

REGENERATIVE HYDROGEN-OXYGEN FUEL CELL
- ELECTROLYZER SYSTEMS FOR ORBITAL ENERGY STORAGE

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INTRODUCTION

Fuel cells have played a major role in spacecraft power generation. The Gemini and Apollo programs used fuel cell power plants as the primary source of mission electrical power, with batteries as the backup. The current NASA use for fuel cells is in the orbiter program. Here, low temperature alkaline fuel cells provide all of the on-board power with no backup power source. Three power plants per shipset are utilized. The original fuel cell power plant configuration contained two 32-cell substacks connected in parallel. This configuration was flown on STS-1 through STS-8. Starting with STS-9, a three substack configuration (three 32-cell substacks connected in parallel) will be used to obtain longer life and better voltage performance.

Fuel cells will continue to have a major role in space power generation and storage. With the addition of an electrolysis capability, the regenerative fuel cell system is expected to provide multikilowatt-hour energy storage capability for large orbiting spacecraft which are dependent upon photovoltaic solar arrays for primary power. These future space applications will require one to two orders of magnitude greater power (up to 250 kW) than has been needed up to now. These applications include unmanned platforms in low-earth orbit (LEO) and geosynchronous orbit (GEO), and a permanently manned space operations center in LEO. All of NASA's capabilities have complimentary military interest for surveillance, command, and weapons applications in space.

The main thrust of the OAST fuel cell technology program in NASA since 1979 has been focused on LEO energy storage applications. The effort is a combined program conducted by Johnson Space Center (JSC) and Lewis Research Center (LeRC). The goal is to demonstrate functional feasibility of regenerative fuel cell (RFC) systems, both acidic and alkaline, in breadboard test article configurations by 1984. At that time, an engineering model will be built for a technology readiness demonstration by early 1987. The engineering model system will be supported by long term endurance testing of multiple cell stacks of full size hardware tested toward a goal of 40,000 hours.

Although the overall efficiency (50-60 percent) of the integrated hydrogen-oxygen fuel cell-electrolyzer system is not as high as the nickel-cadmium and nickel-hydrogen battery systems, point design comparisons of the RFC with these battery systems yield results which, from a total system standpoint, show the RFC to have the best effective energy density, minimum weight, and the greatest projected life before subsystem replacement over a 10-year period. In addition, the RFC is the only near-term energy conversion/storage system that offers the potential advantages of full integration with life support, space manufacturing, and station-keeping propulsion systems.

RECENT STUDIES

Previous design studies (1, 2, 3) on orbital energy storage systems for LEO have evaluated weight optimized 100 kW systems based on launch weight and weight to orbit over a 5 to 10 year period. The weights included fuel cell and electrolyzer components, reactant gases and tanks, radiators, and solar array. Electrical efficiency ranged from 36 to 50 percent. The recent Boeing

study (4) compares the RFC energy storage system with other energy storage systems optimized for efficiency. This optimization is achieved by reducing current density, thereby improving electrical efficiency to approximately 60 percent for the RFC systems. The optimization increases the weight of fuel cell and electrolyzer components, but greatly reduces the weight and area of the solar array, which on weight optimized systems accounted for approximately 70 percent of the total system weight. Reduction of solar array reduces orbital drag which reduces the fuel requirement for altitude maintenance of the spacecraft. Thus, it becomes obvious that all impacted areas of the vehicle must be properly treated in comparison studies to identify the genuinely optimized concept.

COMPONENT TECHNOLOGY DEVELOPMENT

There are four technology requirements common to energy storage systems for LEO:

1. increased life; 40,000 hours (5 years) has been established as a goal,
2. increased reliability; a minimum 2-year life on components,
3. increased efficiency; greater than 50 percent overall electrical efficiency,
4. higher voltage; an apparent optimum voltage range exists between 100V to 240V.

The combined JSC-LeRC program has focused upon improving fuel cell-electrolyzer component life, and electrical efficiency. The requirements of increased reliability, and higher voltage will be formally addressed as part of the engineering model development effort.

