N87-11075

ENERGY STORAGE SYSTEMS COMPARISON FOR THE SPACE STATION

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INTRODUCTION

The Space Station represents one of the largest space power system applications under serious consideration at this time. Definition and Preliminary Design studies under Phase B of the Space Station Program are in process at most NASA centers and a large group of contractors. In the Work Package 4 Power System studies, NASA Lewis Research Center with contractor teams led by Rocketdyne (with major team members Ford Aerospace, Harris, Garrett, and Sundstrand) and TRW (with General Dynamics and General Electric) is defining the Power System. This effort has progressed through conceptual design of various options, and elimination of some options to a final selection process which is now beginning.

This paper provides an overview of the requirements, options, selection criteria and other considerations, and current status with regard to the energy storage subsystem (ESS) for the photovoltaic power system alternative for the Space Station, presented from the perspective of Ford Aerospace as a member of the Rocketdyne team.

ENERGY STORAGE SYSTEM REQUIREMENTS

Technical Performance Requirements

The current requirements to which the power system is being designed are summarized in Table 1. Significant for the ESS is, beside the 75 kW base load, the contingency requirement which demands the ability to support half the station load for a full orbit after eclipse completion. This limits depth of discharge (DOD) to about 38-40 % for nominal eclipse operation. Peaking support is not very severe in a relative sense, but needs to be factored into DOD and contingency capability for ESS sizing purposes. A design life of five years has been used as a goal. Physical constraints for the ESS derive from the 9 x 9 x 9 foot envelope of the "utility centers" located just outboard of the transverse boom alpha joints, see Figure 1.

Technology Readiness Requirements

Table 2 summarizes the technology readiness and risk implications of the Space Station schedule, which has a goal of a 1992 Initial Operating Capability (IOC) with growth beginning a few years later.

For IOC the desired technology should be scalable to Space Station proportions at low risk, while the growth Station permits more advanced technologies for which both risk and payoff are higher.

IOC Cost Requirements

The cost of the IOC configuration of the Space Station is limited to $ 8B. This must be accommodated by cost-effective design of each subsystem, but in particular by ensuring that the overall system cost is minimized, even if this means choosing a more costly option for a given subsystem. As suggested in Table 3, cost of the ESS should not be minimized in itself, but must be combined with cost impacts on solar arrays, thermal control hardware, power management and distribution (PMAD) equipment, and others as a basis for overall system cost optimization. These cost impacts result from ESS roundtrip efficiency, heat dissipation, and electrical control requirements. Commonality with other subsystems, platforms and free-flyers to save development costs, and modularity and simplicity to save production costs, are desirable to minimize IOC expenses.

Launch and Operations Cost Requirements

Launch cost is a key element of overall cost, and here mass impacts must be accounted for that are caused by ESS selection and design in other subsystems. Volume may in some cases be a stronger launch cost driver than mass, and must be accounted for similarly. As summarized in Table 4, other elements of life cycle cost include operational and maintenance expenses. For the Space Station, operations costs are affected strongly by the need to supply fuel to maintain orbit altitude; this drives the ESS to high efficiency to minimize solar array and radiator size. Replacement costs include considerations of high reliability and wear-out life, and minimal cost of replacement.

SPACE STATION ESS OPTIONS

ESS Options Considered

Within the above framework of requirements, and as quantitatively as possible, a range of ESS options has been evaluated. Table 5 shows the major options considered. The first elimination round involved a global judgement of readiness of each technology and its ability to meet the IOC date. This led to elimination of energy wheels, sodium-sulfur batteries and hydrogen-halogen fuel cells. Bipolar Ni-H_2 batteries were borderline in readiness potential.

For some of the eliminated options an estimate of performance was nevertheless done to estimate the potential for growth. Table 6, discussed in more detail later, gives a comparison of some major representatives of each ESS class. Designs are summarized below.

