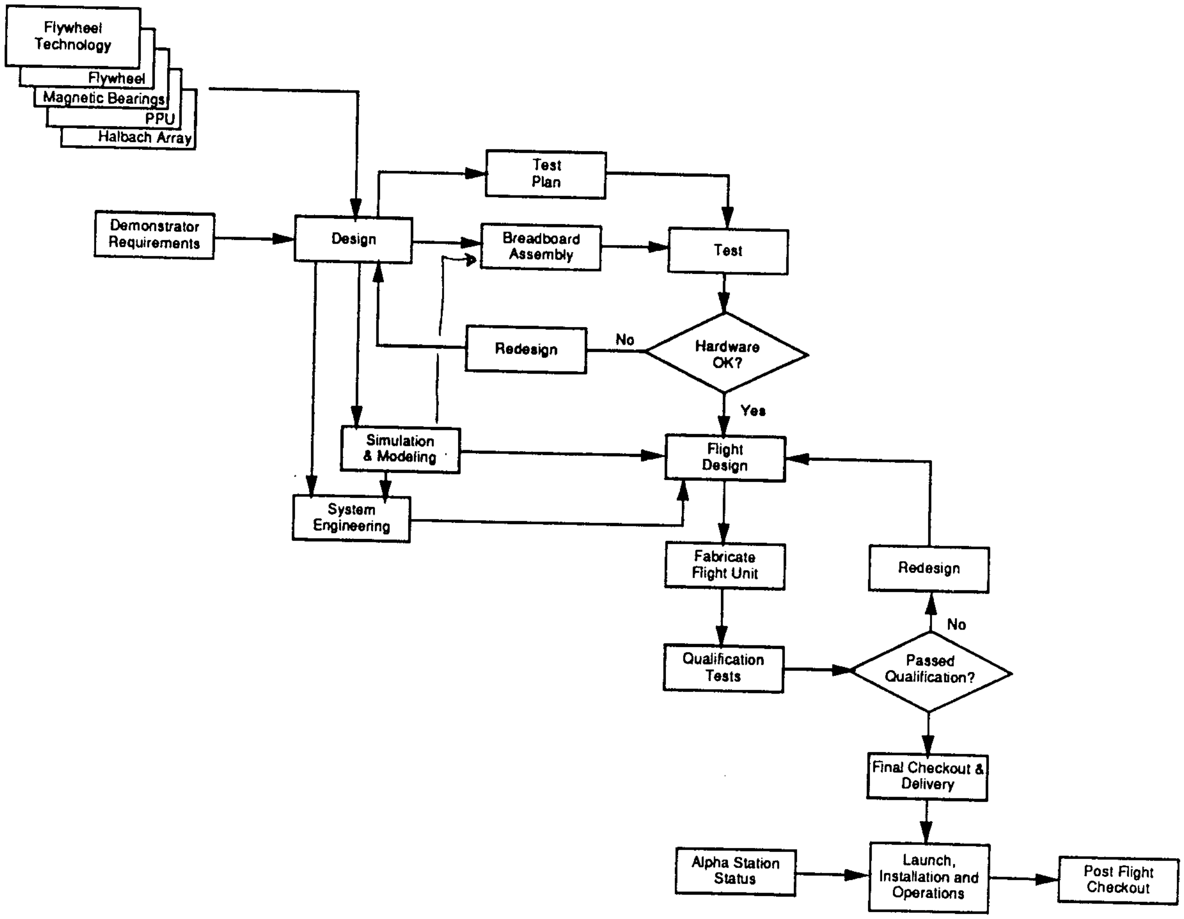


Figure 8-8
Flywheel Demonstrator Development Plan Program Logic.

- Transient analysis.
- Design support.
- Demonstrator test program development.
- Space Station Alpha EPS interface impacts.
- Failure mode analysis.
- Software development.

These results are fed throughout the design, development and qualification of the flight unit as required.

The flywheel development subtask has two primary objectives:

- Development of a laboratory breadboard system that demonstrates the total flywheel demonstrator system meets all specifications.
- Development of the prototype demonstrator that will be flight qualified.

It is estimated that these objectives can be met over a two year period. Breadboard development and testing will be conducted at the Space Electronics Laboratory (SPEL) facility at the Rocketdyne Division of Rockwell International. This breadboard demonstrator package is a significant milestone, as a total space-based EM energy storage system has never been demonstrated. Design feedback from these tests are a critical input into the system engineering of the flight system and the program was sequentially designed to critically analyze the breadboard prior to a fabrication commitment of the flight system. In other words, flight design activities leading to the flight unit will not occur until all breadboard problems are satisfactorily resolved. At that point in the program, the flight prototype unit is fabricated and subjected to the flight qualification process.

After the prototype unit is flight qualified, the actual flight unit is fabricated and tested. Once these tests are complete the unit and any ground support equipment transferred to KSC. Flight operations consist of prelaunch ground preparation, launch, installation on Space Station Alpha, actual demonstrator tests, and the post flight checkout. These activities are highly dependent upon the status of the Space Station Alpha. Delays in construction or power capacity buildup will impact the flywheel demonstrator objectives and schedule. Assuming no delays occur and shuttle bay room is available, the demonstrator will be launched in early CY2000. The demonstrator package is designed to expedite Space Station installation with minimal structural/electrical scarring. The actual demonstrator operation is dependent upon Space Station conditions, but the testing program is flexible within the designated three month test period to allow for intermittent activity. Once all tests are completed the demonstrator package is returned by available shuttle for a post test evaluation. These tests consist of both a detailed inspection of all demonstrator hardware and electronics and an evaluation of the test results. With favorable results, the technology readiness of the flywheel technology jumps from TRL 5 to TRL 9. This is the end result of the flywheel demonstrator program, with hopefully positive results that prove to be the springboard to both the Space Station battery/BCDU ORU replacement program and general acceptance of EM energy storage technology to other space missions.

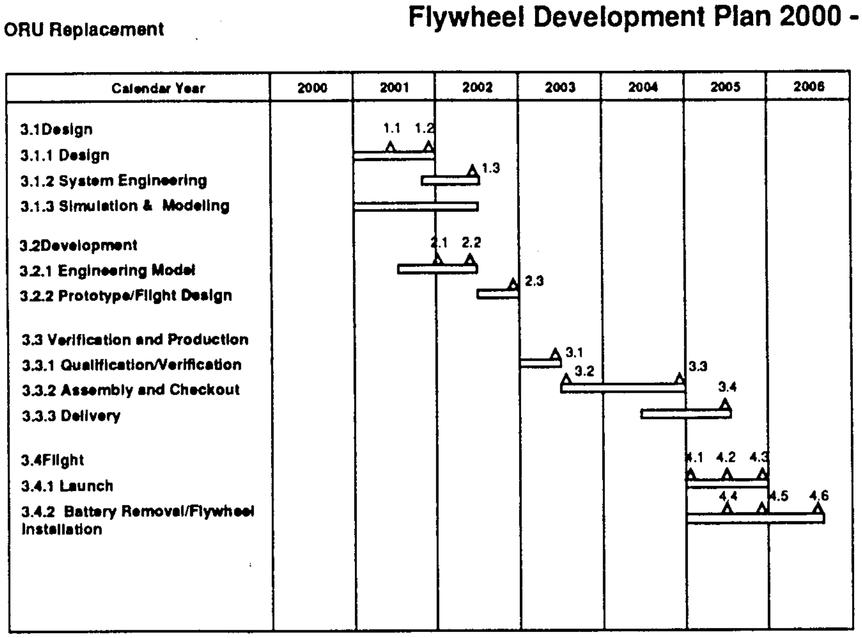
8.4 Flywheel ORU Development Plan

The decision to eventually replace all Space Station Alpha battery/BCDU ORUs with flywheel ORUs is a complex one, with several technical, economic, schedule considerations. As demonstrated in section 6.0, the design life of both the Space Station and flywheel system dictate the economic benefit of flywheels. Changes to either these parameters may make it economically unfeasible to deploy flywheel ORUs. Removal of all technical risk of the flywheel technology through the flywheel technology development program and the flywheel demonstrator flight experiment is critical to establish the integrity of EM energy storage. The overall flywheel development schedule (including the ORU replacement program) must meet the Space Station battery/BCDU 5-year replacement milestone in CY2005 when the battery units are scheduled for replacement. Assuming all precursor requirements are fulfilled and the decision favorable, the flywheel ORU replacement program can proceed. This section describes the 5 1/2 year program that culminates in CY2006 with the replacement of all Space Station Alpha battery/BCDU units with flywheel ORUs.

The program plan for the flywheel ORU development is built upon the foundation of the two previous flywheel programs; the flywheel component technology programs and demonstrator experiment program. There may certainly be other paths that eliminate these two initial steps and proceed directly with the ORU replacement program. The history of flight-qualified space-based energy production and storage systems demonstrates that dynamic devices, such as the flywheel, are not favored (despite specific energy, efficiency, design life advantages) because of perceived high technical risk. Thus, it is assumed that all technical issues must be resolutely resolved before the flywheel system can be deployed on a manned vehicle. In this case it is hoped that these technical issues are resolved in the two previous flywheel programs. Furthermore, the actual flight experience of the demonstrator experiment is a critical design input into the ORU design process.

The proposed ORU replacement development commences in CY2001 after the successful flywheel demonstrator experiment takes place. The program ends in CY2006 when the last battery/BCDU ORU in the P4 IEA is replaced. The overall program schedule is shown in Fig. 8-9. The ORU replacement program is divided into four major subtasks; design, development, verification, and flight. Like the demonstrator experiment program, these subtasks are logically connected as shown in Fig. 8-10. As previously mentioned, there are several key inputs into the flywheel ORU specification; the state of flywheel technology, the state of Space Station Alpha and the design feedback from the demonstrator experiment.

The design subtask commences when the flywheel ORU specifications are determined. Since the demonstrator flywheel system is exactly the same as the proposed ORU replacement system, the design task will be similar to the demonstrator experiment design subtask. Two design milestones, a PDR and CDR are performed during the first year. System engineering and simulation tasks are defined to examine design and off-design issues, investigate Space Station Alpha interface problems, examine possible modes of failure, and develop the flywheel control software. It is desired that the similarity between the flywheel demonstrator unit and the ORU replacement unit simplifies and expedites all these tasks.



Milestone List

Number	Description
1.1	ORU Replacement PDR
1.2	ORU Replacement CDR
1.3	System Engineering Complete
2.1	Engineering Model Completed
2.2	Engineering Tests Completed
2.3	Flight Design Completed
3.1	ORU Replacement Flight Unit Qualified
3.2	Manufacture Production Units Begins
3.3	Production Completed
3.4	All Units Delivered
4.1	Flight 1: S4 IEA Units
4.2	Flight 2: S6 IEA Units
4.3	Flight 3: P4 IEA Units
4.4	S4 IEA Replacement Completed
4.5	S6 IEA Replacement Completed
4.6	P4 IEA Replacement Completed

Figure 8-9
Seventy Month Flywheel ORU Replacement Development Plan Schedule.

The development subtask emphasis is on qualification of the ORU flight unit. Despite the similarity to the demonstrator flywheel system, a prototype ORU consisting of the flywheel box and PPU box are developed and tested. Once the basic flywheel ORU unit is qualified, flight units are produced, checked out and delivered to KSC.

The flywheel/PPU ORUs are installed in each IEA over an eighteen month period, dependent upon Space Shuttle scheduling. Three Shuttle flights are required to deliver the full manifest of flywheel/PPU ORUS for the three IEAs. The first flight of flywheel ORUs occurs in early CY2005 followed by the second flight six months later and the third flight six months after that. Replacement of the battery/BCDU units is systematically conducted for each IEA until all battery/BCDUs are replaced in mid CY2006.

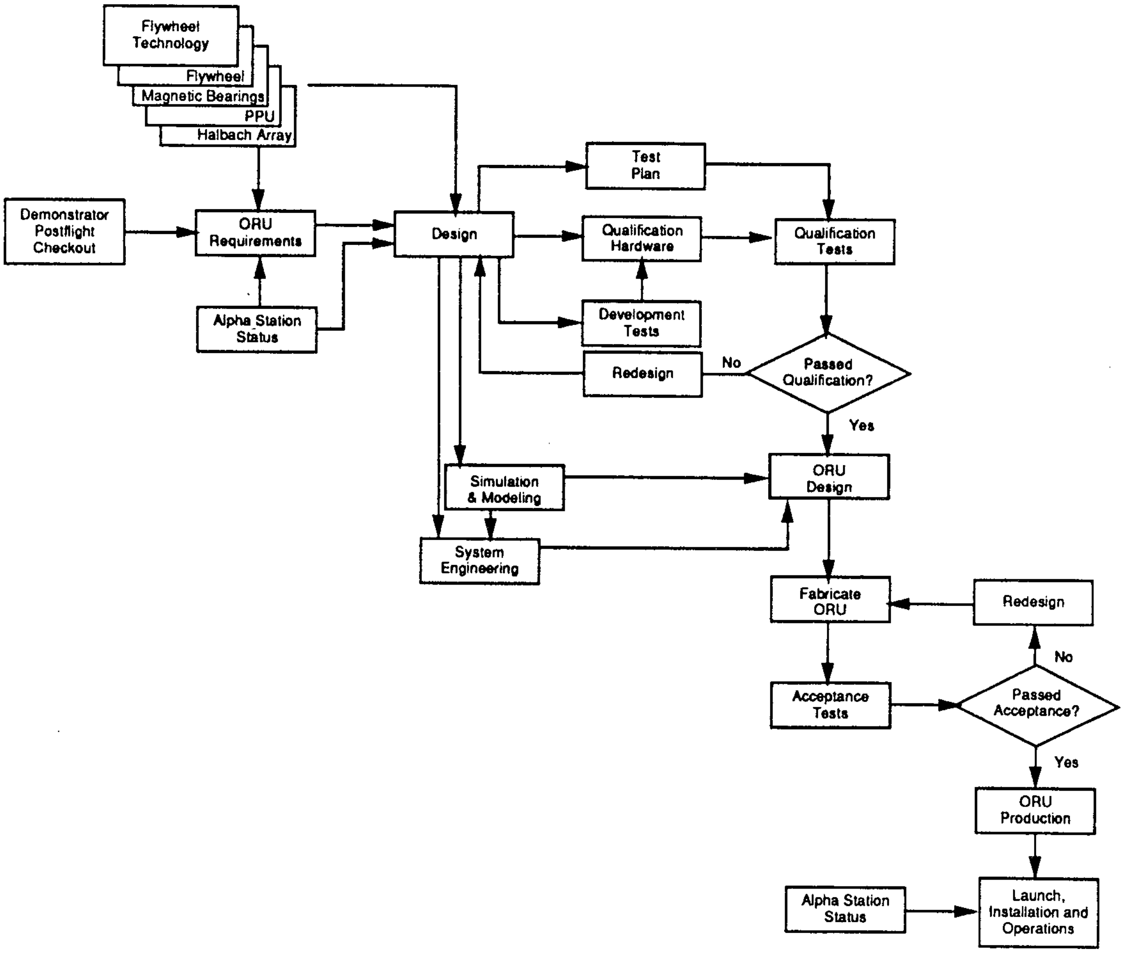


Figure 8-10
Flywheel ORU Replacement Development Plan Program Logic.

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9.0 Conclusions

This study has examined Space Station Alpha-flywheel ORU interface issues, conceptualized a flywheel demonstrator experiment for the Space Station, estimated development and production costs for the flywheel replacement ORU program, and proposed a development plan for the three flywheel programs.

The interface between the flywheel and PPU ORUs and the Station EPS was clarified, and no major engineering interface issues were found that overtly prevents the flywheel replacement program. Nonetheless, the decision to replace the first set of battery/BCDU ORUs after their design life expires is a complex one that is based on more factors than simply the engineering feasibility issue. Station life, flywheel development costs, flywheel life, component technology status and development all play critical roles in this decision.

A generic flywheel demonstrator experiment was proposed for the Space Station that could resolve many technology issues and operational concerns, and would be a major step towards eventual flywheel deployment aboard Space Station Alpha. Indeed, this experiment would be a major step for eventual flywheel use for a wide variety of space missions. A small flywheel test bed was proposed to serve as the principal interface between the flywheel demonstrator and Space Station. This platform could also serve as a generic space-based test bed for other power generation/energy storage devices besides the flywheel systems, such as solar dynamic devices (Rankine, Brayton, Stirling), advanced battery technologies, and thermal management technology. It is recommended that additional work on this space power technology test bed concept for the Space Station investigate this multiple use possibility.

This study also performed a cursory life-cycle cost analysis of the flywheel that showed that the flywheel replacement of the battery system is feasible only for Space Station life greater than ten years. Furthermore, the design life of the flywheel system must be maximized to increase these savings. The inherent problem is the double development cost incurred by investing in two different technologies, first batteries and then flywheels. This cost can only be recovered by committing to both longer Station life and flywheel design life, thereby amortizing the original investment over a longer period of time. The difficult decision is to commit to an early flywheel technology development program that will not pay for itself until many years in the future.

A twelve year flywheel program that starts with basic technology development and ends with Station battery replacement in CY2006 was proposed. This program was partially based on Rocketdyne's Work Package 4 experience, the revised Space Station Alpha master schedule, and specific flywheel technology goals. Again, there were no severe programmatic problems identified, but it was noted that the critical path to accomplish all three programs; technology development, demonstrator, and ORU replacement program begins in the early development phase. That is, flywheel component technology levels must be increased sufficiently early in the program to meet the Space Station master schedule and meet the goals of the flywheel programs. Without the basic flywheel component technology the demonstrator and ORU replacement programs will be postponed to extinction. This is why a multiple technology program that encompasses the four key areas, composite flywheel, Halbach Array, magnetic bearings, and power electronics was proposed.

Overall, this study discovered no basic reasons why flywheel technology cannot be deployed on the Space Station or other space platforms, provided the basic flywheel technology is improved beyond the current level. Unfortunately, the cursory nature of this study could not investigate several areas of engineering interest, including;

- Flywheel system transient response to EPS fault conditions.
- Flywheel system stability computation.
- SINDA Thermal analysis of the flywheel ORU and demonstrator package.
- Preliminary design of flywheel demonstrator.
- Power electronics and Halbach array transient and steady-state response.
- Space Station structural dynamics and center of mass computations for the demonstrator and ORU replacement scenarios.
- Power technology Space Station Test Bed requirements and design.

These issues can be resolved with additional study in these areas.