Regenerative Fuel Cell Feasibility Demonstrations

The feasibility demonstration of regenerative fuel cells has focused upon improving fuel cell-electrolyzer component life and electrical efficiency. A 5-year (40,000 hour) life has been established as a goal with an overall electrical efficiency goal for the storage subsystem of 60 percent in a voltage range of 100 to 200 volts. Both the acid (SPE) and alkaline RFC systems are to be evaluated at JSC using breadboard test articles with periodic up-grading of component and system technology.

Acid (SPE) Breadboard System

The acid breadboard was delivered to the Johnson Space Center on February 1, 1983. The breadboard consists of a fuel cell subsystem for power generation, an electrolysis subsystem for H₂-O₂ generation, a reactant storage subsystem, and a remote control console. The remote control console allows for individual operation of the fuel cell and electrolysis subsystems, operation of both subsystems simultaneously, and for the operation of the two subsystems in a cyclic mode. The remote control console also automatically monitors the subsystems and will shut down the breadboard safely if any parameters go out of limits. A sketch of the acid regenerative fuel cell breadboard system is shown in Figure 1. The system is located in the Thermal Test Area (TTA) at JSC.

The initial objective of demonstrating the feasibility of using a RFC as an energy storage subsystem for a LEO energy storage system has been accomplished with the breadboard having accumulated 1025 LEO cycles as of September 20, 1983. Several of these cycles have been acquired with the solar power station