Overview of ESS Designs

Regenerative Fuel Cell. The alkaline regenerative fuel cell system (RFCS) consists of four identical assemblies. Each includes a fuel cell module (FCM), a water electrolysis module (WEM), a FCM accessory section, and a WEM accessory section. The accessory sections contain the valves, pumps, regulators, heat exchangers, etcetera, required for RFCS operation. A set of hydrogen and oxygen tanks serves two of the assemblies. The electrode areas of the FCM and WEM are sized to provide a relatively high efficiency of 62%, which includes losses associated with accessory section operation. Typical operating voltages of the FCM and WEM stacks are 155 V.

IPV Ni-H_2 Battery. The individual pressure vessel (IPV) Ni-H_2 battery option consists of four batteries of 275 Ah capacity. Each battery has 105 cells of 275 Ah capacity in series, distributed over five identical assemblies. These assemblies hold their 21 cells supported on structural beams that carry heat pipes for efficient heat removal. Twenty assemblies are held in two "oven-rack" type arrangements, one per utility center. Typical discharge voltage is 133 V averaged over the 35-minute, 40% DOD discharge.

Bipolar Ni-H_2 Battery. The bipolar Ni-H_2 battery uses the design concept developed by Ford Aerospace and Yardney under NASA-LeRC sponsorship. It consists of four batteries, each with three assemblies in parallel. The assemblies each consist of a pressure vessel containing two cell stacks of 52 cells in series, with a capacity of 90 Ah. The cells have the long, rectangular configuration: about 12 cm wide by 160 cm long. Each assembly also contains redundant coolant pumps and a heat exchanger interface.

Ni-Cd Battery. The Ni-Cd system consists of 16 batteries of 125 Ah capacity and with 104 series cells. Each battery is divided into four 26-cell battery packs, mounted on a honeycomb panel with embedded heat pipes. The 16 panels are mounted in "oven-rack" type arrangements in the Station utility centers.

Na-S Battery. The sodium-sulfur (Na-S) battery, operating at 300 to 400°C, uses cell sizes close to those being produced currently. The 75-kW system would consist of four batteries each with four 87-kg modules of 70 cells of 65 Ah capacity, delivering about 126 V on discharge. Each module has a variable conductance radiator system on its external surface. The modules are placed on the outside of the utility module.

Energy Wheels. The energy wheel data shown represents a blend of various approaches. This was necessary because of the extremely wide range of characteristics reported for point designs for Space Station flywheels.

ESS OPTIONS COMPARISON

Performance

Table 6 provides a comparison of ESS alternatives described above. The alkaline H_2-O_2 RFCS is used as the baseline in this comparison.

The RFCS has a much lower mass than the other feasible systems, the Ni-Cd, IPV Ni-H_2, and bipolar Ni-H_2 batteries. However, its thermal control equipment is considerably heavier than that of the others, because of the RFCS's relatively low roundtrip efficiency and its resulting high heat rejection rate, albeit at a higher temperature. In the case of the room-temperature systems it is also feasible to use a common thermal control loop for the ESS and PMAD, which is difficult to do with the RFCS. The roundtrip efficiency difference also results in a solar array mass "credit" for the non-RFCS systems. When all the impacts have been included, the RFCS has still the lowest mass, but the other systems become more competitive.

By far the most attractive is the Na-S battery system; however, this technology has not reached the maturity required for serious consideration for the IOC Space Station. It provides low mass, high efficiency, and minimal thermal support requirements due to the high rejection temperature. With sufficient development its benefits may be applicable to the growth station.

Maturity

Table 7 summarizes for the options with initial readiness potential the estimated maturity level using the NASA 1 to 8 rating scale. The levels shown here represent (abbreviated definitions):

- 4 - Critical function breadboard demonstration
- 5 - Component or brassboard model tested in relevant environment
- 6 - Prototype or engineering model tested in relevant environment
- 7 - Engineering model tested in space
- 8 - Baselined into production design

The rating for the alkaline/alkaline RFCS is dual: while the fuel cell part has been demonstrated on the STS Orbiters with success, and can be considered a prototype for the Space Station version, the electrolyzer has so far been demonstrated only as a breadboard in the laboratory and rates a 4. The IPV Ni-H_2 battery has a dual rating of 6 for the qualification of smaller LEO cells, and 5 for the slightly lower maturity of the 275-Ah cells. A 220-Ah cell is being demonstrated in December 1985 by Ford Aerospace and Yardney.