10.0 References

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Appendix A

Halbach Array Data

Figures

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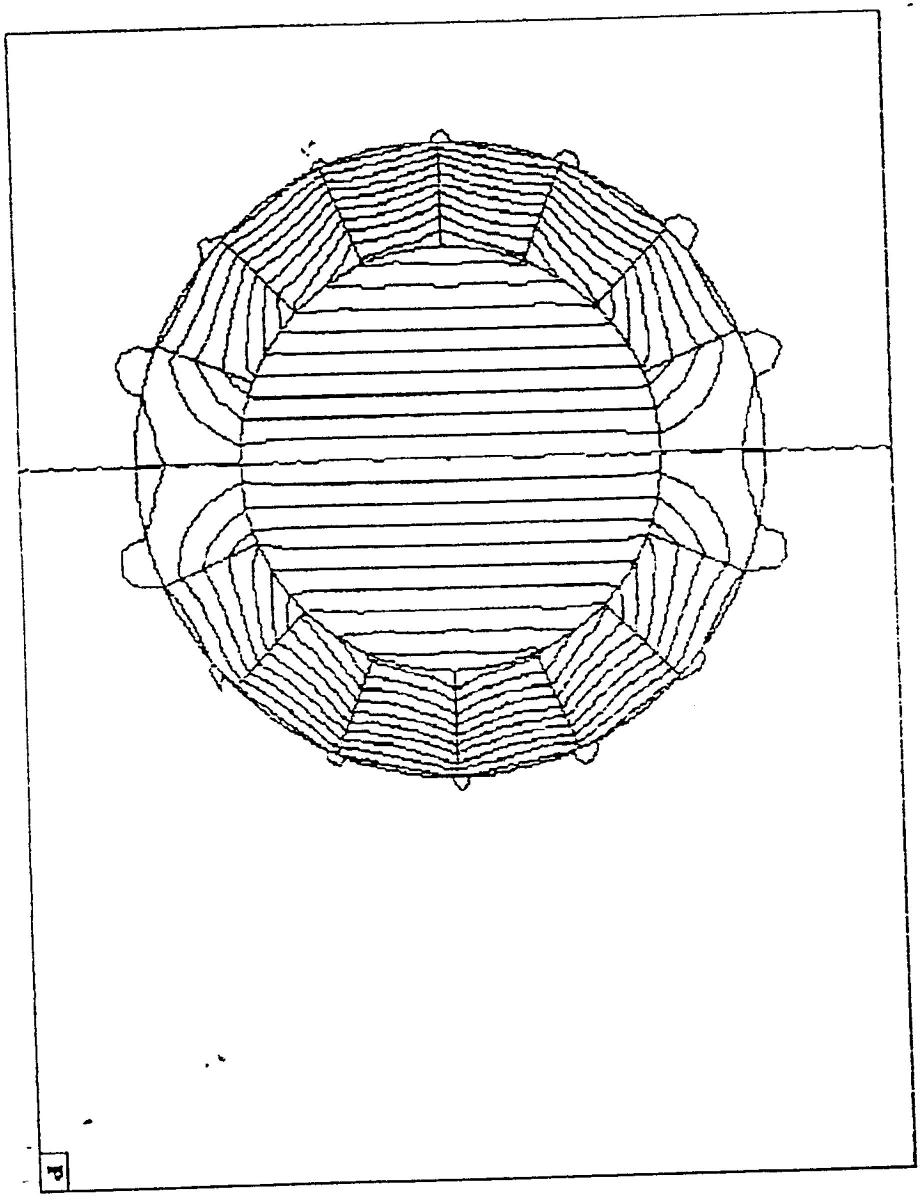

```
DATE = 27/93/  1      TIME= 11:24:13.95
Current database: C:\MAGNETO\DATA\ROCKDYNE
Current file:  rd1
Mode of analysis:  MAGNETO 2D Field analysis
Analysis type:          Static mode
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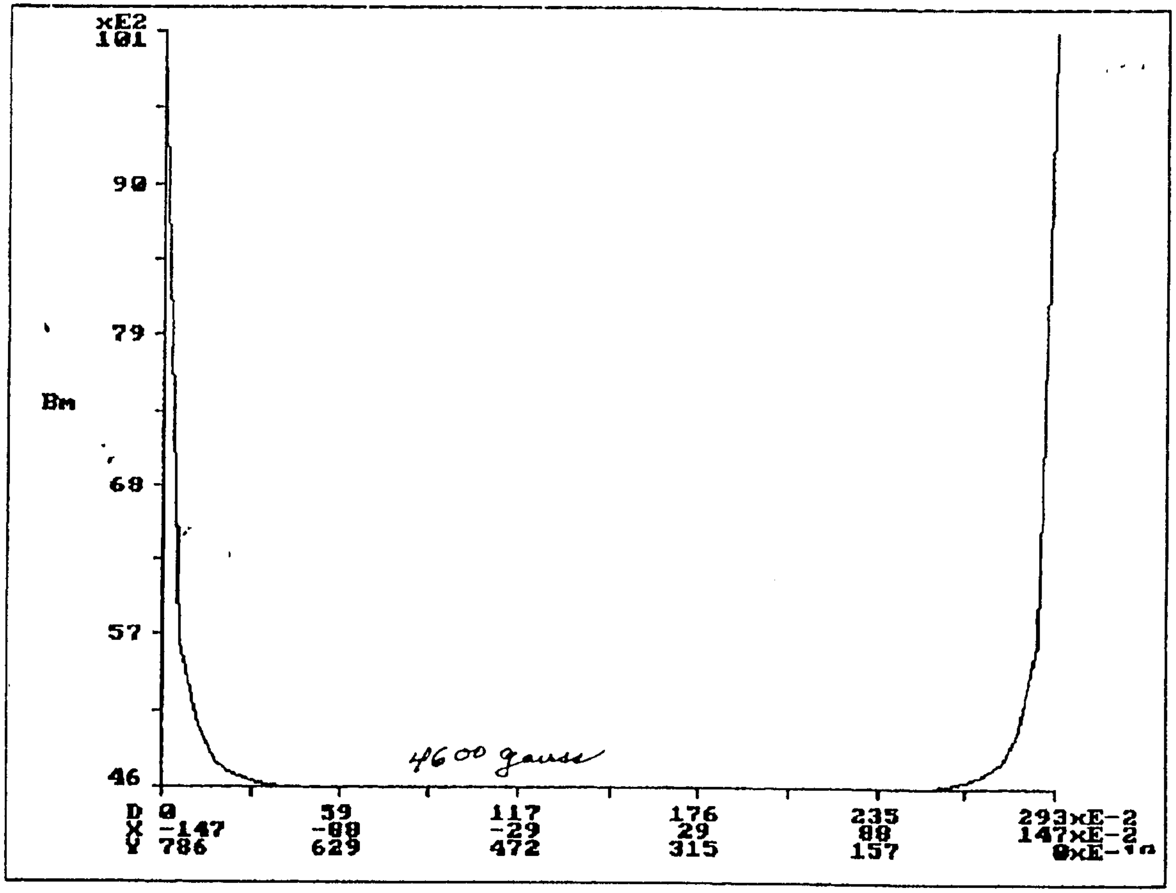

Dipole field, no steel in stator

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DATE = 27/93/   1      TIME= 11:14:47.83
Current database: C:\MAGNETO\DATA\ROCKDYNE
Current file:  rd1
Mode of analysis:   MAGNETO 2D Field analysis
Analysis type:           Static mode
```

ISS-DEMO-5-26-94

	Gene Espiritu Santo	8.41 DESIGN NUMBER	MOTOR / GENERATOR HALBACH ARRAY					
	ROCKETDYNE DIV.							
	5/26/94		RUN # 1		RUN # 2		RUN # 3	
	EMB DEMO		DATA	CALC	DATA	CALC	DATA	CALC
	WINDING PARAMETERS,(stator)							
1	l: (m), coil length		0.160		0.160		0.160	
2	l: (In)		6.299		6.299		6.299	
3	Wire Ga #		12		12		12	
4	Cd: (m) cond/insul diameter		0.0021		0.0021		0.0021	
5	Cd: (In)		0.0808		0.0808		0.0808	
6	A:(sq-In),wire cross section		0.0051		0.0051		0.0051	
7	A:(sq-mm),wire cross section		3.3081		3.3081		3.3081	
8	Im:(A),conductor max current			29.8		29.8		29.8
9	q: (A-mm^2),current density		9		9		9	
	FIRST LAYER WINDING (1L)							
10	n1: 1L turns per layer		12		12		12	
11	S1=3*2*n1*Cd,(m)1L mean circunf.		0.148		0.148		0.148	
12	d1=S1/π,(m)1L mean diameter		0.047		0.047		0.047	
13	r1=d1/2,(m) 1L mean radii		0.024		0.024		0.024	
	SECOND LAYER WINDING (2L)							
14	r2=r1-Cd,(m) 2L mean radii		0.021		0.021		0.021	
15	d2=2*r2,(m) 2L mean diameter		0.043		0.043		0.043	
16	S2=π*d2,(m)2L mean circunf.		0.135		0.135		0.135	
17	k4=S2/Cd, 2L max # conductors		65.72		65.72		65.72	
18	n2'=k4/6, 2L max turns/layer			10.95		10.95		10.95
19	n2:(DATA),2L turns per layer		0		0		0	
20	n=n1+n2 coil turns per phase		12		12		12	
	STATOR DIMENSIONS							
21	STAr=d1/2+Cd/2,(m)outer stator radii		0.025		0.025		0.025	
22	STAr: (In)			0.966		0.966		0.966
23	STAd=d1+Cd,(m) outer stator diam.		0.049		0.049		0.049	
24	STAd: (In)			1.933		1.933		1.933
	RESISTANCE							
25	St=St1+St2,(m)total length/Ø		20.38		20.38		20.38	
26	St1=2(l+(2*d1))*n1,(m) 1L length/Ø		6.21		6.21		6.21	
27	St1: (ft)		20.38		20.38		20.38	
28	St2=2(l+(2*d2))*n2,(m) 2L length/Ø		0.00		0.00		0.00	
29	St2:(ft)		0.00		0.00		0.00	
30	k2=1.588 ohms/1000ft		1.588		1.588		1.588	
31	Rs=St*k2/1000,(ohms)resistance/1Ø			0.032		0.032		0.032
	INDUCTANCE							
32	L1=μ*(n1)^2*A1/(l1+0.45d1),(Hy)			2.97E-05		2.97E-05		2.97E-05
33	L2=μ*(n2)^2*A2/(l2+0.45d2),(Hy)			0		0		0
34	μ=4π*10^-7		1.3E-06		1.3E-06		1.3E-06	
35	A1=d1*l,(m^2)1L coil cross section		0.0075		0.0075		0.0075	
36	A2=d2*l,(m62)2L coil cross section		0.0069		0.0069		0.0069	
37	l1=n1*Cd,(m)1L coil width		0.0246		0.0246		0.0246	
38	l2=n2*Cd,(m)2L coil width		0.0000		0.0000		0.0000	
39	Vl=w*L*Irms, rms back-emf							
40	L=L1+L2,(Hy)inductance/1Ø			2.97E-05		2.97E-05		2.97E-05
41	XL=6.28fL, (ohms)			0.16		0.14		0.12
42	f=N/60, (Hz)		833		750		667	
	MAGNETIC FIELD							
43	B=Brem*LN(Mr2/Mr1)*u, (Kgauss)			4.42		4.42		4.42
44	u=sin(6.28/M)/(6.28/M)			0.90		0.90		0.90
45	M: # Magnets		8		8		8	
46	Brem, (Kgauss)		12.1		12.1		12.1	
47	Mr2/Mr1, magnet design ratio		1.50		1.50		1.50	
48	Mr1=STAd/2+Gap,(m)inner mag. radii		0.025		0.025		0.025	

Figure B-5

	Gene Espiritu Santo	8.41 DESIGN NUMBER	MOTOR / GENERATOR					
	ROCKETDYNE DIV.		HALBACH ARRAY					
	5/26/94		RUN # 1		RUN # 2		RUN # 3	
	EMB DEMO		DATA	CALC	DATA	CALC	DATA	CALC
49	Mr1: (in)			0.981		0.981		0.981
50	Mr2=1.5*r1, (m)outer magnet radii		0.037		0.037		0.037	
51	Mr2: (in)			1.472		1.472		1.472
52	Gap, (m),rotor-stator gap		0.00038		0.00038		0.00038	
53	Gap, (in)		0.0150		0.0150		0.0150	
	MOT/GENERATOR VOLTAGE							
54	Eg1=(0.707)B*l*v1,(Vrms)1L V/turn			12.301		11.071		9.840
55	Eg2=(0.707)B*l*v2,(Vrms)2L V/turn			11.227		10.104		8.982
56	B: Teslas,(10Kgauss=Tesla)		0.442		0.442		0.442	
57	v1=r1*w, (m/sec)1L cond. velocity		123.1		110.8		98.5	
58	v2=r2*w, 2L conductor velocity		112.3		101.1		89.9	
59	N:(RPM), rotor speed		50000		45000		40000	
60	w=N*k1,(rad/sec) rotor speed		5233		4710		4187	
61	k1=2*π/60		0.105		0.105		0.105	
62	Vg1=n1*Eg1,(Vrms)1L volts/layer		147.6		132.8		118.1	
63	Vg2=n2*Eg2,(Vrms)2L volts/layer		0.0		0.0		0.0	
64	Vg(1Ø)=Vg1+Vg2,(Vrms)volts/1Ø			148		133		118
65	Vg(L-L)=√3*Vg, (Vrms)volts,line voltage			255.7		230.1		204.5
	1st Method inductance calc. approach.							
66	GEN VOLTAGE & PWR AT CONST LOAD							
67	R(load): (ohms) generator load		5		5		5	
68	Z=√((Rs+Rl)^2+XL^2), (ohms)circuit Z			5.03		5.03		5.03
69	I=Vg/Z,(Irms),const. load current			29.3		26.4		23.5
70	k3=w*L		0.156		0.140		0.125	
71	Power=(I^2)*R(l), watts per phase		4298		3482		2751	
72	Power(3Ø)= 3*(I^2)*R(l)/1000,kW			12.9		10.4		8.3
	Power(3Ø)=√3*V(L-L)*I*pf,W,checkpoint		12982					
73	pf, power factor		1.00		1.00		1.00	
74	Ploss=I^2*Rs,(W) P loss per 1Ø		28		23		18	
75	Ploss(3Ø)			83		68		53
76	Eff'cy=(P-Ploss3Ø/P)*100			99.4		99.4		99.4
	GEN VOLTAGE AT CONSTANT CURRENT							
77	Im:(A),conductor max current			29.8		29.8		29.8
78	Vs=Vg-I(√Rs^2+XL^2),		147		133		118	
79	Vs(L-L)=√3*Vs, line voltage (volts)			255		230		204
80	VA(1Ø)= (Vg-(Vg-Vs))*I,apparent pwr		4323		3502		2767	
81	KVA (3Ø): apparent power			13.0		10.5		8.3
82	Ploss=Rs*I^2,(W) P loss per 1Ø		29		29		29	
83	Ploss(3Ø)			86		86		86
84	Eff'cy=(P-Ploss3Ø/P)*100			99.3		99.2		99.0
	2nd Method Calculations for inductance and constant current							
85	L= 0.004 (a log e 2a/Wr +b log e 2b/Wr + 2 (a^2+b^2)^1/2-a sinh a/b - b sinh b/a -2(a+b)+ Wμ/4(a+b)) N^2, (μh).							
86	L1: μH		62.12		62.12		62.12	
87	L2: μH		0.00		0.00		0.00	
88	Wr: wire radii, cm		0.103		0.103		0.103	
89	Wμ: permeability wire material		1		1		1	
90	XL1= 2πfL1,(ohms),reactance first layer		0.33		0.29		0.26	
91	XL2=2πfL2		0.00		0.00		0.00	
92	Xp=XL1+XL2,(ohms),total reactance		0.33		0.29		0.26	
	GEN VOLTAGE & PWR AT CONST LOAD							
93	R(load): (ohms) generator load		5		5		5	
94	Z=√((Rs+Rl)^2+XL^2), (ohms)circuit Z			5.04		5.04		5.04
95	I=Vg/Z,(Irms),const. load current			29.3		26.4		23.4
96	k3=w*L		0.33		0.29		0.26	
97	Power=(I^2)*R(l), watts per phase		4284		3473		2746	

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	Gene Espiritu Santo	8.41 DESIGN NUMBER	MOTOR / GENERATOR HALBACH ARRAY					
	ROCKETDYNE DIV.							
	5/26/94		RUN # 1		RUN # 2		RUN # 3	
	EMB DEMO		DATA	CALC	DATA	CALC	DATA	CALC
98	Power(3Ø)= 3*(I^2)*R(I)/1000,kW			12.9		10.4		8.2
99	pf, power factor		1.00		1.00		1.00	
100	Ploss=I^2*Rs,(W) P loss per 1Ø		28		22		18	
101	Ploss(3Ø)			83		67		53
102	Eff'cy=(P-Ploss3Ø/P)*100			99.4		99.4		99.4
	GEN VOLTAGE AT CONSTANT CURRENT							
102	Im:(A),conductor max current			29.8		29.8		29.8
103	Vs=Vg-I(√Rs^2+XL^2),		138		124		110	
104	Vs(L-L)=√3*Vs, line voltage (volts)			239		215		191
105	VA(1Ø)= (Vg-(Vg-Vs))*I,apparent pwr		4105		3694		3283	
106	KVA (3Ø):apparent power			12.3		11.1		9.9
107	Ploss=Rs*I^2,(W) P loss per 1Ø		29		29		29	
108	Ploss(3Ø)			86		86		86
109	Eff'cy=(P-Ploss3Ø/P)*100			99.3		99.2		99.1
	MAGNETS WEIGHT		ENGLISH	MKS				
110	Magnet IR		0.981	2.4925				
111	Magnet OR		1.472	3.7387				
112	Magnet length		6.299	16.0				
113	VOL:cin-ccm		23.82	390.35				
114	WT: Lbs-Kg		6.35	2.889				
	PROGRAM INPUT DATA DESCRIPTION		PROGRAM INPUT DATA					
115	Rotor speed,(RPM)		50000		45000		40000	
116	Mr2/Mr1,Mag OD/ID ratio		1.5		1.5		1.5	
117	Brem,(Kgauss)		12.1		12.1		12.1	
118	Turns 1L		12		12		12	
119	Turns 2L		0		0		0	
120	q: (A-mm^2),current density		9		9		9	
121	AWG, Coil wire gage		12		12		12	
122	AWG, wire diameter(in),(m)		0.0808	0.0021	0.0808	0.0021	0.0808	0.0021
123	Coil length,(m),(in)		0.16	6.30	0.16	6.30	0.16	6.30
124	k2=1.588 ohms/1000ft		1.588		1.588		1.588	
125	Load impedance, (ohms)		5.0		5.0		5.0	
126	M: # Magnets		8		8		8	
127	pf: power factor		1.00		1.00		1.00	

	Gene Espiritu Santo	8.41 DESIGN NUMBER						
	ROCKETDYNE DIV.							
	5/26/94		RUN # 4		RUN # 5		RUN # 6	
	EMB DEMO		DATA	CALC	DATA	CALC	DATA	CALC
	WINDING PARAMETERS,(stator)							
1	l: (m), coil length		0.160		0.160		0.160	
2	l: (in)		6.299		6.299		6.299	
3	Wire Ga #		12		12		12	
4	Cd: (m) cond/insul diameter		0.0021		0.0021		0.0021	
5	Cd: (in)		0.0808		0.0808		0.0808	
6	A:(sq-in),wire cross section		0.0051		0.0051		0.0051	
7	A:(sq-mm),wire cross section		3.3081		3.3081		3.3081	
8	Im:(A),conductor max current			29.8		29.8		29.8
9	q: (A-mm^2),current density		9		9		9	
	FIRST LAYER WINDING (1L)							
10	n1: 1L turns per layer		12		12		12	
11	S1=3*2*n1*Cd,(m)1L mean circunf.		0.148		0.148		0.148	
12	d1=S1/π,(m)1L mean diameter		0.047		0.047		0.047	
13	r1=d1/2,(m) 1L mean radii		0.024		0.024		0.024	
	SECOND LAYER WINDING (2L)							
14	r2=r1-Cd,(m) 2L mean radii		0.021		0.021		0.021	
15	d2=2*r2,(m) 2L mean diameter		0.043		0.043		0.043	
16	S2=π*d2,(m)2L mean circunf.		0.135		0.135		0.135	
17	k4=S2/Cd, 2L max # conductors		65.72		65.72		65.72	
18	n2'=k4/6, 2L max turns/layer			10.95		10.95		10.95
19	n2:(DATA),2L turns per layer		0		0		0	
20	n=n1+n2 coil turns per phase		12		12		12	
	STATOR DIMENSIONS							
21	STAr=d1/2+Cd/2,(m)outer stator radii		0.025		0.025		0.025	
22	STAr: (in)			0.966		0.966		0.966
23	STAd=d1+Cd,(m) outer stator diam.		0.049		0.049		0.049	
24	STAd: (in)			1.933		1.933		1.933
	RESISTANCE							
25	St=St1+St2,(m)total length/Ø		20.38		20.38		20.38	
26	St1=2(l+(2*d1))*n1,(m) 1L length/Ø		6.21		6.21		6.21	
27	St1: (ft)		20.38		20.38		20.38	
28	St2=2(l+(2*d2))*n2,(m) 2L length/Ø		0.00		0.00		0.00	
29	St2:(ft)		0.00		0.00		0.00	
30	k2=1.588 ohms/1000ft		1.588		1.588		1.588	
31	Rs=St*k2/1000,(ohms)resistance/1Ø			0.032		0.032		0.032
	INDUCTANCE							
32	L1=μ*(n1)^2*A1/(l1+0.45d1),(Hy)			2.97E-05		2.97E-05		2.97E-05
33	L2=μ*(n2)^2*A2/(l2+0.45d2),(Hy)			0		0		0
34	μ=4π*10^-7		1.3E-06		1.3E-06		1.3E-06	
35	A1=d1*l,(m^2)1L coil cross section		0.0075		0.0075		0.0075	
36	A2=d2*l,(m62)2L coil cross section		0.0069		0.0069		0.0069	
37	l1=n1*Cd,(m)1L coil width		0.0246		0.0246		0.0246	
38	l2=n2*Cd,(m)2L coil width		0.0000		0.0000		0.0000	
39	Vl=w*L*Irms, rms back-emf							
40	L=L1+L2,(Hy)inductance/1Ø			2.97E-05		2.97E-05		2.97E-05
41	XL=6.28fL, (ohms)			0.11		0.09		0.08
42	f=N/60, (Hz)		583		500		417	
	MAGNETIC FIELD							
43	B=Brem*LN(Mr2/Mr1)*u, (Kgauss)			4.42		4.42		4.42
44	u=sin(6.28/M)/(6.28/M)			0.90		0.90		0.90
45	M: # Magnets		8		8		8	
46	Brem, (Kgauss)		12.1		12.1		12.1	
47	Mr2/Mr1, magnet design ratio		1.50		1.50		1.50	
48	Mr1=STAd/2+Gap,(m)inner mag. radii		0.025		0.025		0.025	