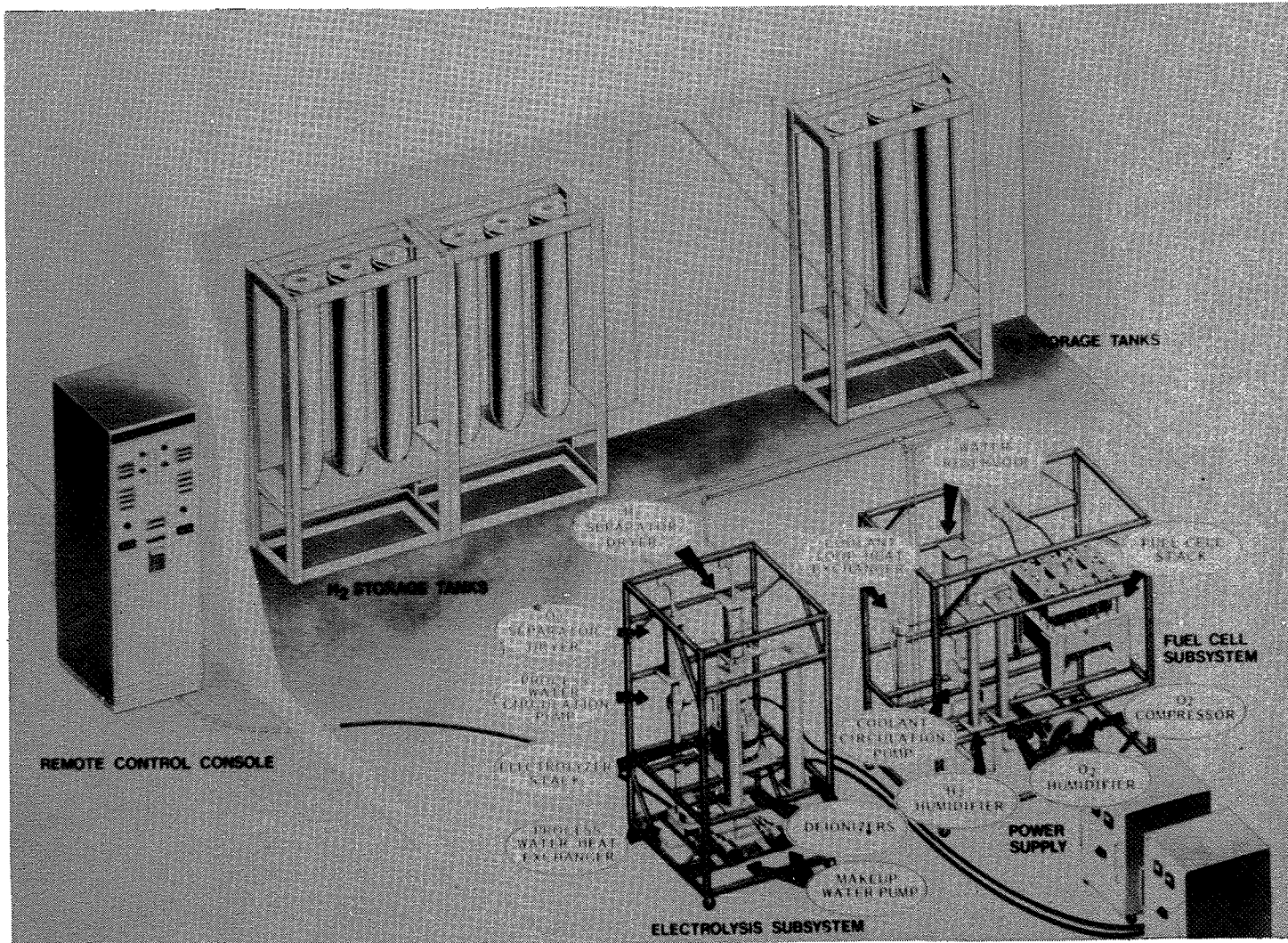


Figure 1. Breadboard regenerative fuel cell energy storage system.

connected directly (no power conditioning equipment used) to the electrolysis subsystem. The LEO cycle consists of running the electrolysis subsystem for 54 minutes, and the fuel cell subsystem for 36 minutes. The electrolysis unit consists of 22 cells (0.23 ft²) and operates at the following parameters; 24 amps, 36 volts, and 73° F. The gas is stored at 130 psia for the H₂ and 115 for the O₂. The fuel cell consists of eight cells (1.1 ft²) operating at 112 amps, 6.5 volts, 160° F. The LEO cyclic mode is a closed loop operation.

The following findings have been observed about the acid system. No measurable water loss has been found, however, apparently four percent more gas is produced than is consumed. This is mostly due to the diffusion of the gases across the SPE membrane. There has been no permanent cell performance degradation detected in either the fuel cells or electrolysis cells. Also, the remote control console is working very well and is shutting the system down whenever tolerance limits are reached.

A synopsis of endurance test data base supporting the acid RFC is shown in Figure 2, along with the projected efficiency of the total storage system and the major technology problems associated with the system.

Future plans for the acid RFC breadboard include continued operation in the LEO cyclic mode, operation for 30 days of a scaled-down version of a Space Station power profile, and open-ended testing of both the fuel cell and electrolysis subsystems to establish a better endurance data base. The breadboard will also be utilized as a test bed for advanced cell and component development verification.

Alkaline Breadboard System

The alkaline RFC breadboard is scheduled for delivery at JSC in early January 1984. It will integrate a 30-cell alkaline electrolysis unit (0.1 ft^2) with an Orbiter fuel cell power plant (#708). The 30-cell electrolyzer unit (1.5 kW nominal) will be replaced in April 1984 with a 6-cell 1 ft^2 electrolyzer unit (3 kW nominal) which is considered full size hardware for the space station mission. It also provides a better power match with the 4.5 kW Orbiter power plant.

The alkaline RFC is supported by endurance testing of the electrolyzer and fuel cell components. Electrolysis endurance testing has surpassed 23,000 hours (September 20, 1983) in the LEO regime with 0.1 ft^2 single cells at 180° F , 150 ASF, at ambient pressure with no voltage degradation. Figure 3 shows cell voltage vs. time for a cell containing a "SUPER" anode catalyst.

A complete electrolysis subsystem containing a 6-cell stack of 1 ft^2 cells, and the controller is scheduled to begin a 20,000 hour endurance test in April 1984.

A fuel cell stack of 6 cells (Orbiter-size hardware) has accumulated 8600 hours of LEO cycle endurance testing with a voltage degradation rate of less than 1 microvolt/hour. A plot of average cell voltage vs. time is shown in Figure 4. A minimum endurance test goal of 20,000 hours is anticipated. The 6-cell stack is operating at 200 ASF, 60 psia, and 140° F .