In addition to the maturity level, the degree of current development activity, interest, and funding is an important factor in the assessment of potential technology readiness. Qualitative estimates are shown in Table 7.

Combination of the maturity and activity estimates leads to the judgement that only the alkline/alkaline RFCS, the Ni-Cd battery and the IPV $Ni-H_2$ battery are viable options for Space Station energy storage.

Cost

Costs for the three surviving options are undergoing extensive refinement and therefore quantitative values would be very preliminary. However, a broad qualitative comparison can be made in the different cost categories, and is expected to remain valid. Table 8 summarizes the data. Development costs follow the maturity levels as expected. Production costs are lowest for the $Ni-H_2$ system due to low complexity, moderate modularity and replication. Ni-Cd batteries are highest because of the large quantity of cells and battery packs. The RFCS is intermediate due to greater complexity and lower modularity. Solar array costs and thermal control system costs are somewhat higher for the RFCS because of the greater heat rejection requirement. Launch costs follow the net mass figures of Table 6. Overall, the IOC costs appear lowest for $Ni-H_2$ batteries, with the RFCS not very far behind, and Ni-Cd considerably more expensive.

Operations costs for the three options compare as follows. The drag-related fuel costs will be higher for the RFCS due to the larger solar arrays. Random failure occurences will be higher for the RFCS, but the items to be replaced will be generally the accessory sections, which are small and lightweight. While the replaced mass may thus be less than for the batteries, the extravehicular activity repair events are higher in number and therefore more costly.

SUMMARY AND CONCLUSION

Evaluation of ESS options for the Space Station has led to the selection of H_2-O_2 alkaline RFCS, IPV $Ni-H_2$ batteries, and Ni-Cd batteries, as potentially able to meet requirements. Of these, the Ni-Cd batteries are too heavy and too costly to be a serious contender. $Ni-H_2$ batteries appear somewhat lower in overall IOC cost and operational costs, and are also favored slightly in non-quantitative criteria, such as maintainability, safety, etcetera. The RFCS has a mass advantage, but has an overall small disadvantage in IOC cost and development risk.

The RFCS versus IPV $Ni-H_2$ battery decision will be the subject of further sensitivity and trade studies to ascertain the potential effects of evolution of requirements. The final selection is to be made by March 1986 and will involve consideration of all Space Station system impacts.

TABLE 1. SPACE STATION POWER SYSTEM REQUIREMENTS

- IOC - NOMINAL LOAD POWER : 75 kW
  PEAKING : 100 kW FOR 15 MIN PER ORBIT
  CONTINGENCY : 37.5 kW FOR 1 FULL ORBIT (AFTER ECLIPSE)
- GROWTH - NOMINAL LOAD POWER : 300 kW
  PEAKING : 350 kW FOR 15 MIN PER ORBIT
  CONTINGENCY : 150 kW FOR 1 FULL ORBIT (AFTER ECLIPSE)
- IOC COST CONSISTENT WITH $ 8 BILLION (1987$) TOTAL STATION COST
- MINIMAL LIFE CYCLE COST