Figure 3-6

	Gene Espiritu Santo						
	ROCKETDYNE DIV.	8.41					
	5/26/94	DESIGN	RUN # 4		RUN # 5		RUN # 6
	EMB DEMO	NUMBER	DATA	CALC	DATA	CALC	DATA	CALC
49	Mr1: (In)			0.981		0.981		0.981
50	Mr2=1.5*r1, (m)outer magnet radii		0.037		0.037		0.037	
51	Mr2: (In)			1.472		1.472		1.472
52	Gap, (m),rotor-stator gap		0.00038		0.00038		0.00038	
53	Gap, (In)		0.0150		0.0150		0.0150	
	MOT/GENERATOR VOLTAGE							
54	Eg1=(0.707)B*l*v1,(Vrms)1L V/turn			8.610		7.380		6.150
55	Eg2=(0.707)B*l*v2,(Vrms)2L V/turn			7.859		6.736		5.614
56	B: Teslas,(10Kgauss=Tesla)		0.442		0.442		0.442	
57	v1=r1*w, (m/sec)1L cond. velocity		86.2		73.8		61.5	
58	v2=r2*w, 2L conductor velocity		78.6		67.4		56.2	
59	N:(RPM), rotor speed		35000		30000		25000	
60	w=N*k1,(rad/sec) rotor speed		3663		3140		2617	
61	k1=2*π/60		0.105		0.105		0.105	
62	Vg1=n1*Eg1,(Vrms)1L volts/layer		103.3		88.6		73.8	
63	Vg2=n2*Eg2,(Vrms)2L volts/layer		0.0		0.0		0.0	
64	Vg(1Ø)=Vg1+Vg2,(Vrms)volts/1Ø			103		89		74
65	Vg(L-L)=√3*Vg, (Vrms)volts,line voltage			179.0		153.4		127.8
	1st Method inductance calc. approach.							
66	GEN VOLTAGE & PWR AT CONST LOAD							
67	R(load): (ohms) generator load		5		5		5	
68	Z=√((Rs+Rl)^2+XL^2), (ohms)circuit Z			5.03		5.03		5.03
69	I=Vg/Z,(Irms),const. load current			20.5		17.6		14.7
70	k3=w*L		0.109		0.093		0.078	
71	Power=(I^2)*R(l), watts per phase		2107		1548		1075	
72	Power(3Ø)= 3*(I^2)*R(l)/1000,kW			6.3		4.6		3.2
	Power(3Ø)=√3*V(L-L)*I*pf,W,checkpoint							
73	pf, power factor		1.00		1.00		1.00	
74	Ploss=I^2*Rs,(W) P loss per 1Ø		14		10		7	
75	Ploss(3Ø)			41		30		21
76	Eff'cy=(P-Ploss3Ø/P)*100			99.4		99.4		99.4
	GEN VOLTAGE AT CONSTANT CURRENT							
77	Im:(A),conductor max current			29.8		29.8		29.8
78	Vs=Vg-I(√Rs^2+XL^2),		103		88		74	
79	Vs(L-L)=√3*Vs, line voltage (volts)			179		153		128
80	VA(1Ø)= (Vg-(Vg-Vs))*I,apparent pwr		2119		1557		1081	
81	KVA (3Ø): apparent power			6.4		4.7		3.2
82	Ploss=Rs*I^2,(W) P loss per 1Ø		29		29		29	
83	Ploss(3Ø)			86		86		86
84	Eff'cy=(P-Ploss3Ø/P)*100			98.6		98.2		97.3
	2nd Method Calculations for inductance and con							
85	L= 0.004 (a log e 2a/Wr +b log e 2b/Wr + 2 (a^2+b							
86	L1: µH		62.12		62.12		62.12	
87	L2: µH		0.00		0.00		0.00	
88	Wr: wire radii, cm		0.103		0.103		0.103	
89	Wµ: permeability wire material		1		1		1	
90	XL1= 2πfL1,(ohms),reactance first layer		0.23		0.20		0.16	
91	XL2=2πfL2		0.00		0.00		0.00	
92	Xp=XL1+XL2,(ohms),total reactance		0.23		0.20		0.16	
	GEN VOLTAGE & PWR AT CONST LOAD							
93	R(load): (ohms) generator load		5		5		5	
94	Z=√((Rs+Rl)^2+XL^2), (ohms)circuit Z			5.04		5.04		5.03
95	I=Vg/Z,(Irms),const. load current			20.5		17.6		14.7
96	k3=w*L		0.23		0.20		0.16	
97	Power=(I^2)*R(l), watts per phase		2104		1546		1074	

	Gene Espiritu Santo	8.41						
	ROCKETDYNE DIV.							
	5/26/94	DESIGN	RUN # 4		RUN # 5		RUN # 6	
	EMB DEMO	NUMBER	DATA	CALC	DATA	CALC	DATA	CALC
98	Power(3Ø)= 3*(I^2)*R(I)/1000,kW			6.3		4.6		3.2
99	pf, power factor		1.00		1.00		1.00	
100	Ploss=I^2*Rs,(W) P loss per 1Ø		14		10		7	
101	Ploss(3Ø)			41		30		21
102	Eff'cy=(P-Ploss3Ø/P)*100			99.4		99.4		99.4
	GEN VOLTAGE AT CONSTANT CURRENT							
102	Im:(A),conductor max current			29.8		29.8		29.8
103	Vs=Vg-I(√Rs^2+XL^2),		96		83		69	
104	Vs(L-L)=√3*Vs, line voltage (volts)			167		143		119
105	VA(1Ø)= (Vg-(Vg-Vs))*I,apparent pwr		2872		2461		2050	
106	KVA (3Ø):apparent power			8.6		7.4		6.2
107	Ploss=Rs*I^2,(W) P loss per 1Ø		29		29		29	
108	Ploss(3Ø)			86		86		86
109	Eff'cy=(P-Ploss3Ø/P)*100			99.0		98.8		98.6
	MAGNETS WEIGHT							
110	Magnet IR							
111	Magnet OR							
112	Magnet length							
113	VOL:cin-ccm							
114	WT: Lbs-Kg							
	PROGRAM INPUT DATA DESCRIPTION							
115	Rotor speed,(RPM)		35000		30000		25000	
116	Mr2/Mr1,Mag OD/ID ratio		1.5		1.5		1.5	
117	Brem,(Kgauss)		12.1		12.1		12.1	
118	Turns 1L		12		12		12	
119	Turns 2L		0		0		0	
120	q: (A-mm^2),current density		9		9		9	
121	AWG, Coil wire gage		12		12		12	
122	AWG, wire diameter(in),(m)		0.0808	0.0021	0.0808	0.0021	0.0808	0.0021
123	Coil length,(m),(in)		0.16	6.30	0.16	6.30	0.16	6.30
124	k2=1.588 ohms/1000ft		1.588		1.588		1.588	
125	Load impedance, (ohms)		5.0		5.0		5.0	
126	M: # Magnets		8		8		8	
127	pf: power factor		1.00		1.00		1.00	

Appendix B

Life Cycle Cost Study Details

Figures

file SSFW2I Space Station Flywheel (SSFW) PRICE run SSFW13 & SSFW13B 1.95 wraps on buy items (=1.26*1.29*1.20)

date 6/27/94 PRICE Model Cost Estimate (1994$K) **BEST ESTIMATE** 1.20 wraps on make items (RD G&A & profit)

time 9:08 AM

			Comp Weight (lb)	Weight per ORU (lb)	Quantity NHA	Prototype Quantity	Prod Quantity	Devel Cost	Prod Cost	Total Cost	Amortize UPC	Devel Cost	Prod Cost	Total Cost	Amortized UPC
								PRICE model output				RD price including G&A & profit			
7	SSFW			411.00		3	18	66,967	21,286	88,253	1,182.56	90,063	28,526	118,590	1,584.80
8		Flywheel	125.50	251.00	2	6	36	17,795	4,838	22,633	134.39	31,057	8,789	39,846	244.13
9	buy	Composite Shell	100.00	200.00	1	6	36	10,155	1,866	12,021	51.83	19,807	3,640	23,447	101.10
10	make	Titanium Hub	12.00	24.00	1	6	36	1,118	503	1,621	13.97	1,342	604	1,945	16.77
11	make	Titanium Shaft	2.00	4.00	1	6	36	434	193	627	5.36	521	232	752	6.43
12	buy	M/G perm mag assy	5.00	10.00	1	6	36	966	1,067	2,033	29.64	1,884	2,081	3,965	57.81
13	buy	M/G stator assy	2.00	4.00	1	6	36	161	75	236	2.08	314	146	460	4.06
14	buy	Radial act mag bearings	1.50	6.00	2	12	72	1,463	765	2,228	10.63	2,854	1,492	4,346	20.72
15	buy	Ax perm mag bearings	0.50	2.00	2	12	72	161	152	313	2.11	314	296	611	4.12
16	buy	Rotor position sensor	0.25	1.00	2	12	72	23	50	73	0.69	45	98	142	1.35
17	make	DI Flywheel			1	6	36	2,397	0	2,397	0.00	2,876	0	2,876	0.00
18	make	I&T Flywheel			1	6	36	917	167	1,084	4.64	1,100	200	1,301	5.57
19	make	Power Processing Unit	20.00	40.00	2	6	36	18,381	7,101	25,482	197.25	22,057	8,521	30,578	236.70
20	make	Bearing Control Unit	10.00	20.00	2	6	36	23,484	6,419	29,903	178.31	28,181	7,703	35,884	213.97
21	make	ORU Housing	100.00	100.00	1	3	18	312	1,870	2,182	103.89	374	2,244	2,618	124.67
22	make	I&T SSFW			1	3	18	6,995	1,058	8,053	58.78	8,394	1,270	9,664	70.53

* Input cost for ECIRP

PRICE model inputs PLTFM=2.5

			Qty NHA	WS (lb)	WE (lb)	WT (lb)	MCPLXS	MCPLXE	INTEGS	INTEGE	NEWST	NEWEL	DESRPS	DESRPE	ECMPLX	SPLANS	EPLANS	DLEVS
31	SSFW																	
32	make	Flywheel	2															
33	buy	Composite Shell	1	100.00		100.00	6.331		0.50		1.00		0.00		1.90			1.00
34	make	Titanium Hub	1	12.00		12.00	6.834		0.50		1.00		0.00		1.00			
35	make	Titanium Shaft	1	2.00		2.00	7.453		0.50		1.00		0.00		1.00			
36	buy	M/G perm mag assy	1	5.00		5.00	8.418		0.50		1.00		0.00		0.70			1.00
37	buy	M/G stator assy	1	2.00		2.00	6.447		0.50		1.00		0.00		0.70			1.00
38	buy	Radial act mag bearings	2	1.50		1.50	8.632		0.50		1.00		0.00		1.60			1.00
39	buy	Ax perm mag bearings	2	0.50		0.50	7.964		0.50		1.00		0.00		0.70			1.00
40	buy	Rotor position sensor	2	0.25		0.25	7.369		0.50		1.00		0.00		0.20			1.00
41	make	Design Integ Flywheel	1															
42	make	I&T Flywheel	1						0.50							0.70		
43	make	Power Processing Unit	2	13.30	6.70	20.00	6.000	10.000	0.50	0.50	0.90	0.90	0.00	0.00	1.60			
44	make	Bearing Control Unit	2	4.00	6.00	10.00	6.000	10.000	0.50	0.50	1.00	1.00	0.00	0.00	1.90			
45	make	ORU Housing	1	100.00		100.00	6.501		0.50									
46	make	I&T SSFW	1													0.70	0.70	

	A	B	C	D	E	U	V	W	X	Y	Z	AA	AB
1		file	SSFW2l	Space Station Flywh									
2		date	6/27/94	PRICE Model Cost Es									
3		time	9:08 AM										
4													
5													
6													
7	SSFW												
8		Flywheel											
9	buy		Composite Shell										
10	make		Titanium Hub										
11	make		Titanium Shaft										
12	buy		M/G perm mag assy										
13	buy		M/G stator assy										
14	buy		Radial act mag bearings										
15	buy		Ax perm mag bearings										
16	buy		Rotor position sensor										
17	make		DI Flywheel										
18	make		I&T Flywheel										
19	make	Power Processing Unit											
20	make	Bearing Control Unit											
21	make	ORU Housing											
22	make	I&T SSFW											
23													
24													
25													
26													
27									PRICE model conceptual complexity generator inputs				
28					Qty				weight	primary	mach. index	platform	no. of parts
29					NHA	MCPLXS	construction	function	range	material	MI	PLTFM	NP
30													
31	SSFW												
32	make	Flywheel			2								
33	buy		Composite Shell		1	6.331	laminated	cylindrical shaped, filament wound	20-500	composites	18	2.5	2
34	make		Titanium Hub		1	6.834	machined	precision machined parts in assembly	5-50	titanium, nickel base alloys	25	2.5	1
35	make		Titanium Shaft		1	7.453	machined	precision machined parts in assembly	<5	titanium, nickel base alloys	25	2.5	1
36	buy		M/G perm mag assy		1	8.418	machined	precision machined parts in assembly	<5	composites, glass, ceramics	5	2.5	8
37	buy		M/G stator assy		1	6.447	machined	machined parts for support/containment	<5	tungsten, copper alloys	40	2.5	2
38	buy		Radial act mag bearing		2	8.632	machined	precision machined parts in assembly	<5	composites, glass, ceramics	5	2.5	15
39	buy		Ax perm mag bearings		2	7.964	machined	precision machined parts in assembly	<5	composites, glass, ceramics	5	2.5	2
40	buy		Rotor position sensor		2	7.369	machined	precision machined parts in assembly	<5	tungsten, copper alloys	40	2.5	1
41	make		Design Integ Flywheel		1								
42	make		I&T Flywheel		1								
43	make	Power Processing Unit			2								
44	make	Bearing Control Unit			2								
45	make	ORU Housing			1								
46	make	I&T SSFW			1								
47													

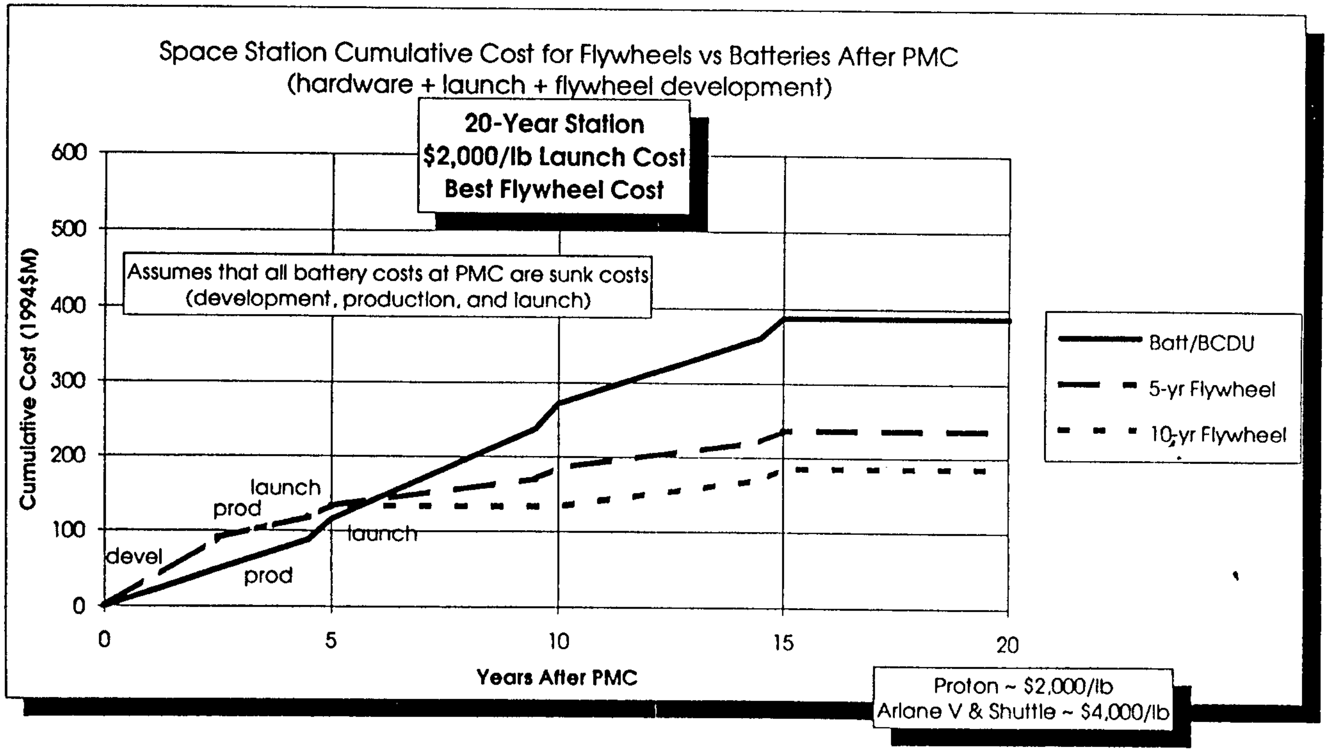
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	file	SSFW13E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW13 & SSFW13B										
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							BEST ESTIMATE									
3	time	9:37 AM		(cost to the government, 1994$M)																
5					Battery		BCDU			5-yr Flywheel		10 yr Flywheel								
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18								
7	initial ORU cost (1993$M)				1.82		1.38													
8	1.042	1993-->1994 escalation factor																		
9	initial ORU cost (1994$M)				1.90		1.44			1.58		1.58								
10	1.3	replacement ORU cost factor																		
11	replacement ORU cost (1994$M)				2.47		1.87			2.05		2.05								
12	weight per ORU (lb)				375		196			411		411								
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00								
15	development cost (1994$M)				0 sunk		0 sunk			90		90								
16	initial HW cost/SS (1994$M)				0 sunk		0 sunk			28		28								
17	replacement HW cost/SS (1994$M)				89		34			37		37								
18									20-Year Station											
19	$2,000	/lb launch cost (with FSE factor of 1.2)																		
20	launch cost/SS (1994$M)				27		7			15		15								
21									Battery											
22					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw13e1 chart				flywheel savings	
23	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywh	10-yr Flyw	5-yr Flywh	10-yr Flyw
24	0				0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
25	2.5	flywheel devel		batt prod (	49	49	0	0	49	90	90	90	90		3	49	90	90	-41	-41
26	4.5	prod		batt prod (	39	89	0	0	89	28	118	28	118		5	89	118	118	-30	-30
27	5	launch			27	116	0	0	116	15	133	15	133		5	116	133	133	-17	-17
28	9.5	prod			89	205	34	34	238	37	170	0	133		10	238	170	133	68	105
29	10	launch			27	232	7	41	272	15	185	0	133		10	272	185	133	87	139
30	14.5	prod			89	320	0	41	361	37	222	37	170		15	361	222	170	139	191
31	15	launch			27	347	0	41	388	15	237	15	185		15	388	237	185	151	203
32	20				0	347	0	41	388	0	237	0	185		20	388	237	185	151	203
33									20-Year Station											
34	$2,000	/lb launch cost (with FSE factor of 1.2)																		
35	launch cost/SS (1994$M)				27		7			15		15								
36									Battery											
37					Battery		BCDU		+BCDU	7.5-yr Flywheel		10-yr Flywheel			ssfw13e1 chart				flywheel savings	
38	years				delta	Battery	delta	BCDU	Batt/BCI	delta	7.5-yr Fly	delta	10-yr Flywheel		years	Batt/BCDI	7.5-yr Flyw	10-yr Flyw	7.5-yr Flyw	10-yr Flyw
39	0				0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
40	2.5	flywheel devel		batt prod (	49	49	0	0	49	90	90	90	90		3	49	90	90	-41	-41
41	4.5	prod	fw	att prod (	39	89	0	0	89	28	118	28	118		5	89	118	118	-30	-30
42	5	launch	fw		27	116	0	0	116	15	133	15	133		5	116	133	133	-17	-17
43	9.5	prod	b		89	205	34	34	238		133		133		10	238	133	133	105	105
44	10	launch	b		27	232	7	41	272		133		133		10	272	133	133	139	139
45	12	prod	fw			232		41	272	37	170		133		12	272	170	133	102	139
46	12.5	launch	fw			232		41	272	15	185		133		13	272	185	133	87	139
47	14.5	prod	b		89	320	0	41	361		185	37	170		15	361	185	170	176	191
48	15	launch	b		27	347	0	41	388		185	15	185		15	388	185	185	203	203
49	20				0	347	0	41	388	0	185	0	185		20	388	185	185	203	203

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	file	SSFW13E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW13 & SSFW13B										
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							BEST ESTIMATE									
3	time	9:37 AM		(cost to the govemment, 1994$M)																
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel								
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18								
7	initial ORU cost (1993$M)				1.82		1.38													
8	1.042	1993-->1994 escalation factor																		
9	initial ORU cost (1994$M)				1.90		1.44			1.58		1.58								
10	1.3	replacement ORU cost factor																		
11	replacement ORU cost (1994$M)				2.47		1.87			2.05		2.05								
12	weight per ORU (lb)				375		196			411		411								
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00								
15	development cost (1994$M)				0	sunk	0	sunk		90		90								
16	initial HW cost/SS (1994$M)				0	sunk	0	sunk		28		28								
17	replacement HW cost/SS (1994$M)				89		34			37		37								
50								20-Year Station												
51	$4,000	/lb launch cost (with FSE factor of 1.2)																		
52	launch cost/SS (1994$M)				54		14			30		30								
53									Battery											
54					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw13e2 chart				flywheel savings	
55	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywh	10-yr Flyw	5-yr Flywh	10-yr Flyw
56	0				0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
57	2.5	flywheel devel		batt prod (	49	49	0	0	49	90	90	90	90		3	49	90	90	-41	-41
58	4.5	prod		batt prod (	39	89	0	0	89	28	118	28	118		5	89	118	118	-30	-30
59	5	launch			54	143	0	0	143	30	148	30	148		5	143	148	148	-5	-5
60	9.5	prod			89	232	34	34	265	37	185	0	148		10	265	185	148	80	117
61	10	launch			54	286	14	48	333	30	215	0	148		10	333	215	148	119	185
62	14.5	prod			89	374	0	48	422	37	252	37	185		15	422	252	185	170	237
63	15	launch			54	428	0	48	476	30	281	30	215		15	476	281	215	195	261
64	20				0	428	0	48	476	0	281	0	215		20	476	281	215	195	261