ENDURANCE TESTING (LIFE)

FUEL CELL: >40000 hr IN SUBSCALE CELLS
2000 hr CONTINUOUS TEST AT 180⁰ F, 60 psia IN
1.1 ft² CELLS

ELECTROLYZER: 45000 hr IN 0.23 ft² CELLS (NAVY OXYGEN GEN-
ERATION PROGRAM) CONTINUOUS TESTING AT
1000 ASF, 120⁰ F

INTEGRATED SYSTEM: DELIVERED TO JSC FEB. 1983. SIMULATED ORBITAL
TESTING STARTED IN APRIL, 1983. - 1540 hr, 1025
CYCLES (SEPT. 20, 1983)

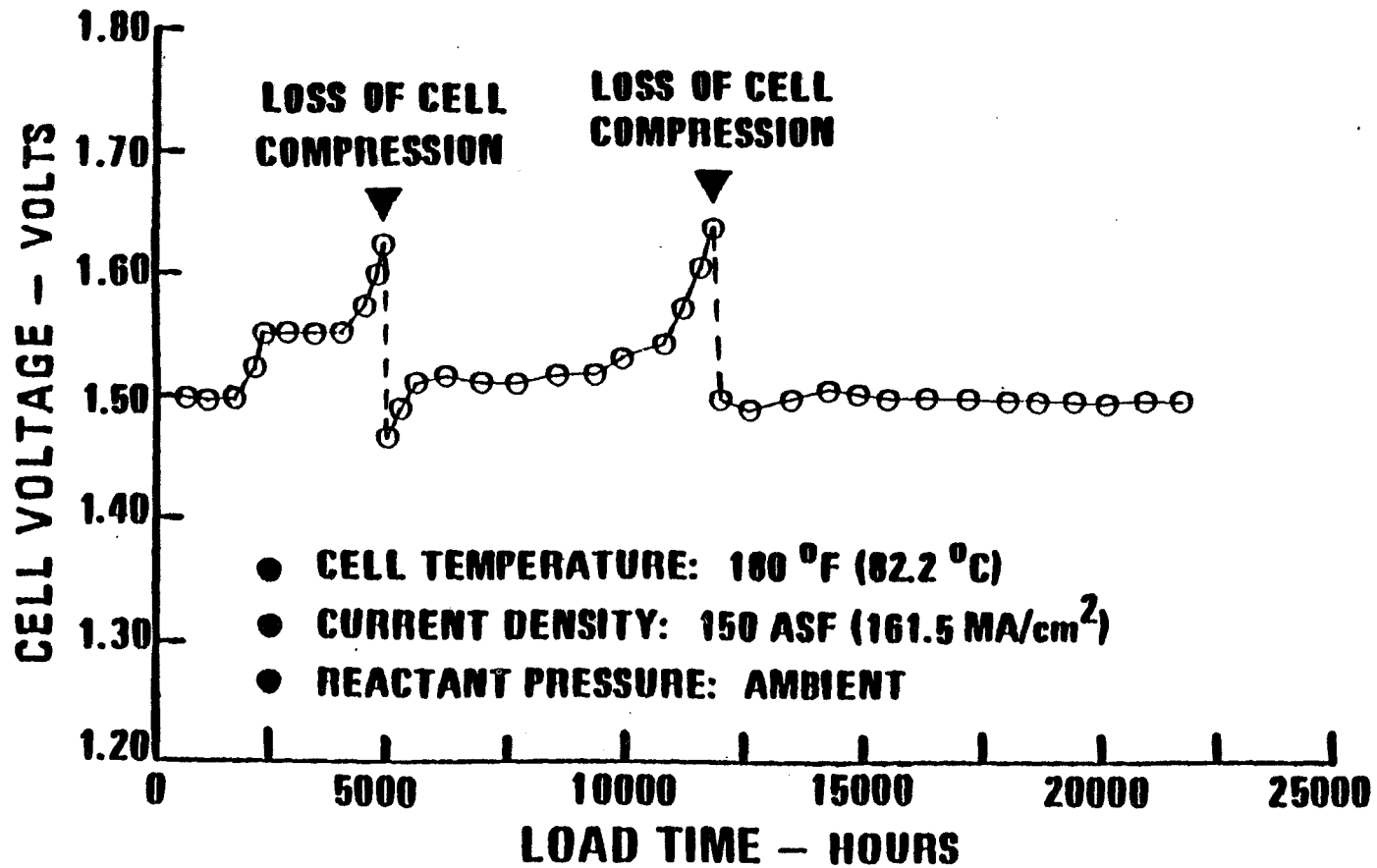
PROJECTED EFFICIENCY (TOTAL STORAGE SYSTEM)