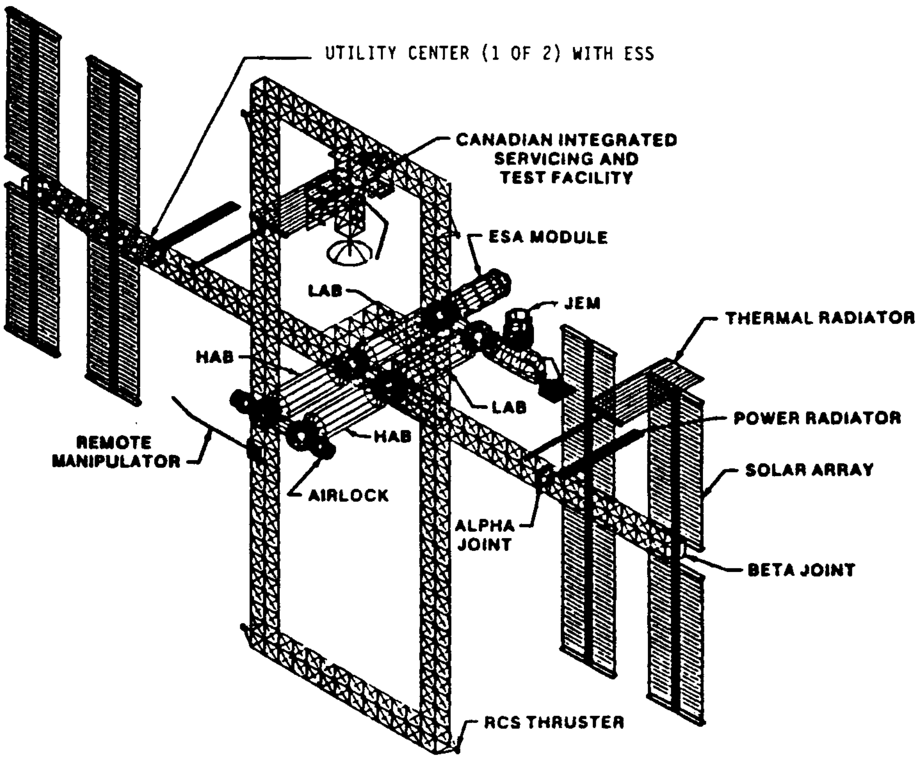

Figure 1. PHOTOVOLTAIC SPACE STATION CONFIGURATION

TABLE 2. SPACE STATION ENERGY STORAGE SUBSYSTEM PERFORMANCE REQUIREMENTS

- IOC : 75 kW + CONTINGENCY + PEAKS
  - LOW RISK SCALE-UP OF CURRENT TECHNOLOGY FEASIBLE
  - TECHNOLOGY READINESS ADEQUATE TO MEET IOC SCHEDULE
  - ABILITY TO MEET PEAK REQUIREMENTS
- GROWTH : 300 kW + CONTINGENCY + PEAKS
  - MEDIUM RISK SCALE-UP OF CURRENT TECHNOLOGY FEASIBLE
    - MORE ADVANCED TECHNOLOGY PERMITTED
  - TECHNOLOGY READINESS ADEQUATE TO MEET GROWTH SCHEDULE
  - ABILITY TO MEET PEAK REQUIREMENTS

TABLE 3. SPACE STATION ENERGY STORAGE SUBSYSTEM IOC COST REQUIREMENTS

- COST CONSISTENT WITH $ 8 BILLION IOC STATION COST

- LOW DEVELOPMENT COST
  - HIGH MATURITY LEVEL
  - HIGH MODULARITY LEVEL
  - LOW COMPLEXITY
- LOW PRODUCTION COST
  - HIGH MODULARITY LEVEL
  - LOW COMPLEXITY
- MINIMAL ADVERSE IMPACT ON OTHER SYSTEMS/SUBSYSTEMS
  - POWER GENERATION SUBSYSTEM
  - POWER MANAGEMENT AND DISTRIBUTION
  - THERMAL CONTROL SUBSYSTEM
  - - ETC -
- HIGH COMMONALITY
  - WITH OTHER SYSTEMS/SUBSYSTEMS
  - WITH PLATFORMS AND FREE-FLYERS