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	file	SSFW13E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW13 & SSFW13B										
2	date	6/27/94		**PRICE Model Cost Estimate for Flywheels**							**BEST ESTIMATE**									
3	time	9:37 AM		**(cost to the government, 1994$M)**																
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel								
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18								
7	initial ORU cost (1993$M)				1.82		1.38													
8	1.042	1993-->1994 escalation factor																		
9	initial ORU cost (1994$M)				1.90		1.44			1.58		1.58								
10	1.3	replacement ORU cost factor																		
11	replacement ORU cost (1994$M)				2.47		1.87			2.05		2.05								
12	weight per ORU (lb)				375		196			411		411								
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00								
15	development cost (1994$M)				0	sunk	0	sunk		90		90								
16	initial HW cost/SS (1994$M)				0	sunk	0	sunk		28		28								
17	replacement HW cost/SS (1994$M)				89		34			37		37								
65									**15-Year Station**											
66	**$2,000**	/lb launch cost (with FSE factor of 1.2)																		
67	launch cost/SS (1994$M)				27		7			15		15								
68									Battery											
69					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw13e3 chart				flywheel savings	
70	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDl	5-yr Flywh	10-yr Flyw	5-yr Flywh	10-yr Flyw
71	0				0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
72	2.5 flywheel devel			batt prod (	49	49	0	0	49	90	90	90	90		3	49	90	90	-41	-41
73	4.5 prod			batt prod (	39	89	0	0	89	28	118	28	118		5	89	118	118	-30	-30
74	5 launch				27	116	0	0	116	15	133	15	133		5	116	133	133	-17	-17
75	9.5 prod				89	205	34	34	238	37	170	0	133		10	238	170	133	68	105
76	10 launch				27	232	7	41	272	15	185	0	133		10	272	185	133	87	139
77	15				0	232	0	41	272	0	185	0	133		15	272	185	133	87	139
78																				
79																				
80									**15-Year Station**											
81	**$2,000**	/lb launch cost (with FSE factor of 1.2)																		
82	launch cost/SS (1994$M)				27		7			15		15								
83									Battery											
84					Battery		BCDU		+BCDU	5-yr Flywheel		7.5-yr Flywheel			ssfw13e3 chart				flywheel savings	
85	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	7.5-yr Flywheel		years	Batt/BCDl	5-yr Flywh	7.5-yr Flyw	5-yr Flywh	7.5-yr Flyw
86	0				0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
87	2.5 flywheel devel			batt prod (	49	49	0	0	49	90	90	90	90		3	49	90	90	-41	-41
88	4.5 prod		b & fw	att prod (	39	89	0	0	89	28	118	28	118		5	89	118	118	-30	-30
89	5 launch		b & fw		27	116	0	0	116	15	133	15	133		5	116	133	133	-17	-17
90	9.5 prod		b & BCDU		89	205	34	34	238	37	170	0	133		10	238	170	133	68	105
91	10 launch		b & BCDU		27	232	7	41	272	15	185	0	133		10	272	185	133	87	139
92	12 prod		fw			232		41	272		185	37	170		12	272	185	170	87	102
93	12.5 launch		fw			232		41	272		185	15	185		13	272	185	185	87	87
94	15				0	232	0	41	272	0	185	0	185		15	272	185	185	87	87
95																				
96																				

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	file	SSFW13E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW13 & SSFW13B										
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							BEST ESTIMATE									
3	time	9:37 AM		(cost to the government, 1994$M)																
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel								
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18								
7	initial ORU cost (1993$M)				1.82		1.38													
8	1.042	1993–>1994 escalation factor																		
9	initial ORU cost (1994$M)				1.90		1.44			1.58		1.58								
10	1.3	replacement ORU cost factor																		
11	replacement ORU cost (1994$M)				2.47		1.87			2.05		2.05								
12	weight per ORU (lb)				375		196			411		411								
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00								
15	development cost (1994$M)				0 sunk		0 sunk			90		90								
16	initial HW cost/SS (1994$M)				0 sunk		0 sunk			28		28								
17	replacement HW cost/SS (1994$M)				89		34			37		37								
97								15-Year Station												
98	$4,000	/lb launch cost (with FSE factor of 1.2)																		
99	launch cost/SS (1994$M)				54		14			30		30								
100									Battery											
101					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw13e4 chart				flywheel savings	
102	years				delta	Battery	delta	BCDU	Batt/BC	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCD	5-yr Flywh	10-yr Flyw	5-yr Flywh	10-yr Flyw
103	0				0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
104	2.5	flywheel devel		batt prod (	49	49	0	0	49	90	90	90	90		3	49	90	90	-41	-41
105	4.5	prod		batt prod (	39	89	0	0	89	28	118	28	118		5	89	118	118	-30	-30
106	5	launch			54	143	0	0	143	30	148	30	148		5	143	148	148	-5	-5
107	9.5	prod			89	232	34	34	265	37	185	0	148		10	265	185	148	80	117
108	10	launch			54	286	14	48	333	30	215	0	148		10	333	215	148	119	185
109	15				0	286	0	48	333	0	215	0	148		15	333	215	148	119	185
110																				
111																				

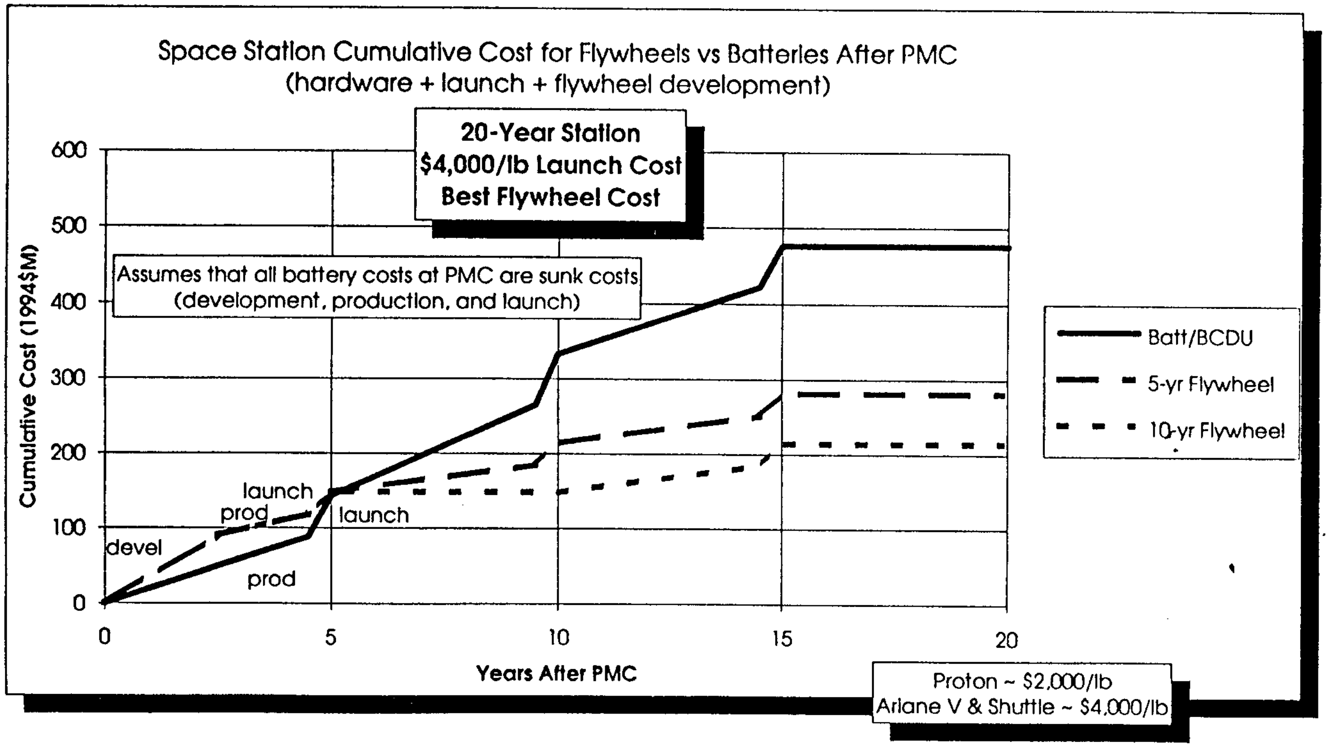
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	file	SSFW13E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW13 & SSFW13B										
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							BEST ESTIMATE									
3	time	9:37 AM		(cost to the government, 1994$M)																
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel								
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18								
7	initial ORU cost (1993$M)				1.82		1.38													
8		1.042	1993-->1994 escalation factor																	
9	initial ORU cost (1994$M)				1.90		1.44			1.58		1.58								
10		1.3	replacement ORU cost factor																	
11	replacement ORU cost (1994$M)				2.47		1.87			2.05		2.05								
12	weight per ORU (lb)				375		196			411		411								
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00								
15	development cost (1994$M)				0	sunk	0	sunk		90		90								
16	initial HW cost/SS (1994$M)				0	sunk	0	sunk		28		28								
17	replacement HW cost/SS (1994$M)				89		34			37		37								
112									10-Year Station											
113	$2,000	/lb launch cost (with FSE factor of 1.2)																		
114	launch cost/SS (1994$M)				27		7			15		15								
115									Battery											
116					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw13e5 chart				flywheel savings	
117	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywheel		5-yr Flywheel	
118	0				0	0	0	0	0	0	0	0	0		0	0	0		0	
119	2.5 devel			batt prod (	49	49	0	0	49	90	90	90	90		3	49	90		-41	
120	4.5 prod			batt prod (	39	89	0	0	89	28	118	28	118		5	89	118		-30	
121	5 launch				27	116	0	0	116	15	133	15	133		5	116	133		-17	
122	10				0	116	0	0	116	0	133	0	133		10	116	133		-17	
123																				
124																				
125																				
126																				
127									10-Year Station											
128	$4,000	/lb launch cost (with FSE factor of 1.2)																		
129	launch cost/SS (1994$M)				54		14			30		30								
130									Battery											
131					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw13e6 chart				flywheel savings	
132	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywheel		5-yr Flywheel	
133	0				0	0	0	0	0	0	0	0	0		0	0	0		0	
134	2.5 devel			batt prod (	49	49	0	0	49	90	90	90	90		3	49	90		-41	
135	4.5 prod			batt prod (	39	89	0	0	89	28	118	28	118		5	89	118		-30	
136	5 launch				54	143	0	0	143	30	148	30	148		5	143	148		-5	
137	10				0	143	0	0	143	0	148	0	148		10	143	148		-5	
138																				
139																				
140																				
141																				


Space Station Cumulative Cost for Flywheels vs Batteries After PMC (hardware + launch + flywheel development)

20-Year Station
$2,000/lb Launch Cost
Best Flywheel Cost

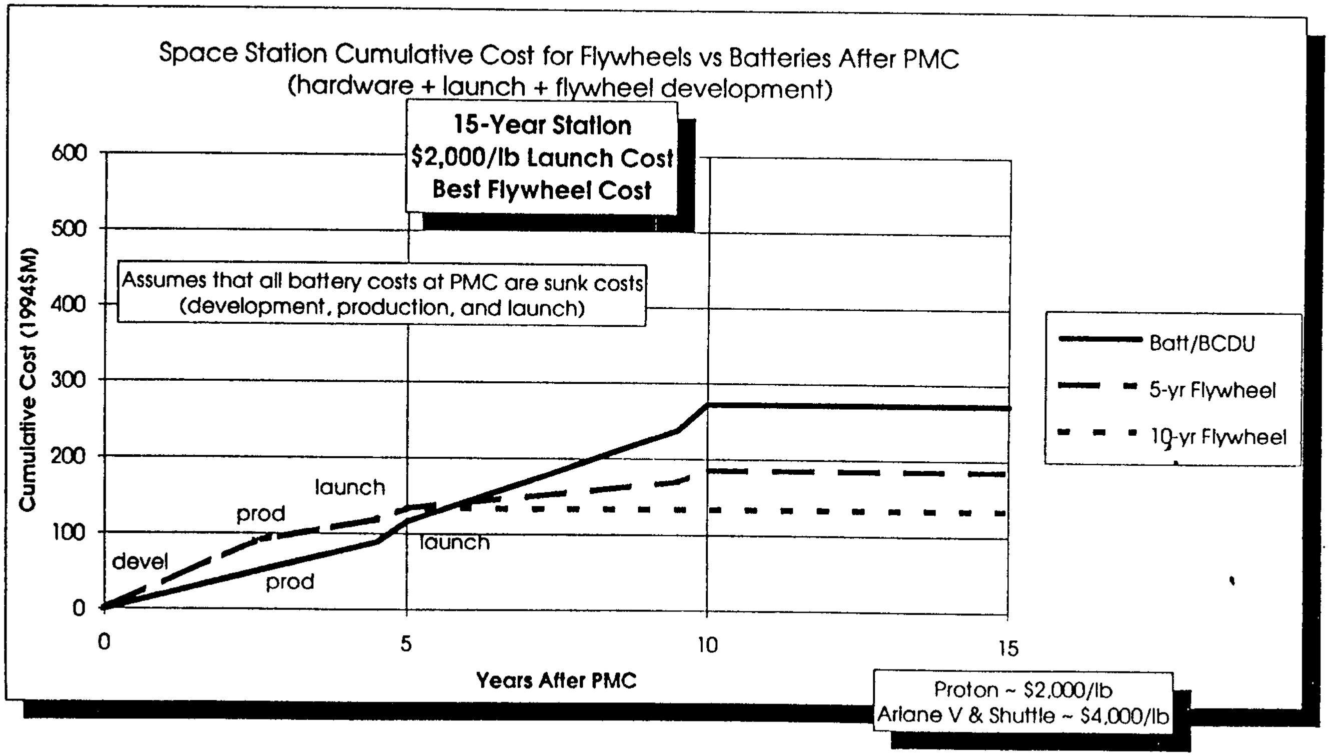
Assumes that all battery costs at PMC are sunk costs (development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

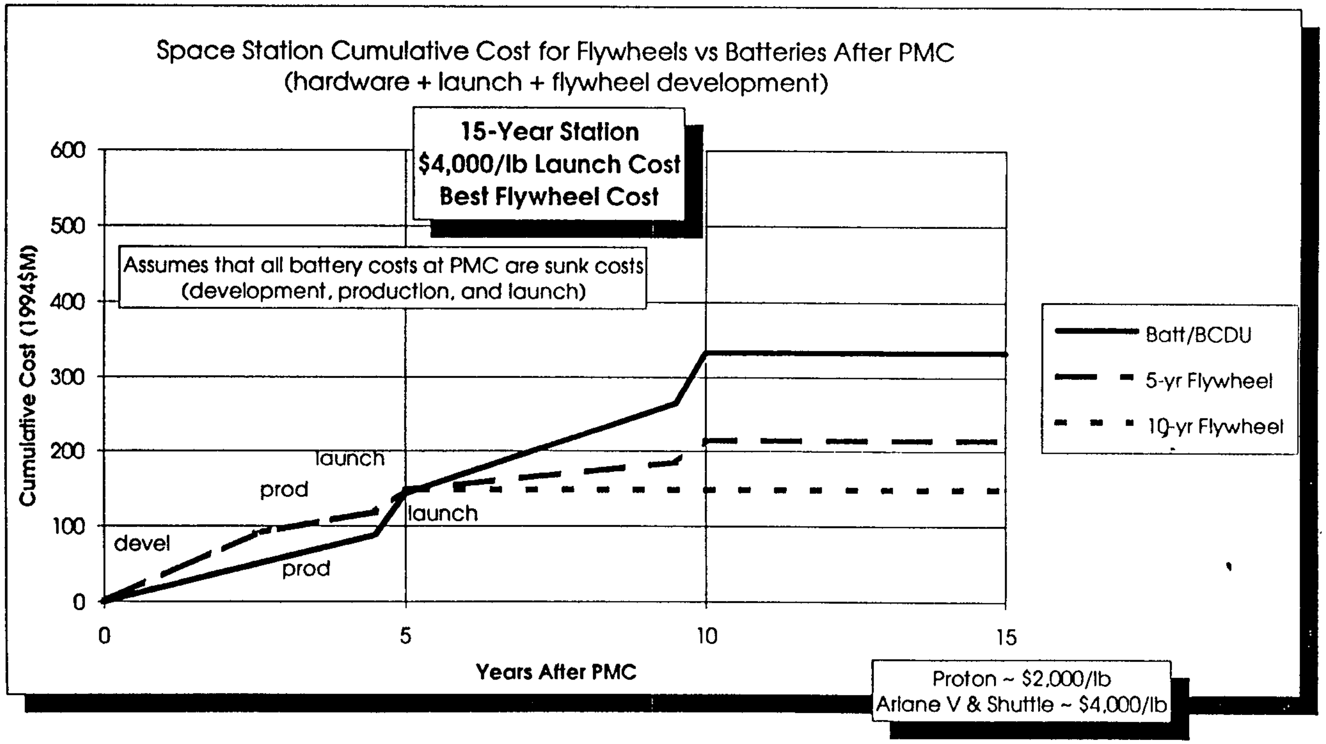


2.

SSFW13E2.XLC 6/16/94 11:27 AM



SSFW13E3.XLC 6/16/94 11:25 AM

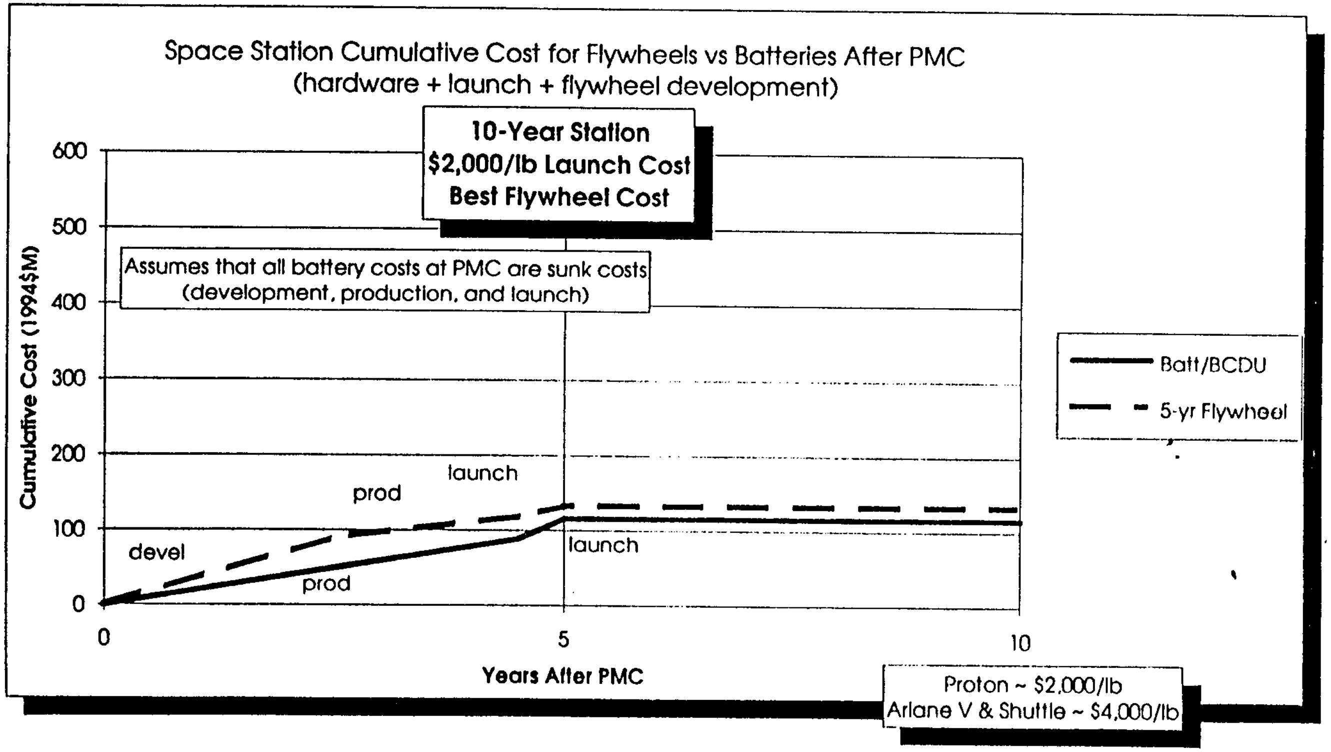

Space Station Cumulative Cost for Flywheels vs Batteries After PMC
(hardware + launch + flywheel development)

15-Year Station
$4,000/lb Launch Cost
Best Flywheel Cost

Assumes that all battery costs at PMC are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW13E4.XLC 6/16/94 11:24 AM



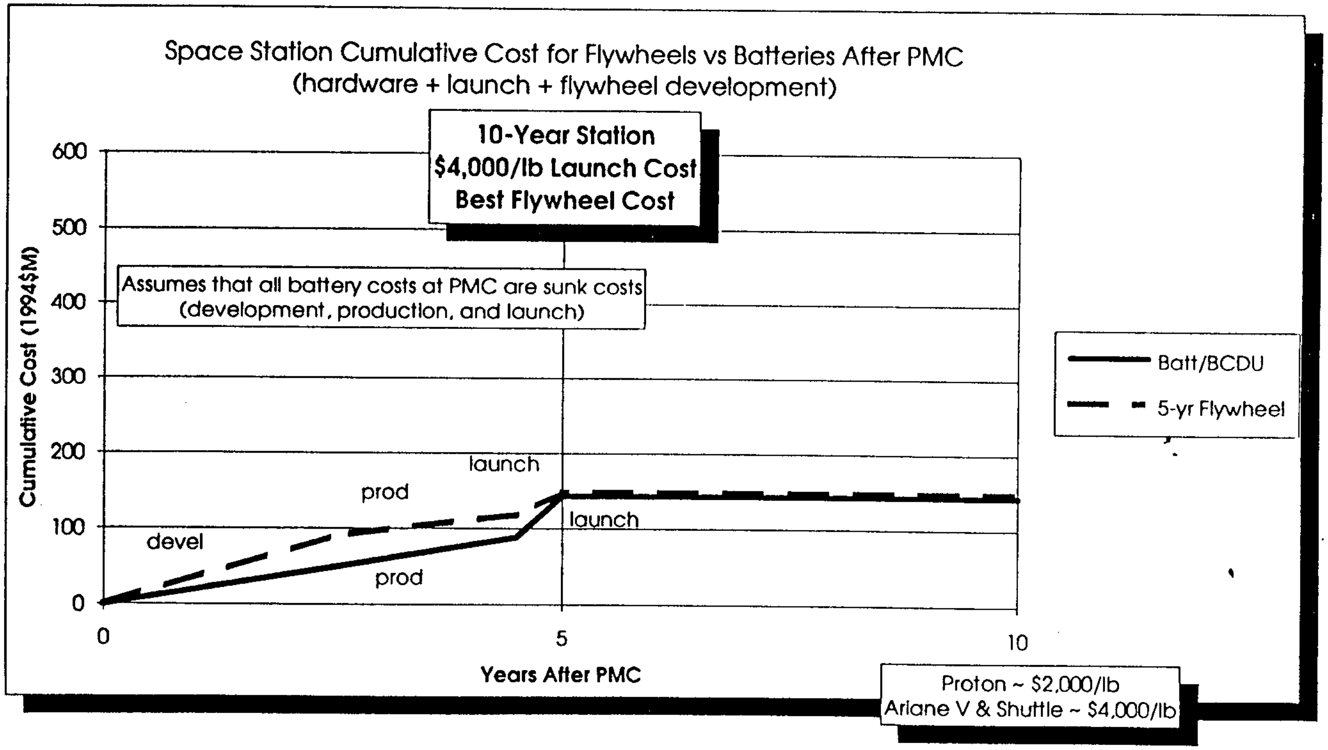
Space Station Cumulative Cost for Flywheels vs Batteries After PMC
(hardware + launch + flywheel development)