WEIGHT OPTIMIZED 100 KW SYSTEM 48%
OPTIMIZED FOR EFFICIENCY (LOW CURRENT DENSITY) 64%

TECHNOLOGY PROBLEMS

HYDROGEN DIFFUSION THROUGH MEMBRANE (INHERENT PROBLEM)
**HYDROGEN EMBRITTELEMENT OF NIOBIUM COLLECTOR DURING LONG TERM
USE**

Figure 2. Acidic (SPE) fuel cell - electrolyzer system
for orbital energy storage.



- Successfully completed 21600 hours of testing
- Performance remains stable

Figure 3. Super anode cell endurance.

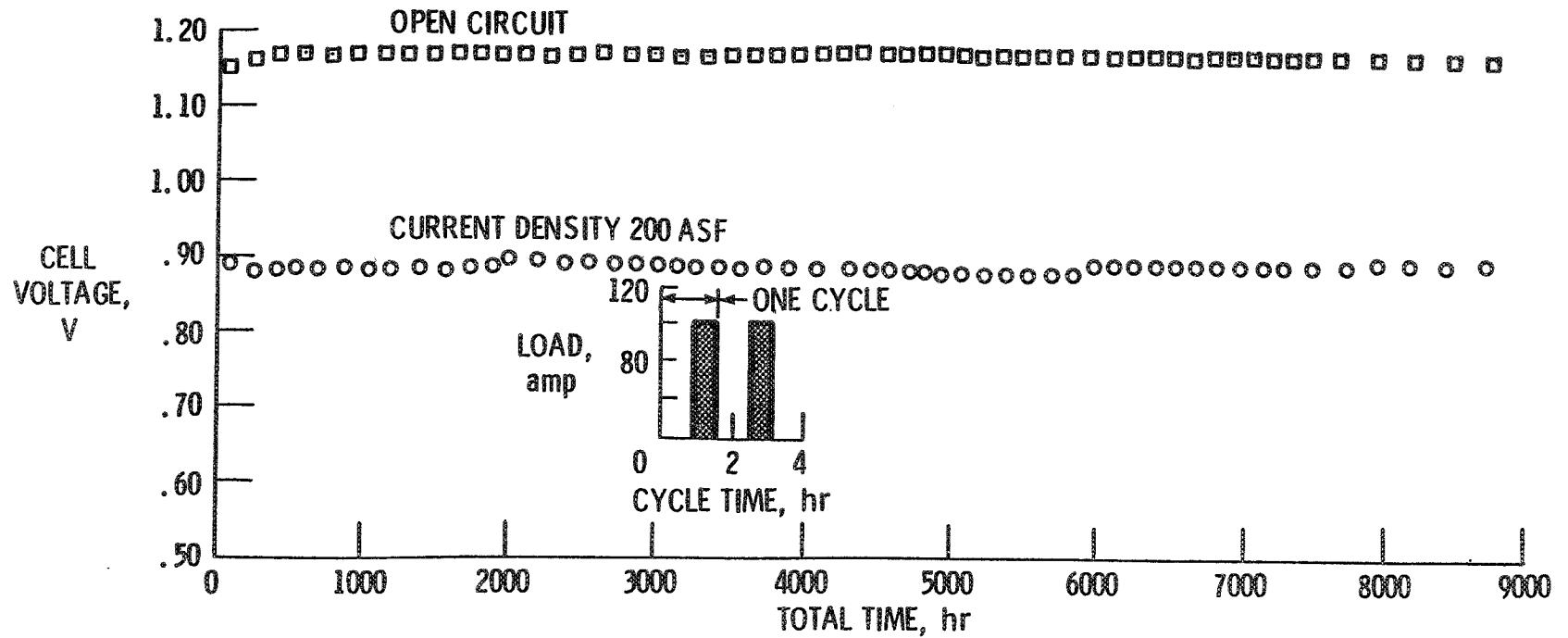


Figure 4. NASA Lewis six-cell stack long term endurance test - successfully completed 8600 hr (5733 cycles) of cyclical operation, performance remains stable, less than 1.0 microvolts per hr voltage reduction.

- **ENDURANCE TESTING**

- FUEL CELL:** - TWO 10000 hr CONTINUOUS TESTS AT 100 ASF IN ORBITER SIZE STACKS DURING DEVELOPMENT PROGRAM FOR SHUTTLE

- 1390 hr AT 200 ASF LEO CYCLIC REGIME TESTING CONFIRMED OPERATION IN CYCLIC MODE

- 6 CELL STACK (ORBITER SIZE COMPONENTS) STARTED ON LEO CYCLIC ENDURANCE TEST IN SEPT. 1982; 8250 hr (5167 SIMULATED ORBITAL CYCLES) AS OF SEPT. 20, 1983; GOAL 20 000 hr BY MARCH, 1985; 200 ASF, 140⁰ F, 60 psia

- ELECTROLYZER:** - 23000 hr ACCUMULATED (SEPT. 20, 1983) IN LEO CYCLIC MODE AT 150 ASF, 180⁰ F, AMBIENT PRESSURE IN 0.1 in² CELLS; VOLTAGE STABLE NEAR INITIAL VOLTAGE

- SCALE UP TO 1in² UNDERWAY; ENDURANCE TESTING TO START MARCH, 1984

- **PROJECTED EFFICIENCY (TOTAL STORAGE SYSTEM)**

- WEIGHT OPTIMIZED 100 KW SYSTEM: 50%

- OPTIMIZED FOR EFFICIENCY: 66%

- **TECHNOLOGY PROBLEMS**

- VOLTAGE DEGRADATION DUE TO CARBONATE (FROM ELECTRODE FRAME MATERIALS)

- ASBESTOS MATRIX INSTABILITY ABOVE 220⁰ F

Figure 5. Alkaline fuel cell - electrolyzer system for orbital energy storage.