TABLE 4. SPACE STATION ENERGY STORAGE SUBSYSTEM LIFE CYCLE COST REQUIREMENTS

● MINIMAL LIFE CYCLE COST

● MINIMAL LAUNCH COST
- • LOW MASS
- • LOW VOLUME

● MINIMAL OPERATIONS COST
- • AUTOMATION
- • MINIMAL IMPACT ON OTHER SUBSYSTEMS
  - POWER GENERATION SUBSYSTEM DRAG
  - THERMAL CONTROL SUBSYSTEM DRAG

● MINIMAL MAINTENANCE/REPLACEMENT COST
- • HIGH RELIABILITY AND LONG WEAR-OUT LIFE
- • LOW REPLACEMENT COST
  - LOW MEAN-TIME-TO-REPAIR
  - MODULARITY
  - LOW MASS AND VOLUME (LAUNCH COST)
  - LOW PRODUCTION COST

TABLE 5. SPACE STATION ENERGY STORAGE OPTIONS

● BATTERY SYSTEMS
- • NICKEL-CADMIUM
- • NICKEL-HYDROGEN IPV
- • NICKEL-HYDROGEN CPV
- • NICKEL-HYDROGEN BIPOLAR
- o SODIUM-SULFUR

● REGENERATIVE FUEL CELL SYSTEMS
- • ALKALINE/ALKALINE HYDROGEN-OXYGEN
- • ALKALINE-FC/SPE-EM HYDROGEN-OXYGEN
- • SPE/SPE HYDROGEN-OXYGEN
- o HYDROGEN-HALOGEN

O ENERGY WHEELS (FLYWHEELS)

● • COULD BE READY FOR IOC
O o CANNOT BE READY FOR IOC

TABLE 6. SPACE STATION ENERGY STORAGE OPTIONS CHARACTERISTICS COMPARISON

CHARACTERISTIC	H_2-O_2 RFCS	Ni-H_2 IPV	Ni-H_2 BIPOLAR	Ni-Cd	Na-S	ENERGY WHEELS
ROUND-TRIP EFFICIENCY (%)	62	80	82	80	85	85
DEPTH-OF-DISCHARGE (%)	(40)	40	40	20	40	40
MASS (KG)						
ENERGY STORAGE	2300	4550	3600	9600	1400	6000
THERMAL CONTROL	2100	1100	1100	1100	100	800
SOLAR ARRAY CREDIT	-	(270)	(270)	(270)	(360)	(360)
* TOTAL *	4400	5380	4430	10430	1140	6440
VOLUME (M^3)	19	14	3	11	2	9
ECLIPSE HEAT REJECTION (KW)	55	19	18	19	18	10
TEMPERATURE (°C)	80	10	10	10	350	30

TABLE 7. SPACE STATION ENERGY STORAGE OPTIONS READINESS AND ACTIVITY ASSESSMENT

ENERGY STORAGE OPTION	MATURITY LEVEL	SPACE DEVELOPMENT ACTIVITY
* ALK/ALK REGENERATIVE FUEL CELL	4/7	HIGH
SPE/SPE REGENERATIVE FUEL CELL	5	LOW
ALK/SPE REGENERATIVE FUEL CELL	5	MED
* NICKEL-CADMIUM BATTERY	8	HIGH
* NICKEL-HYDROGEN IPV BATTERY	5/6	HIGH
NICKEL-HYDROGEN CPV BATTERY	4	LOW
NICKEL-HYDROGEN BIPOLAR BATTERY	4	MED

* = SURVIVOR

TABLE 8. SPACE STATION ENERGY STORAGE OPTIONS QUALITATIVE COST COMPARISON

COST ELEMENT	RFCS	Ni-H2	Ni-Cd
DEVELOPMENT COST	HIGHEST	MEDIUM	LOWEST
PRODUCTION COST	MEDIUM	LOWEST	HIGHEST
SOLAR ARRAY COST	HIGHER	BASIS	BASIS
THERMAL CONTROL COST	HIGHER	BASIS	BASIS
LAUNCH COST	LOWEST	MEDIUM	HIGHEST
OVERALL IOC COST	MEDIUM	LOWEST	HIGHEST