10-Year Station
$2,000/lb Launch Cost
Best Flywheel Cost

Assumes that all battery costs at PMC are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW13E5.XLC 6/16/94 11:23 AM



Space Station Cumulative Cost for Flywheels vs Batteries After PMC
(hardware + launch + flywheel development)

10-Year Station
$4,000/lb Launch Cost
Best Flywheel Cost

Assumes that all battery costs at PMC are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW13E6.XLC 6/16/94 11:22 AM

file SSFW2H **Space Station Flywheel (SSFW)**
date 6/27/94 **PRICE Model Cost Estimate (1994$K)**
time 9:59 AM

PRICE run SSFW12 & SSFW12B

LOW ESTIMATE

1.95 wraps on buy items (=1.26*1.29*1.20)

1.20 wraps on make items (RD G&A & profit)

		Comp Weight (lb)	Weight per ORU (lb)	Quantity NHA	Prototype Quantity	Prod Quantity	Devel Cost	Prod Cost	Total Cost	Amortize UPC	Devel Cost	Prod Cost	Total Cost	Amortized UPC
							PRICE model output				**RD price including G&A & profit**			
SSFW			411.00		3	18	64,526	19,577	84,103	1,087.61	85,995	25,320	111,315	1,406.66
	Flywheel	125.50	251.00	2	6	36	15,472	3,149	18,621	87.47	27,130	5,606	32,736	155.73
buy	Composite Shell	100.00	200.00	1	6	36	10,155	1,866	12,021	51.83	19,807	3,640	23,447	101.10
make	Titanium Hub	12.00	24.00	1	6	36	1,113	500	1,613	13.89	1,336	600	1,936	16.67
make	Titanium Shaft	2.00	4.00	1	6	36	305	107	412	2.97	366	128	494	3.57
buy	M/G perm mag assy	5.00	10.00	1	6	36	393	236	629	6.56	767	460	1,227	12.79
buy	M/G stator assy	2.00	4.00	1	6	36	202	107	309	2.97	394	209	603	5.80
buy	Radial act mag bearings	1.50	6.00	2	12	72	559	140	699	1.94	1,090	273	1,363	3.79
buy	Ax perm mag bearings	0.50	2.00	2	12	72	85	55	140	0.76	166	107	273	1.49
buy	Rotor position sensor	0.25	1.00	2	12	72	17	31	48	0.43	33	60	94	0.84
make	DI Flywheel			1	6	36	1,962	0	1,962	0.00	2,354	0	2,354	0.00
make	I&T Flywheel			1	6	36	681	107	788	2.97	817	128	946	3.57
mak	Power Processing Unit	20.00	40.00	2	6	36	18,381	7,101	25,482	197.25	22,057	8,521	30,578	236.70
mak	Bearing Control Unit	10.00	20.00	2	6	36	23,484	6,419	29,903	178.31	28,181	7,703	35,884	213.97
mak	ORU Housing	100.00	100.00	1	3	18	312	1,870	2,182	103.89	374	2,244	2,618	124.67
mak	I&T SSFW			1	3	18	6,877	1,038	7,915	57.67	8,252	1,246	9,498	69.20

* Input cost for ECIRP

PRICE model inputs PLTFM=2.5

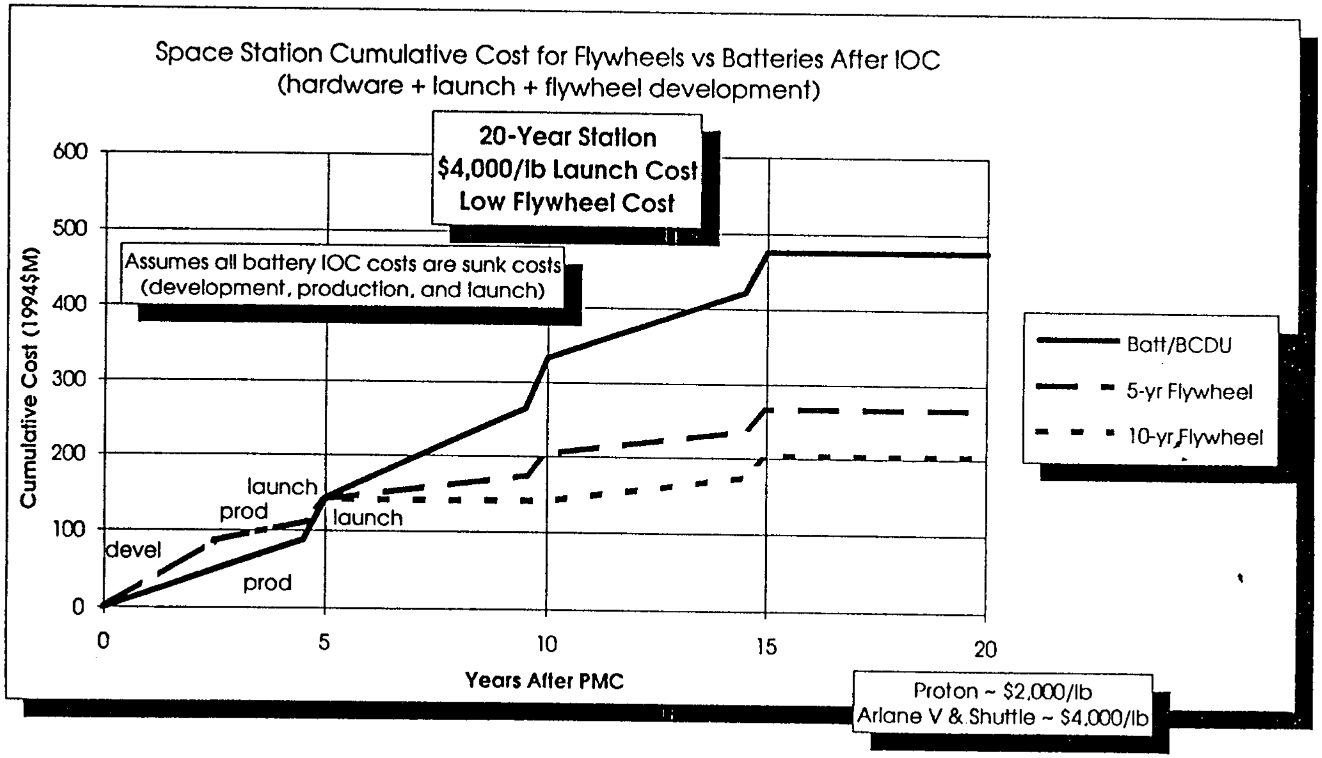
		Qty NHA	WS (lb)	WE (lb)	WT (lb)	MCPLXS	MCPLXE	INTEGS	INTEGE	NEWST	NEWEL	DESRPS	DESRPE	ECMPLX	SPLANS	EPLANS	DLEVS
SSFW																	
mak	Flywheel	2															
buy	Composite Shell	1	100.00		100.00	6.331		0.50		1.00		0.00		1.90			1.00
make	Titanium Hub	1	12.00		12.00	6.827		0.50		1.00		0.00		1.00			
make	Titanium Shaft	1	2.00		2.00	6.827		0.50		1.00		0.00		1.00			
buy	M/G perm mag assy	1	5.00		5.00	6.827		0.50		1.00		0.00		0.70			1.00
buy	M/G stator assy	1	2.00		2.00	6.827		0.50		1.00		0.00		0.70			1.00
buy	Radial act mag bearings	2	1.50		1.50	6.827		0.50		1.00		0.00		1.60			1.00
buy	Ax perm mag bearings	2	0.50		0.50	6.827		0.50		1.00		0.00		0.70			1.00
buy	Rotor position sensor	2	0.25		0.25	6.827		0.50		1.00		0.00		0.20			1.00
make	Design Integ Flywheel	1															
make	I&T Flywheel	1						0.50							0.70		
mak	Power Processing Unit	2	13.30	6.70	20.00	6.000	10.000	0.50	0.50	0.90	0.90	0.00	0.00	1.60			
mak	Bearing Control Unit	2	4.00	6.00	10.00	6.000	10.000	0.50	0.50	1.00	1.00	0.00	0.00	1.90			
mak	ORU Housing	1	100.00		100.00	6.501		0.50									
mak	I&T SSFW	1													0.70	0.70	

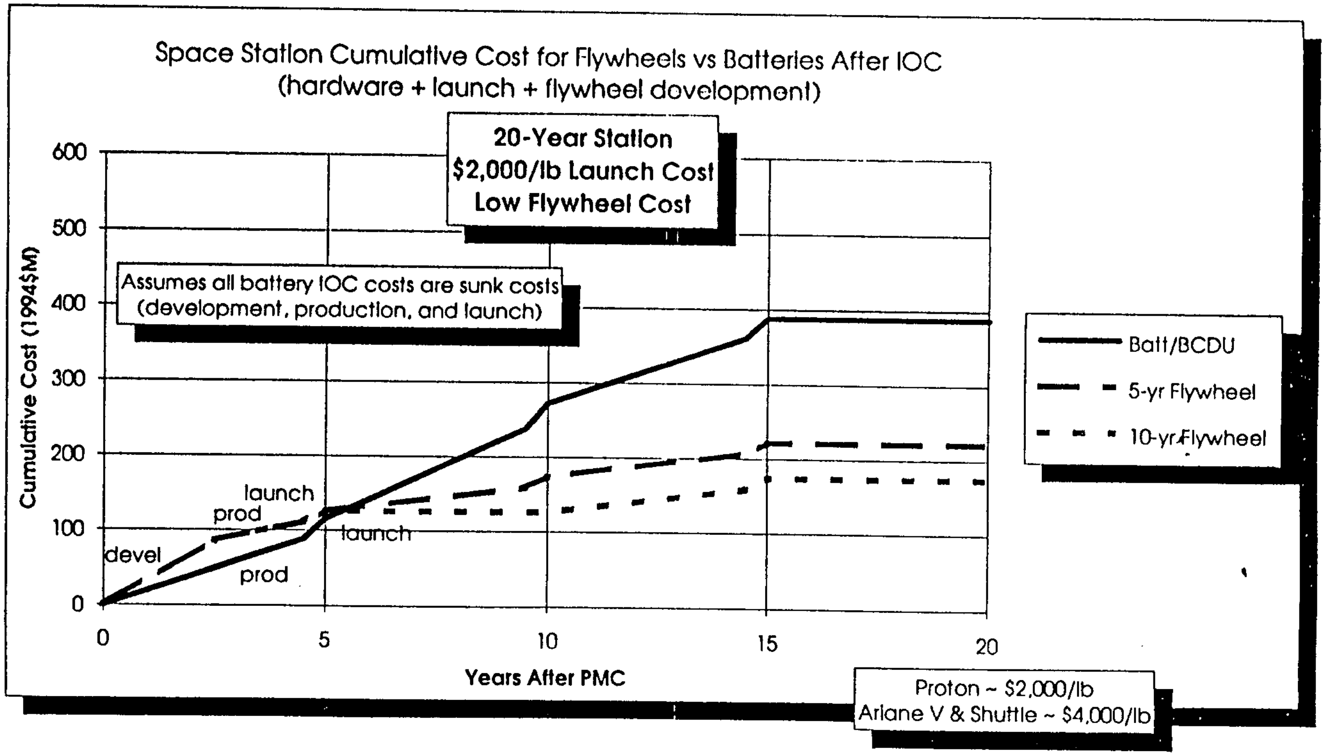
* ECIRP value

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	file	SSFW12E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW12 & SSFW12B									
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							LOW ESTIMATE								
3	time	10:09 AM		(cost to the government, 1994$M)															
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel							
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18							
7	Initial ORU cost (1993$M)				1.82		1.38												
8	1.042	1993->1994 escalation factor																	
9	Initial ORU cost (1994$M)				1.90		1.44			1.41		1.41							
10	1.3	replacement ORU cost factor																	
11	replacement ORU cost (1994$M)				2.47		1.87			1.83		1.83							
12	weight per ORU (lb)				375		196			411		411							
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00							
15	development cost (1994$M)				0	sunk	0	sunk		86		86							
16	Initial HW cost/SS (1994$M)				0	sunk	0	sunk		25		25							
17	replacement HW cost/SS (1994$M)				89		34			33		33							
18								20-Year Station											
19	$2,000	/lb launch cost (with FSE factor of 1.2)																	
20	launch cost/SS (1994$M)				27		7			15		15							
21									Battery										
22					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw12e1 chart				
23	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDl	5-yr Flywh	10-yr Flywheel	
24	0				0	0	0	0	0	0	0	0	0		0	0	0	0	
25	2.5 flywheel devel				49	49	0	0	49	86	86	86	86		3	49	86	86	
26	4.5 prod				39	89	0	0	89	25	111	25	111		5	89	111	111	
27	5 launch				27	116	0	0	116	15	126	15	126		5	116	126	126	
28	9.5 prod				89	205	34	34	238	33	159	0	126		10	238	159	126	
29	10 launch				27	232	7	41	272	15	174	0	126		10	272	174	126	
30	14.5 prod				89	320	0	41	361	33	207	33	159		15	361	207	159	
31	15 launch				27	347	0	41	388	15	222	15	174		15	388	222	174	
32	20				0	347	0	41	388	0	222	0	174		20	388	222	174	
33								20-Year Station											
34	$4,000	/lb launch cost (with FSE factor of 1.2)																	
35	launch cost/SS (1994$M)				54		14			30		30							
36									Battery										
37					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw12e2 chart				
38	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDl	5-yr Flywh	10-yr Flywheel	
39	0				0	0	0	0	0	0	0	0	0		0	0	0	0	
40	2.5 flywheel devel				49	49	0	0	49	86	86	86	86		3	49	86	86	
41	4.5 prod				39	89	0	0	89	25	111	25	111		5	89	111	111	
42	5 launch				54	143	0	0	143	30	141	30	141		5	143	141	141	
43	9.5 prod				89	232	34	34	265	33	174	0	141		10	265	174	141	
44	10 launch				54	286	14	48	333	30	204	0	141		10	333	204	141	
45	14.5 prod				89	374	0	48	422	33	237	33	174		15	422	237	174	
46	15 launch				54	428	0	48	476	30	266	30	204		15	476	266	204	
47	20				0	428	0	48	476	0	266	0	204		20	476	266	204	

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	file	SSFW12E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW12 & SSFW12B									
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							LOW ESTIMATE								
3	time	10:09 AM		(cost to the government, 1994$M)															
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel							
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18							
7	initial ORU cost (1993$M)				1.82		1.38												
8		1.042 1993->1994 escalation factor																	
9	initial ORU cost (1994$M)				1.90		1.44			1.41		1.41							
10		1.3 replacement ORU cost factor																	
11	replacement ORU cost (1994$M)				2.47		1.87			1.83		1.83							
12	weight per ORU (lb)				375		196			411		411							
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00							
15	development cost (1994$M)				0	sunk	0	sunk		86		86							
16	initial HW cost/SS (1994$M)				0	sunk	0	sunk		25		25							
17	replacement HW cost/SS (1994$M)				89		34			33		33							
48								15-Year Station											
49	**$2,000**	/lb launch cost (with FSE factor of 1.2)																	
50	launch cost/SS (1994$M)				27		7			15		15							
51									Battery										
52					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw12e3 chart				
53	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywh	10-yr Flywheel	
54	0				0	0	0	0	0	0	0	0	0		0	0	0	0	
55	2.5 devel				49	49	0	0	49	86	86	86	86		3	49	86	86	
56	4.5 prod				39	89	0	0	89	25	111	25	111		5	89	111	111	
57	5 launch				27	116	0	0	116	15	126	15	126		5	116	126	126	
58	9.5 prod				89	205	34	34	238	33	159	0	126		10	238	159	126	
59	10 launch				27	232	7	41	272	15	174	0	126		10	272	174	126	
60	15				0	232	0	41	272	0	174	0	126		15	272	174	126	
61																			
62																			
63								15-Year Station											
64	**$4,000**	/lb launch cost (with FSE factor of 1.2)																	
65	launch cost/SS (1994$M)				54		14			30		30							
66									Battery										
67					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw12e4 chart				
68	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywh	10-yr Flywheel	
69	0				0	0	0	0	0	0	0	0	0		0	0	0	0	
70	2.5 devel				49	49	0	0	49	86	86	86	86		3	49	86	86	
71	4.5 prod				39	89	0	0	89	25	111	25	111		5	89	111	111	
72	5 launch				54	143	0	0	143	30	141	30	141		5	143	141	141	
73	9.5 prod				89	232	34	34	265	33	174	0	141		10	265	174	141	
74	10 launch				54	286	14	48	333	30	204	0	141		10	333	204	141	
75	15				0	286	0	48	333	0	204	0	141		15	333	204	141	
76																			
77																			

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	file	SSFW12E		**Space Station Flywheel (SSFW) Trade Study**						**PRICE run SSFW12 & SSFW12B**									
2	date	6/27/94		**PRICE Model Cost Estimate for Flywheels**							**LOW ESTIMATE**								
3	time	10:09 AM		**(cost to the government, 1994$M)**															
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel							
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18							
7	Initial ORU cost (1993$M)				1.82		1.38												
8	1.042	1993–>1994 escalation factor																	
9	Initial ORU cost (1994$M)				1.90		1.44			1.41		1.41							
10	1.3	replacement ORU cost factor																	
11	replacement ORU cost (1994$M)				2.47		1.87			1.83		1.83							
12	weight per ORU (lb)				375		196			411		411							
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00							
15	development cost (1994$M)				0 sunk		0 sunk			86		86							
16	Initial HW cost/SS (1994$M)				0 sunk		0 sunk			25		25							
17	replacement HW cost/SS (1994$M)				89		34			33		33							
78								**10-Year Station**											
79	**$2,000**	/lb launch cost (with FSE factor of 1.2)																	
80	launch cost/SS (1994$M)				27		7			15		15							
81									Battery										
82					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw12e5 chart				
83	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDl	5-yr Flywheel		
84	0				0	0	0	0	0	0	0	0	0		0	0	0		
85	2.5 devel				49	49	0	0	49	86	86	86	86		3	49	86		
86	4.5 prod				39	89	0	0	89	25	111	25	111		5	89	111		
87	5 launch				27	116	0	0	116	15	126	15	126		5	116	126		
88	10				0	116	0	0	116	0	126	0	126		10	116	126		
89																			
90																			
91																			
92																			
93								**10-Year Station**											
94	**$4,000**	/lb launch cost (with FSE factor of 1.2)																	
95	launch cost/SS (1994$M)				54		14			30		30							
96									Battery										
97					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw12e6 chart				
98	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDl	5-yr Flywheel		
99	0				0	0	0	0	0	0	0	0	0		0	0	0		
100	2.5 devel				49	49	0	0	49	86	86	86	86		3	49	86		
101	4.5 prod				39	89	0	0	89	25	111	25	111		5	89	111		
102	5 launch				54	143	0	0	143	30	141	30	141		5	143	141		
103	10				0	143	0	0	143	0	141	0	141		10	143	141		
104																			
105																			
106																			
107																			


Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)
20-Year Station
$4,000/lb Launch Cost
Low Flywheel Cost
Assumes all battery IOC costs are sunk costs
(development, production, and launch)
Cumulative Cost (1994$M)
600
500
400
300
200
100
0
0
5
10
15
20
Years After PMC
launch
prod
devel
launch
prod
Batt/BCDU
5-yr Flywheel
10-yr Flywheel
Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb



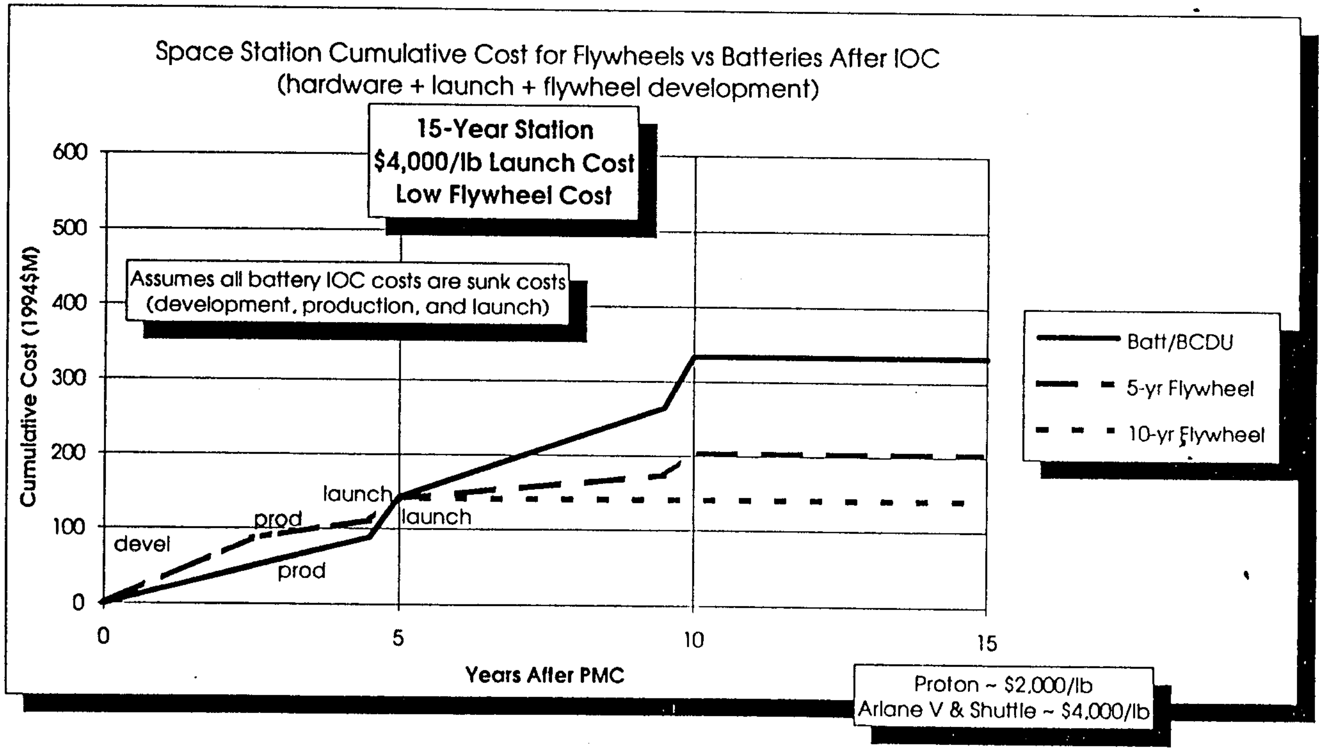
Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

20-Year Station
$2,000/lb Launch Cost
Low Flywheel Cost

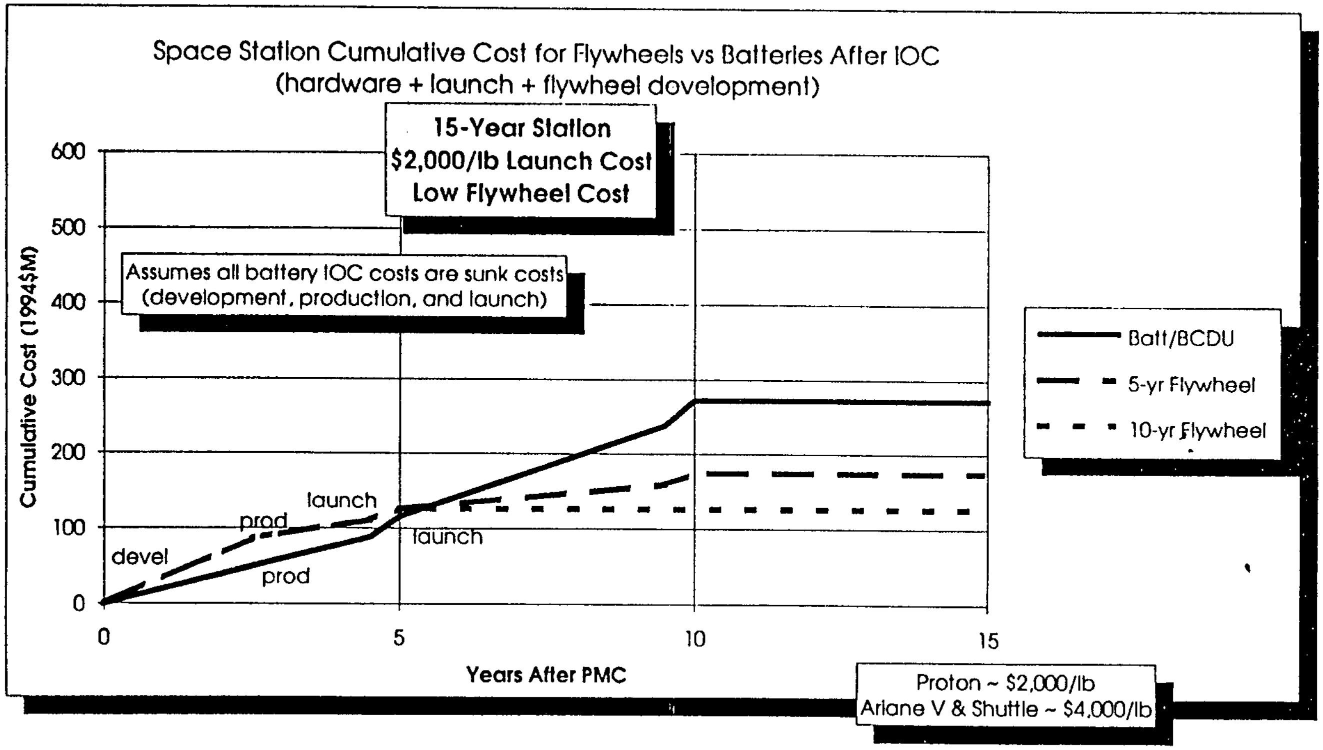
Assumes all battery IOC costs are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW12E1.XLC 6/27/94 1:10 PM


Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

SSFW12E4.XLC 6/27/94 1:08 PM

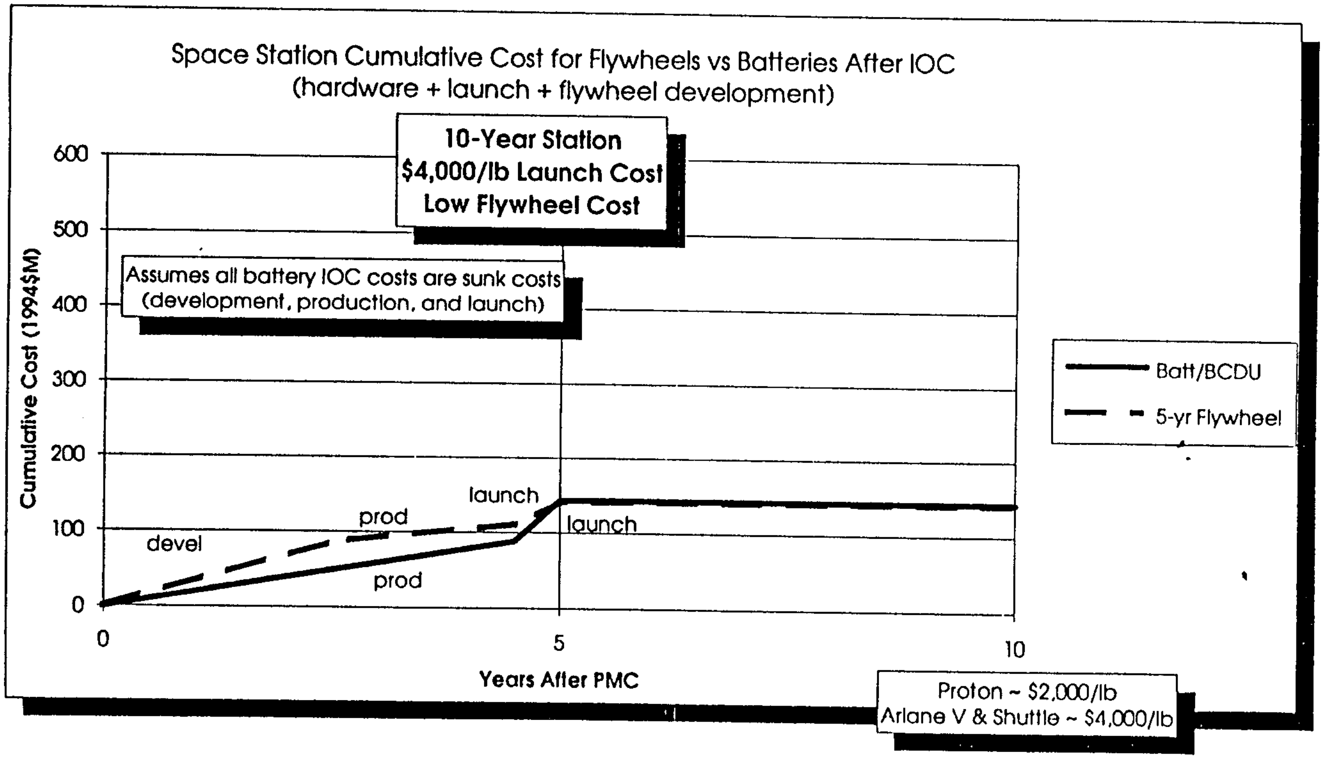

Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

15-Year Station
$2,000/lb Launch Cost
Low Flywheel Cost

Assumes all battery IOC costs are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW12E3.XLC 6/27/94 1:08 PM



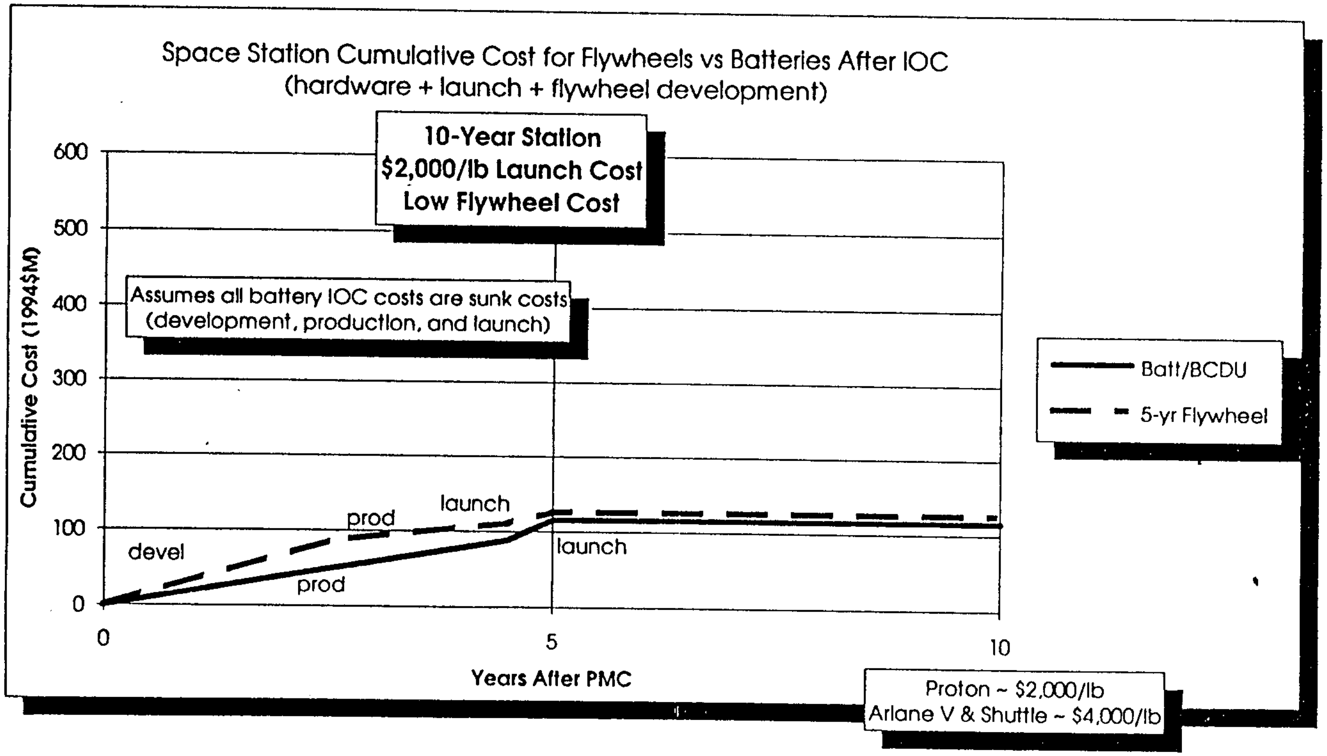
Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

10-Year Station
$4,000/lb Launch Cost
Low Flywheel Cost

Assumes all battery IOC costs are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW12E6.XLC 6/27/94 1:06 PM


Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

10-Year Station
$2,000/lb Launch Cost
Low Flywheel Cost

Assumes all battery IOC costs are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW12E5.XLC 6/27/94 1:07 PM

file SSFW2C Space Station Flywheel (SSFW)
date 6/27/94 **PRICE Model Cost Estimate (1994$K)**
time 11:17 AM

PRICE run SSFW7 & SSFW7B

HIGH ESTIMATE

1.96 wraps on buy items (=1.26*1.29*1.20)
1.20 wraps on make items (RD G&A & profit)

		Componer Weight (lb)	Weight per ORU (lb)	Quantity NHA	Prototype Quantity	Prod Quantity	Devel Cost	Prod Cost	Total Cost	Amortize UPC	Devel Cost	Prod Cost	Total Cost	Amortized UPC
							PRICE model output				**RD price including G&A & profit**			
SSFW			411		3	18	83,880	36,934	120,814	2,052	119,740	58,728	178,468	3,263
	Flywheel	125.500	251	2	6	36	32,302	20,334	52,636	565	57,846	38,808	96,654	1,078
buy	Composite Shell	100.000	200	1	6	36	10,155	1,866	12,021	52	19,807	3,640	23,447	101
make	Titanium Hub	12.000	24	1	6	36	1,113	500	1,613	14	1,336	600	1,936	17
make	Titanium Shaft	2.000	4	1	6	36	305	107	412	3	366	128	494	4
buy	M/G perm mag assy	5.000	10	1	6	36	10,140	13,411	23,551	373	19,778	26,158	45,936	727
buy	M/G stator assy	2.000	4	1	6	36	1,339	424	1,763	12	2,612	827	3,439	23
buy	Radial act mag bearings	1.500	6	2	12	72	2,196	561	2,757	8	4,283	1,094	5,377	15
buy	Ax perm mag bearings	0.500	2	2	12	72	1,557	2,820	4,377	39	3,037	5,500	8,537	76
buy	Rotor position sensor	0.250	1	2	12	72	42	115	157	2	82	224	306	3
make	DI Flywheel			1	6	36	3,663	0	3,663	0	4,396	0	4,396	0
make	I&T Flywheel			1	6	36	1,792	530	2,322	15	2,150	636	2,786	18
mak	Power Processing Unit	20.000	40	2	6	36	20,231	7,123	27,354	198	24,277	8,548	32,825	237
mak	Bearing Control Unit	10.000	20	2	6	36	23,484	6,419	29,903	178	28,181	7,703	35,884	214
mak	ORU Housing	100.000	100	1	3	18	312	1,870	2,182	104	374	2,244	2,618	125
mak	I&T SSFW			1	3	18	7,551	1,188	8,739	66	9,061	1,426	10,487	79

* Input cost for ECIRP

PRICE model inputs PLTFM=2.5

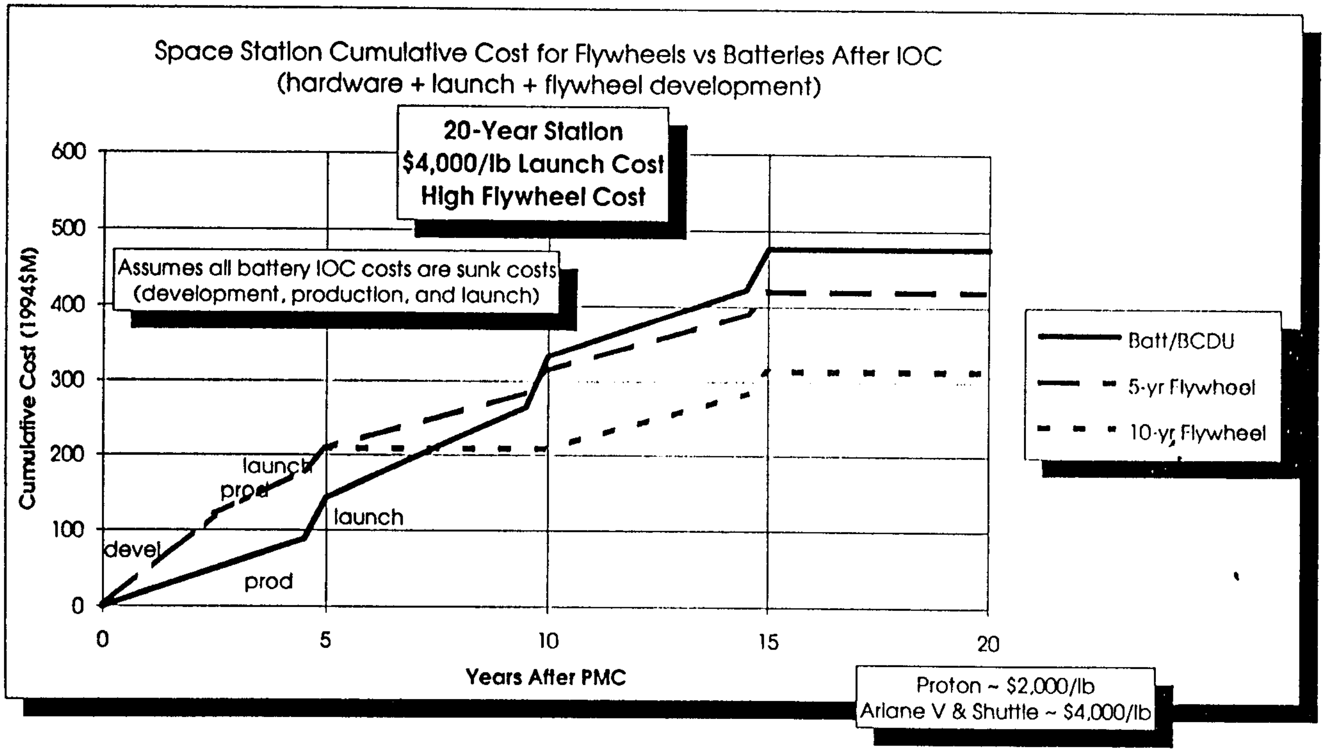
		Qty NHA	WS (lb)	WE (lb)	WT (lb)	MCPLXS	MCPLXE	INTEGS	INTEGE	NEWST	NEWEL	DESRPS	DESRPE	ECMPLX	SPLANS	EPLANS	DLEVS
SSFW																	
mak	Flywheel	2															
buy	Composite Shell	1	100.000		100.000	6.331		0.50		1.00		0.00		1.90			1.00
make	Titanium Hub	1	12.000		12.000	6.827		0.50		1.00		0.00		1.00			
make	Titanium Shaft	1	2.000		2.000	6.827		0.50		1.00		0.00		1.00			
buy	M/G perm mag assy	1	5.000		5.000	10.678		0.50		1.00		0.00		1.60			1.00
buy	M/G stator assy	1	2.000		2.000	8.305		0.50		1.00		0.00		1.60			1.00
buy	Radial act mag bearings	2	1.500		1.500	8.305		0.50		1.00		0.00		2.30			1.00
buy	Ax perm mag bearings	2	0.500		0.500	10.678		0.50		1.00		0.00		1.20			1.00
buy	Rotor position sensor	2	0.250		0.250	8.305		0.50		1.00		0.00		0.20			1.00
make	Design Integ Flywheel	1															
make	I&T Flywheel	1						0.50							0.70		
mak	Power Processing Unit	2	13.300	6.700	20.000	6.000	10.000	0.50	0.50	1.00	1.00	0.00	0.00	1.60			
mak	Bearing Control Unit	2	4.000	6.000	10.000	6.000	10.000	0.50	0.50	1.00	1.00	0.00	0.00	1.90			
mak	ORU Housing	1	100.000		100.000	6.501		0.50									
mak	I&T SSFW	1													0.70	0.70	

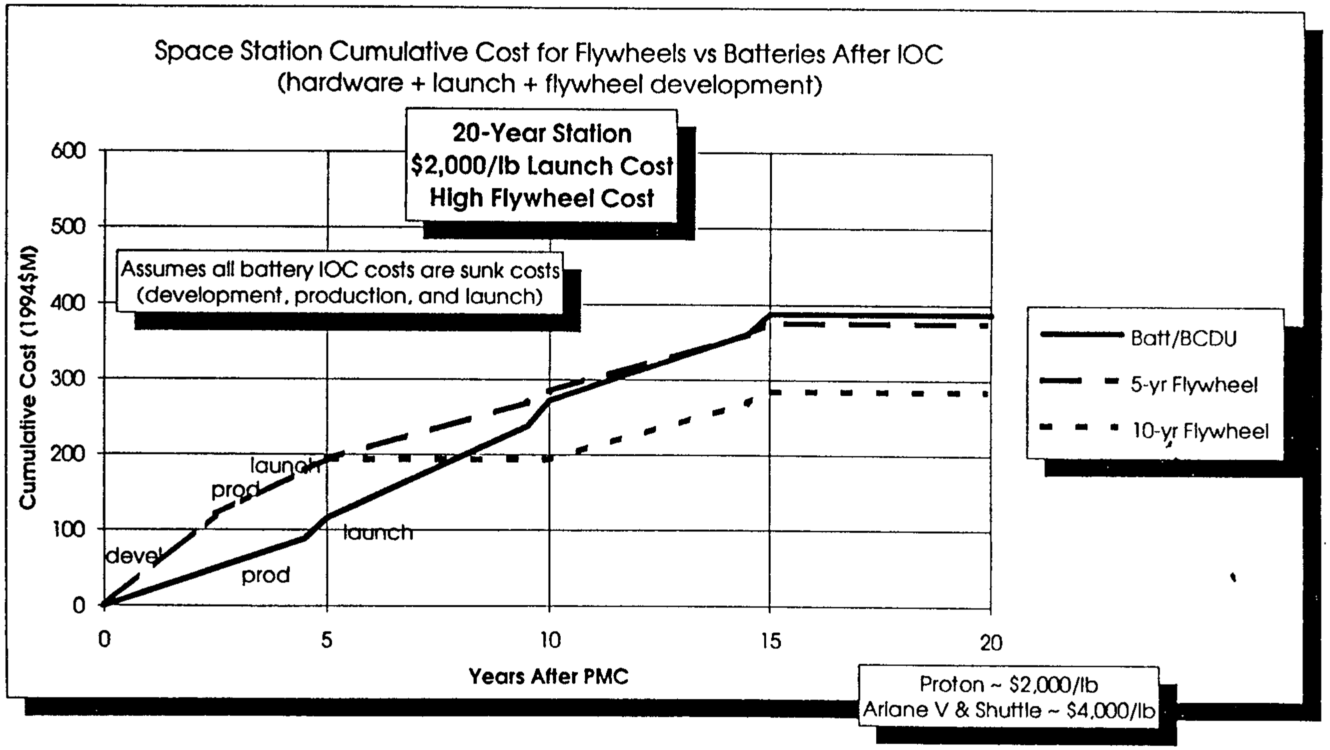
* ECIRP value

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	file	SSFW7E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW7 & SSFW7B									
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							HIGH ESTIMATE								
3	time	1:30 PM		(cost to the government, 1994$M)															
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel							
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18							
7	initial ORU cost (1993$M)				1.82		1.38												
8	1.042	1993-->1994 escalation factor																	
9	initial ORU cost (1994$M)				1.90		1.44			3.26		3.26							
10	1.3	replacement ORU cost factor																	
11	replacement ORU cost (1994$M)				2.47		1.87			4.24		4.24							
12	weight per ORU (lb)				375		196			411		411							
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00							
15	development cost (1994$M)				0 sunk		0 sunk			120		120							
16	initial HW cost/SS (1994$M)				0 sunk		0 sunk			59		59							
17	replacement HW cost/SS (1994$M)				89		34			76		76							
18								20-Year Station											
19	$2,000	/lb launch cost (with FSE factor of 1.2)																	
20	launch cost/SS (1994$M)				27		7			15		15							
21									Battery										
22					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw7e1	chart			
23	years				delta	Battery	delta	BCDU	Batt/BC(	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCD(	5-yr Flywh	10-yr Flywheel	
24	0				0	0	0	0	0	0	0	0	0		0	0	0	0	
25	2.5 flywheel devel				49	49	0	0	49	120	120	120	120		3	49	120	120	
26	4.5 prod				39	89	0	0	89	59	179	59	179		5	89	179	179	
27	5 launch				27	116	0	0	116	15	193	15	193		5	116	193	193	
28	9.5 prod				89	205	34	34	238	76	270	0	193		10	238	270	193	
29	10 launch				27	232	7	41	272	15	285	0	193		10	272	285	193	
30	14.5 prod				89	320	0	41	361	76	361	76	270		15	361	361	270	
31	15 launch				27	347	0	41	388	15	376	15	285		15	388	376	285	
32	20				0	347	0	41	388	0	376	0	285		20	388	376	285	
33								20-Year Station											
34	$4,000	/lb launch cost (with FSE factor of 1.2)																	
35	launch cost/SS (1994$M)				54		14			30		30							
36									Battery										
37					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw7e2	chart			
38	years				delta	Battery	delta	BCDU	Batt/BC(	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCD(	5-yr Flywh	10-yr Flywheel	
39	0				0	0	0	0	0	0	0	0	0		0	0	0	0	
40	2.5 flywheel devel				49	49	0	0	49	120	120	120	120		3	49	120	120	
41	4.5 prod				39	89	0	0	89	59	179	59	179		5	89	179	179	
42	5 launch				54	143	0	0	143	30	208	30	208		5	143	208	208	
43	9.5 prod				89	232	34	34	265	76	285	0	208		10	265	285	208	
44	10 launch				54	286	14	48	333	30	314	0	208		10	333	314	208	
45	14.5 prod				89	374	0	48	422	76	390	76	285		15	422	390	285	
46	15 launch				54	428	0	48	476	30	420	30	314		15	476	420	314	
47	20				0	428	0	48	476	0	420	0	314		20	476	420	314	

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	file	SSFW7E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW7 & SSFW7B									
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							HIGH ESTIMATE								
3	time	1:30 PM		(cost to the government, 1994$M)															
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel							
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18							
7	initial ORU cost (1993$M)				1.82		1.38												
8	1.042	1993-->1994 escalation factor																	
9	initial ORU cost (1994$M)				1.90		1.44			3.26		3.26							
10	1.3	replacement ORU cost factor																	
11	replacement ORU cost (1994$M)				2.47		1.87			4.24		4.24							
12	weight per ORU (lb)				375		196			411		411							
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00							
15	development cost (1994$M)				0 sunk		0 sunk			120		120							
16	initial HW cost/SS (1994$M)				0 sunk		0 sunk			59		59							
17	replacement HW cost/SS (1994$M)				89		34			76		76							
48								15-Year Station											
49	$2,000	/lb launch cost (with FSE factor of 1.2)																	
50	launch cost/SS (1994$M)				27		7			15		15							
51									Battery										
52					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw7e3	chart			
53	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywh	10-yr Flywheel	
54	0				0	0	0	0	0	0	0	0	0		0	0	0	0	
55	2.5 devel				49	49	0	0	49	120	120	120	120		3	49	120	120	
56	4.5 prod				39	89	0	0	89	59	179	59	179		5	89	179	179	
57	5 launch				27	116	0	0	116	15	193	15	193		5	116	193	193	
58	9.5 prod				89	205	34	34	238	76	270	0	193		10	238	270	193	
59	10 launch				27	232	7	41	272	15	285	0	193		10	272	285	193	
60	15				0	232	0	41	272	0	285	0	193		15	272	285	193	
61																			
62																			
63								15-Year Station											
64	$4,000	/lb launch cost (with FSE factor of 1.2)																	
65	launch cost/SS (1994$M)				54		14			30		30							
66									Battery										
67					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw7e4	chart			
68	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywh	10-yr Flywheel	
69	0				0	0	0	0	0	0	0	0	0		0	0	0	0	
70	2.5 devel				49	49	0	0	49	120	120	120	120		3	49	120	120	
71	4.5 prod				39	89	0	0	89	59	179	59	179		5	89	179	179	
72	5 launch				54	143	0	0	143	30	208	30	208		5	143	208	208	
73	9.5 prod				89	232	34	34	265	76	285	0	208		10	265	285	208	
74	10 launch				54	286	14	48	333	30	314	0	208		10	333	314	208	
75	15				0	286	0	48	333	0	314	0	208		15	333	314	208	
76																			
77																			

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	file	SSFW7E		Space Station Flywheel (SSFW) Trade Study						PRICE run SSFW7 & SSFW7B									
2	date	6/27/94		PRICE Model Cost Estimate for Flywheels							HIGH ESTIMATE								
3	time	1:30 PM		(cost to the government, 1994$M)															
5					Battery		BCDU			5-yr Flywheel		10-yr Flywheel							
6	qty of ORUs per SS (in 3 IEAs)				36		18			18		18							
7	initial ORU cost (1993$M)				1.82		1.38												
8	1.042	1993-->1994 escalation factor																	
9	initial ORU cost (1994$M)				1.90		1.44			3.26		3.26							
10	1.3	replacement ORU cost factor																	
11	replacement ORU cost (1994$M)				2.47		1.87			4.24		4.24							
12	weight per ORU (lb)				375		196			411		411							
13	mean replacement interval (yr)				5.00		10.00			5.00		10.00							
15	development cost (1994$M)				0	sunk	0	sunk		120		120							
16	initial HW cost/SS (1994$M)				0	sunk	0	sunk		59		59							
17	replacement HW cost/SS (1994$M)				89		34			76		76							
78								10-Year Station											
79	**$2,000**	/lb launch cost (with FSE factor of 1.2)																	
80	launch cost/SS (1994$M)				27		7			15		15							
81									Battery										
82					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw7e5	chart			
83	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywheel		
84	0				0	0	0	0	0	0	0	0	0		0	0	0		
85	2.5 devel				49	49	0	0	49	120	120	120	120		3	49	120		
86	4.5 prod				39	89	0	0	89	59	179	59	179		5	89	179		
87	5 launch				27	116	0	0	116	15	193	15	193		5	116	193		
88	10				0	116	0	0	116	0	193	0	193		10	116	193		
89																			
90																			
91																			
92																			
93								10-Year Station											
94	**$4,000**	/lb launch cost (with FSE factor of 1.2)																	
95	launch cost/SS (1994$M)				54		14			30		30							
96									Battery										
97					Battery		BCDU		+BCDU	5-yr Flywheel		10-yr Flywheel			ssfw7e6	chart			
98	years				delta	Battery	delta	BCDU	Batt/BCI	delta	5-yr Flyw	delta	10-yr Flywheel		years	Batt/BCDI	5-yr Flywheel		
99	0				0	0	0	0	0	0	0	0	0		0	0	0		
100	2.5 devel				49	49	0	0	49	120	120	120	120		3	49	120		
101	4.5 prod				39	89	0	0	89	59	179	59	179		5	89	179		
102	5 launch				54	143	0	0	143	30	208	30	208		5	143	208		
103	10				0	143	0	0	143	0	208	0	208		10	143	208		
104																			
105																			
106																			
107																			

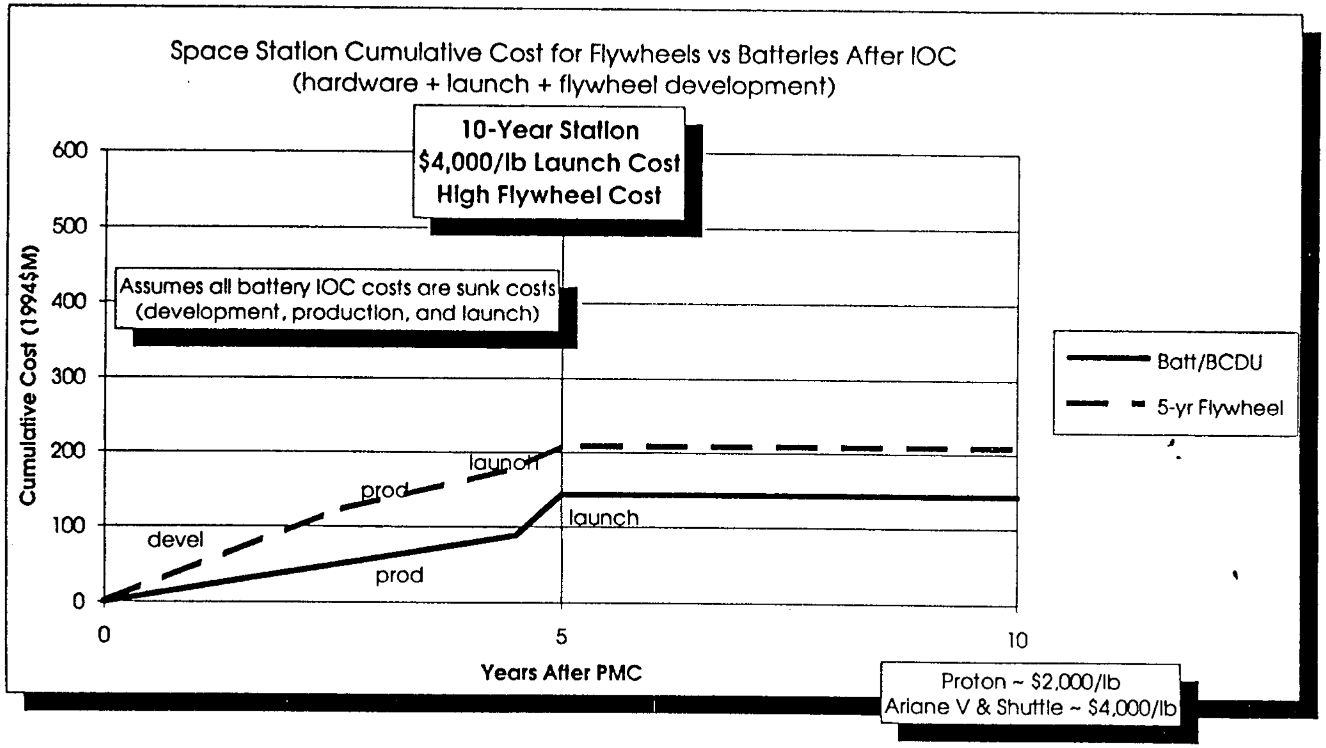

Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)
20-Year Station
$4,000/lb Launch Cost
High Flywheel Cost
Assumes all battery IOC costs are sunk costs
(development, production, and launch)
Cumulative Cost (1994$M)
600
500
400
300
200
100
0
0
5
10
15
20
Years After PMC
devel
prod
launch
prod
launch
Batt/BCDU
5-yr Flywheel
10-yr Flywheel
Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb


Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

20-Year Station
$2,000/lb Launch Cost
High Flywheel Cost

Assumes all battery IOC costs are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb



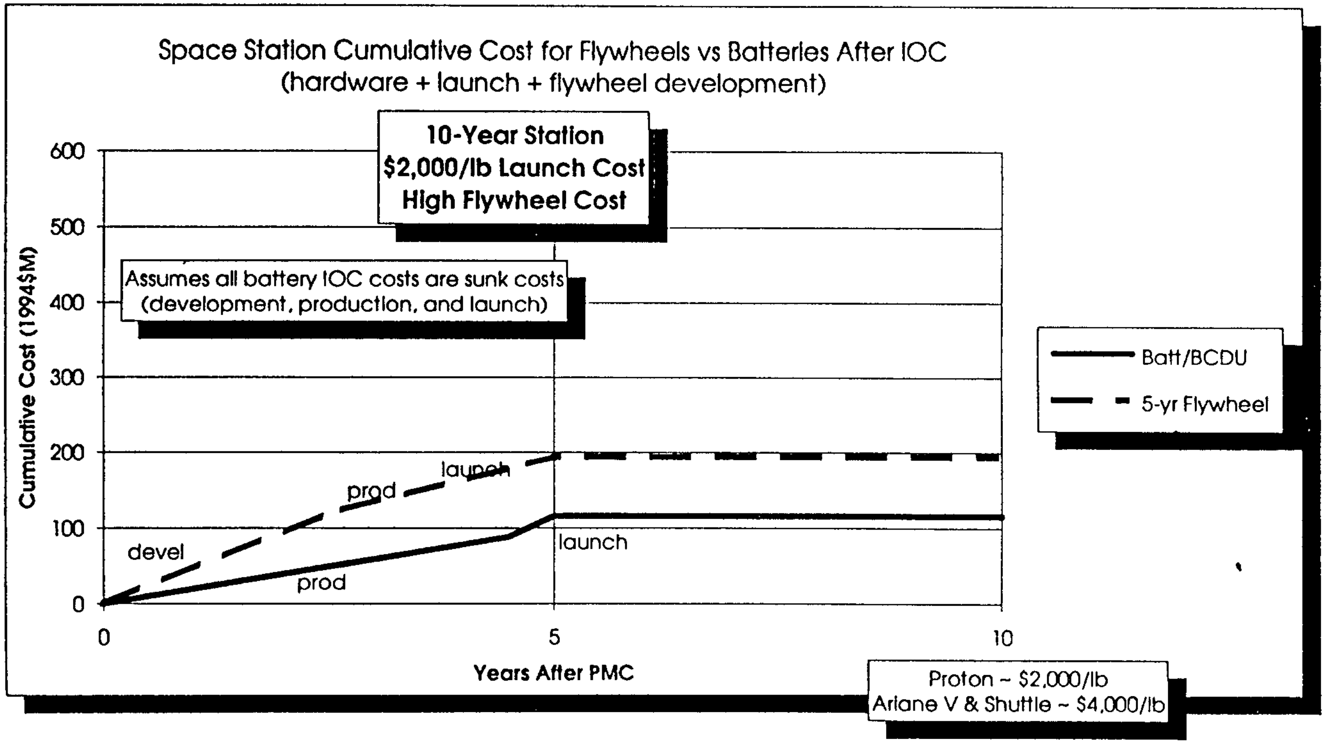
Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

10-Year Station
$4,000/lb Launch Cost
High Flywheel Cost

Assumes all battery IOC costs are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW7E6.XLC 6/27/94 12:58 PM



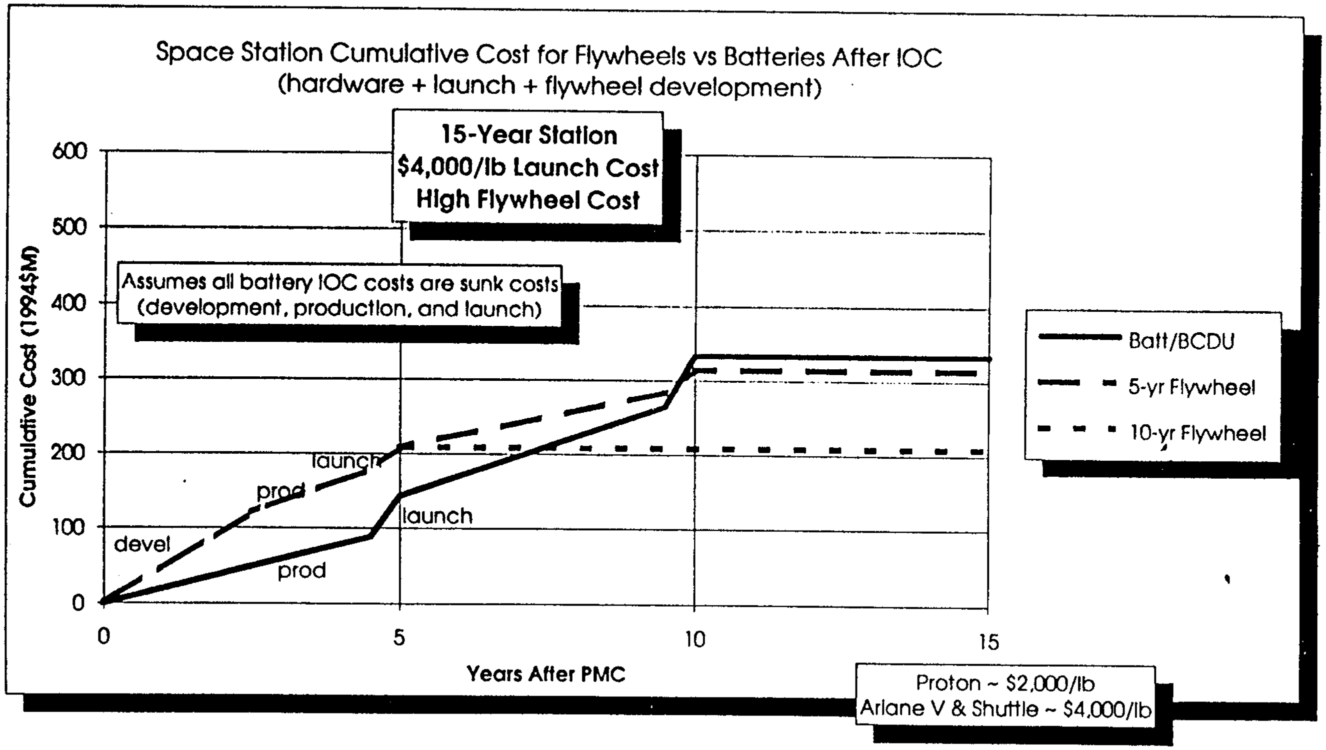
Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

10-Year Station
$2,000/lb Launch Cost
High Flywheel Cost

Assumes all battery IOC costs are sunk costs
(development, production, and launch)

Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW7E5.XLC 6/27/94 1:00 PM



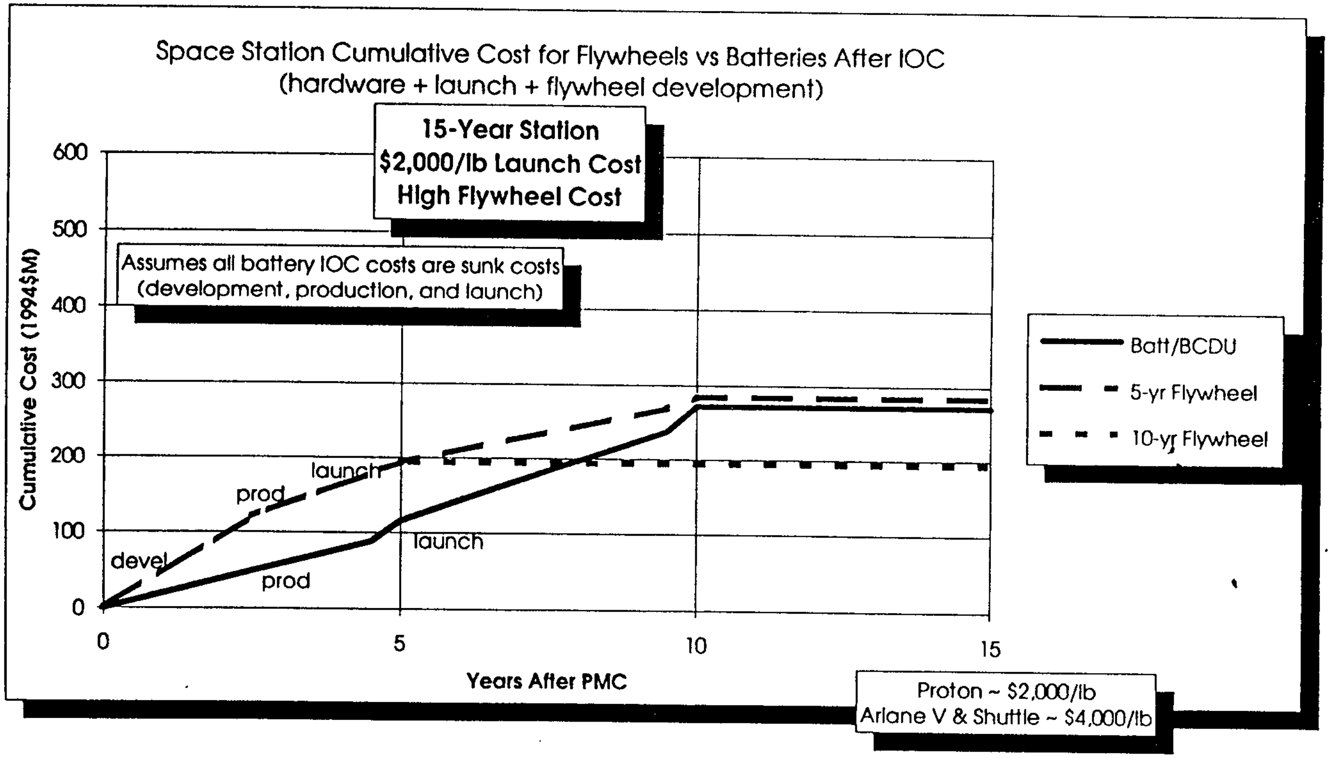
Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

15-Year Station
$4,000/lb Launch Cost
High Flywheel Cost

Assumes all battery IOC costs are sunk costs
(development, production, and launch)

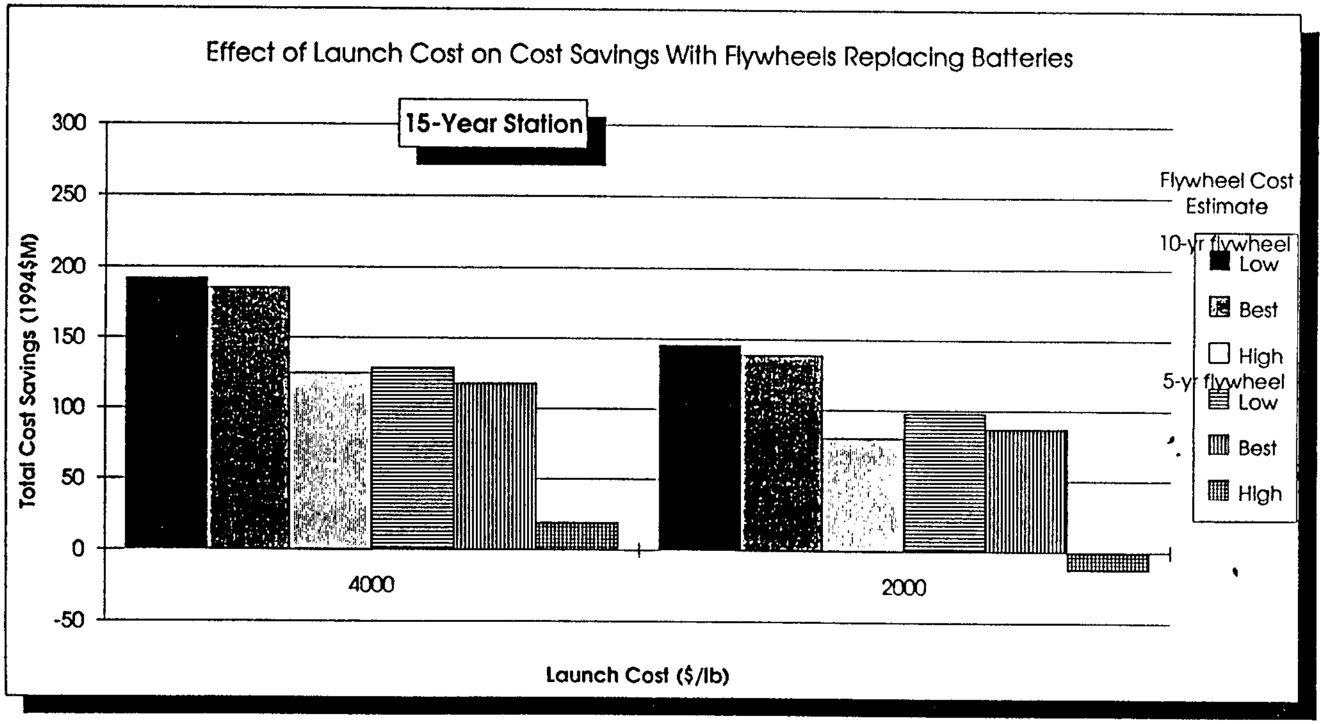
Proton ~ $2,000/lb
Ariane V & Shuttle ~ $4,000/lb

SSFW7E4.XLC 6/27/94 12:56 PM



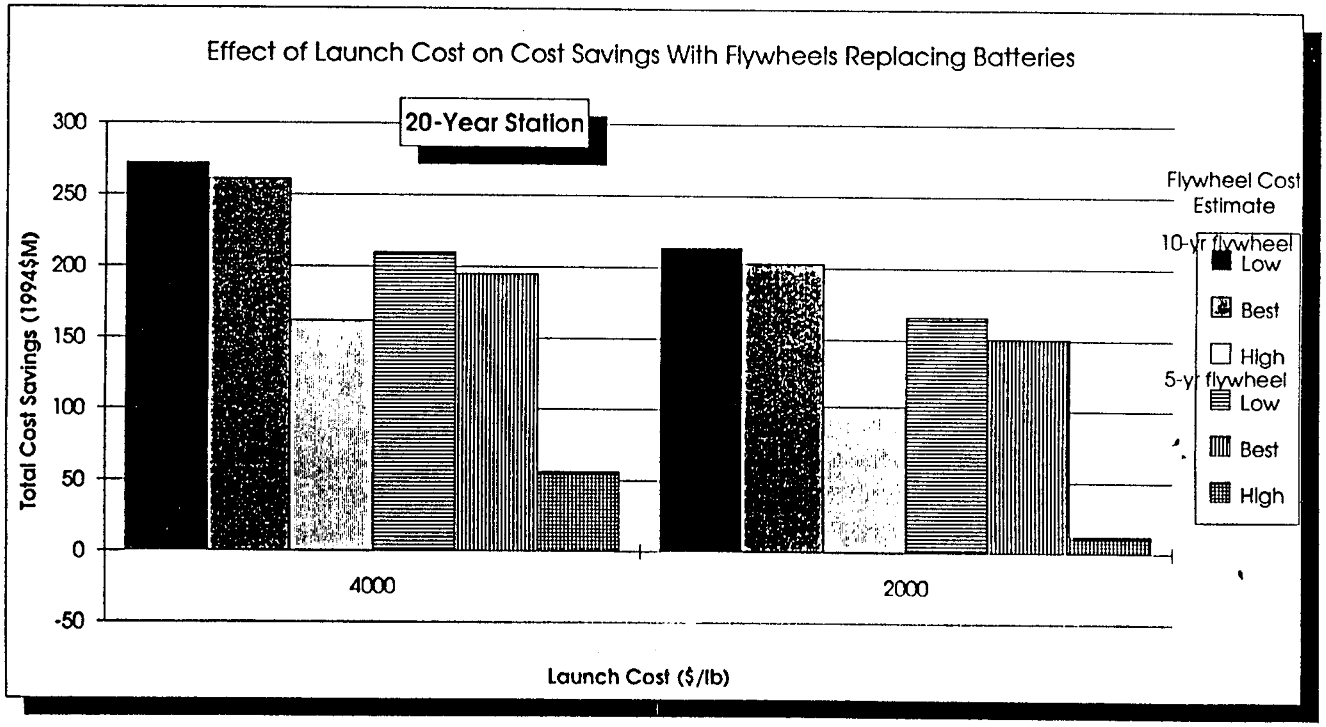
Space Station Cumulative Cost for Flywheels vs Batteries After IOC
(hardware + launch + flywheel development)

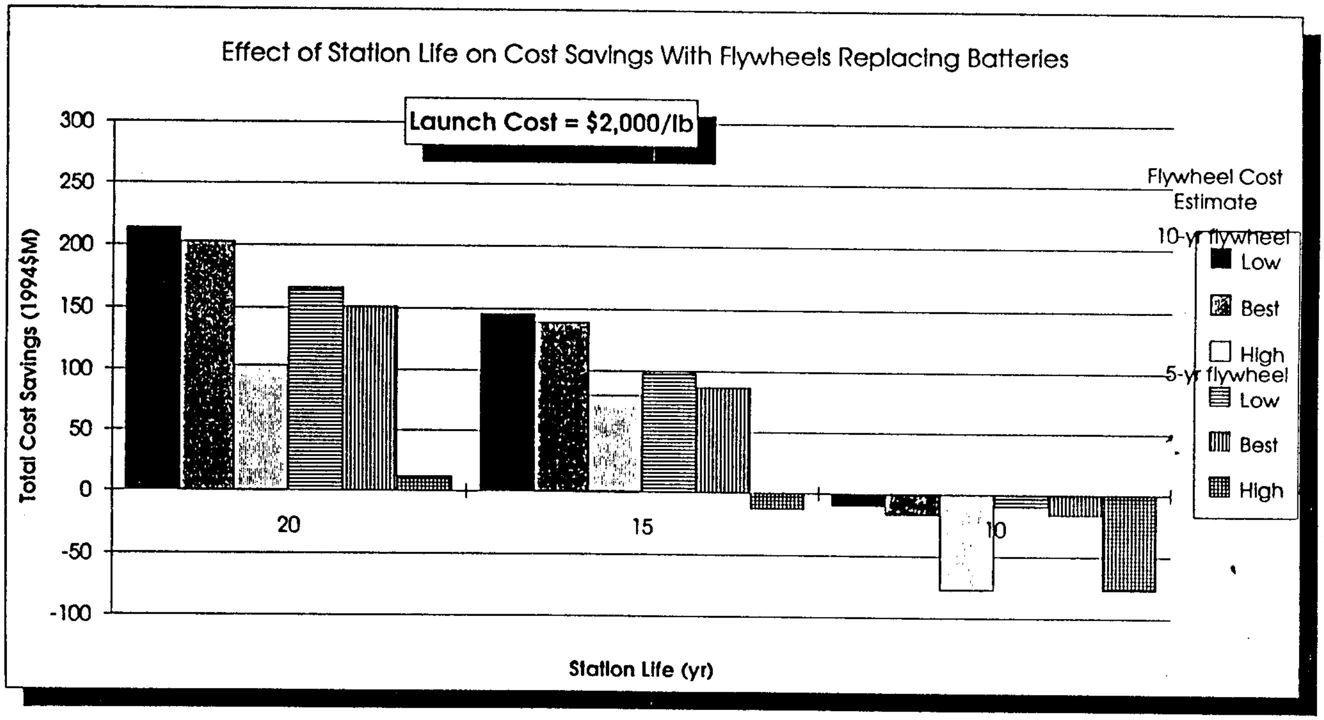
SSFW7E3.XLC 6/27/94 12:56 PM



Effect of Launch Cost on Cost Savings With Flywheels Replacing Batteries

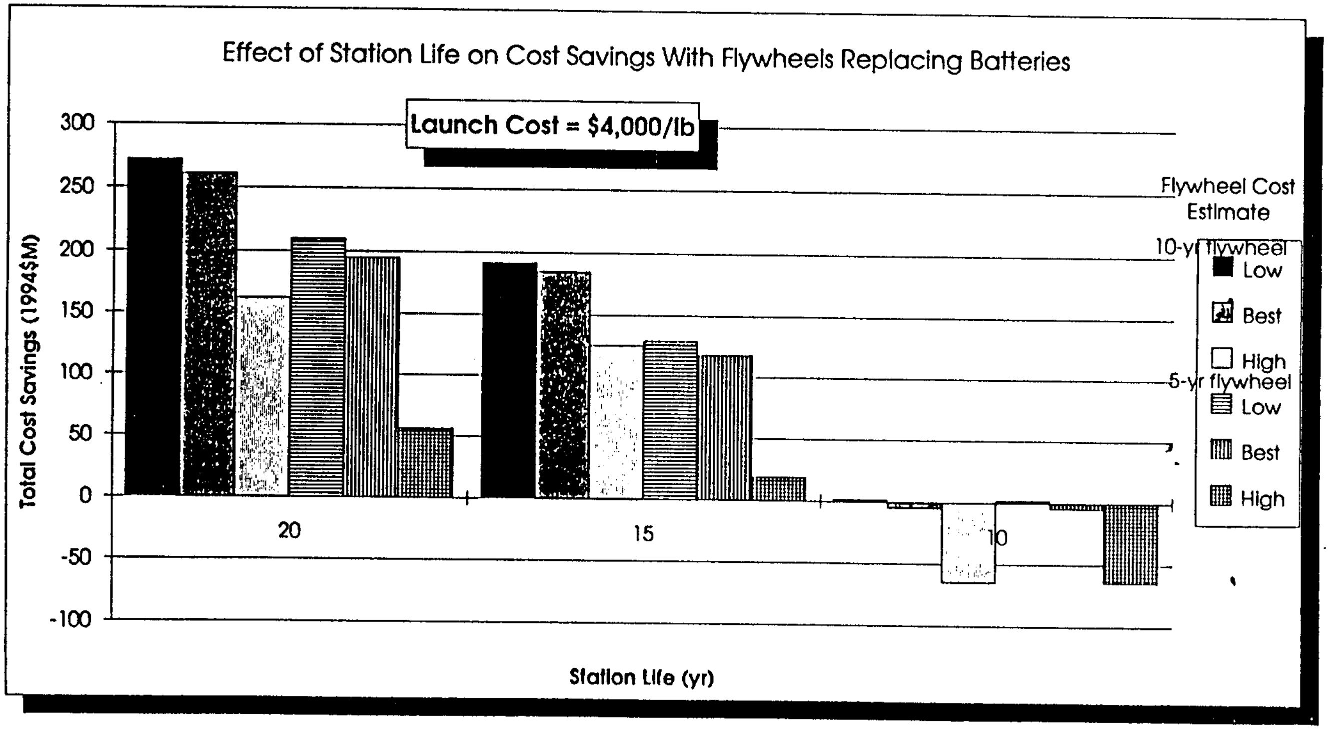
SSFW3C2B.XLC 6/27/94 2:44 PM


Effect of Launch Cost on Cost Savings With Flywheels Replacing Batteries
20-Year Station
Total Cost Savings (1994$M)
300
250
200
150
100
50
0
-50
4000
2000
Launch Cost ($/lb)
Flywheel Cost Estimate
10-yr flywheel
Low
Best
High
5-yr flywheel
Low
Best
High

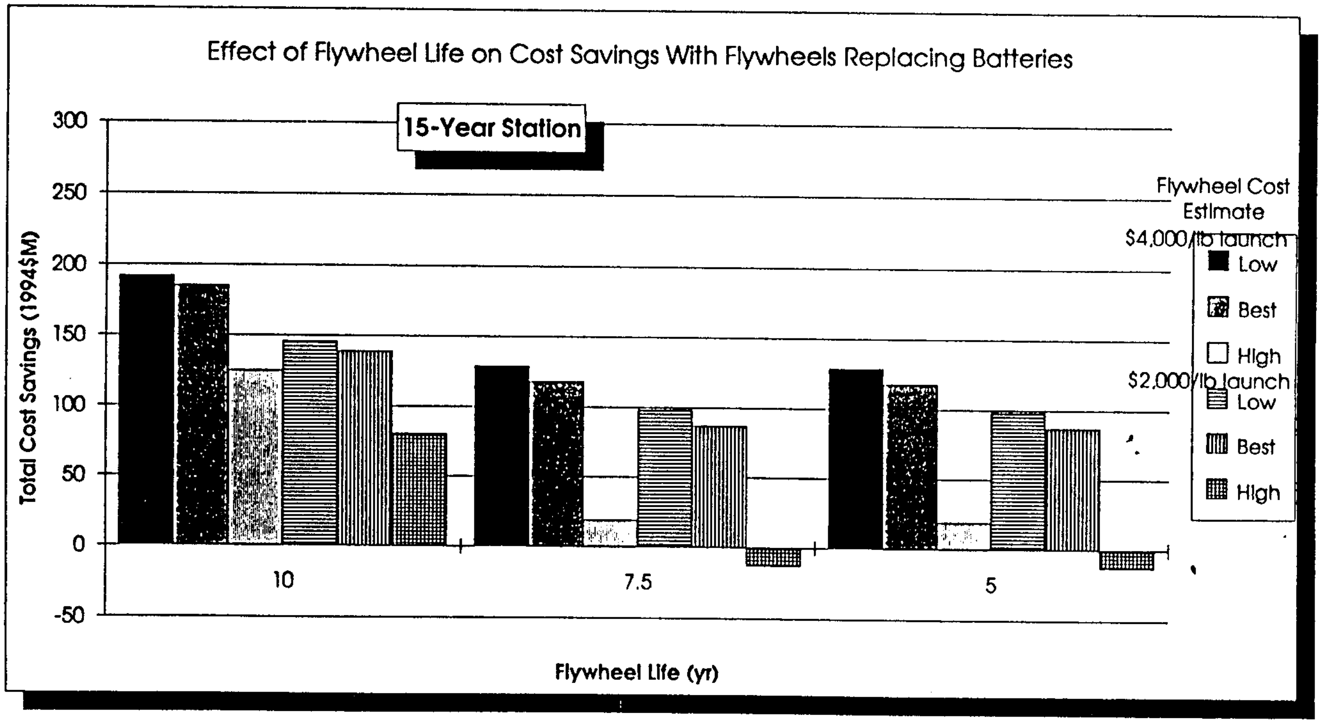


Effect of Station Life on Cost Savings With Flywheels Replacing Batteries

SSFW3C5B.XLC 6/27/94 2:48 PM



SSFW3C4B.XLC 6/27/94 2:46 PM



Effect of Flywheel Life on Cost Savings With Flywheels Replacing Batteries

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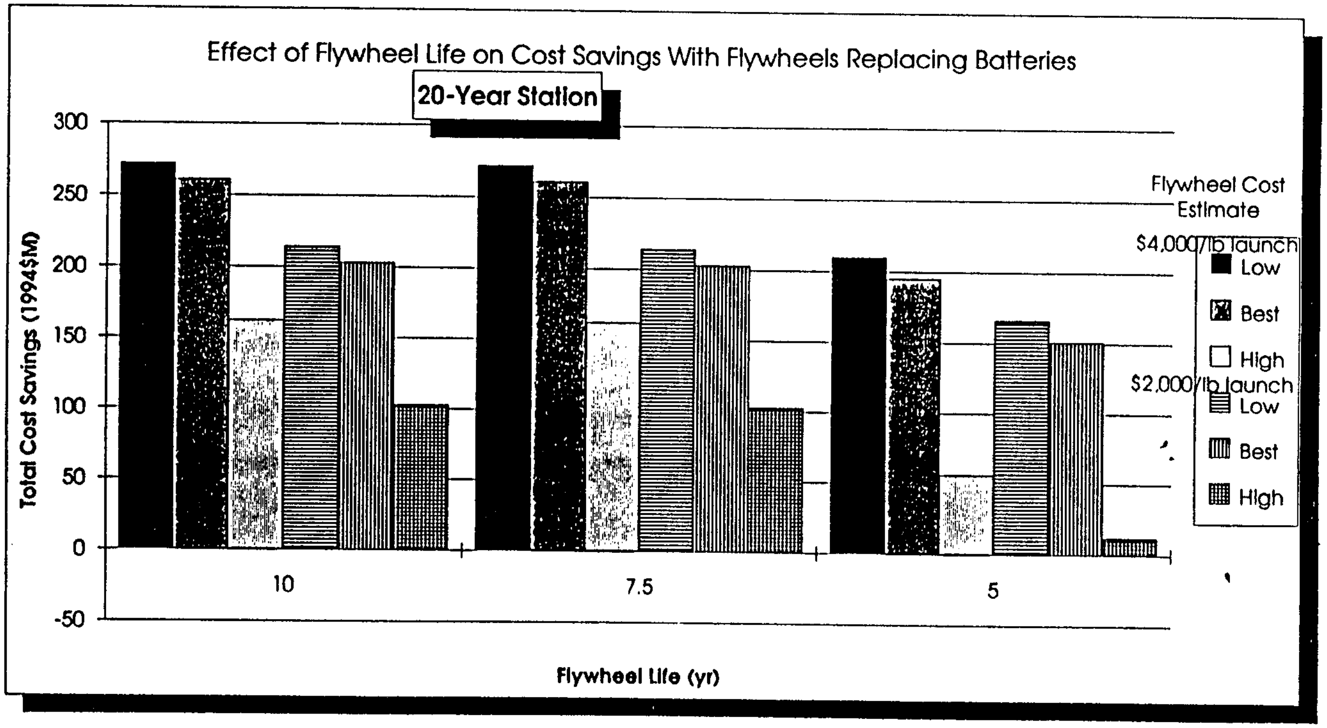

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The objective of this study was to examine the overall feasibility of deploying electromechanical flywheel systems in space used for excess energy storage. Results of previous Rocketdyne studies have shown that the flywheel concept has a number of advantages over the NiH2 battery, including higher specific energy, longer life and higher roundtrip efficiency. Based on this prior work, this current study was broken into four subtasks.The first subtask investigated the feasibility of replacing the NiH2 battery orbital replacement unit (ORU) on the international space station (ISSA) with a flywheel ORU. In addition, a conceptual design of a generic flywheel demonstrator experiment implemented on the ISSA was completed. An assessment of the life cycle cost benefits of replacing the station battery enegy storage ORUs with flywheel ORUs was performed. A fourth task generated a top-level development plan for critical flywheel technologies, the flywheel demonstrator experiment and its evolution into the production unit flywheel replacement ORU.

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