A synopsis of the endurance test data base for the alkaline RFC is shown in Figure 5, along with projected system electrical efficiency and the major technology problems currently being work on in the technology program.

POINT DESIGN COMPARISON

A 60 kW point design comparison was made for an energy storage system for a manned space station in low earth orbit. The design compared two battery systems, Ni/Cd and bipolar Ni/N₂, and the H₂-O₂ RFC system. A list of design requirements are shown in Figure 6. A significant factor in the design was the redundancy requirement imposed on the system, which resulted in two storage modules on each of three main power buses. The configuration also required the system to provide full power with two modules failed. This requirement increases the depth of discharge on the batteries, while increasing the current density of the fuel cell and electrolyzer. The results of the design are given in Figure 7. The RFC has the highest effective energy density, and the lowest weight. Based on current life projections, the Ni/Cd battery system would require replacement in 5 to 6 years, the bipolar Ni/H₂ battery system in 3 to 4 years, and the RFC system in 7 to 8 years. The Ni/Cd life projection was based upon 16 percent DOD for six battery modules (increasing to 25 percent DOD for four modules) and an operating temperature of 10° C. The bipolar nicke hydrogen life was estimated based upon 50 percent DOD for six battery modules (75 percent DOD for four modules) and an operating temperature of 30° C. The RFC estimate of 7 to 8 years was based upon the estimated voltage degradation rate of the fuel cells derived from the carbonate conversion time dependent model from the Orbiter qualifcation programs. The

DESIGN REQUIREMENTS

POWER: **AVERAGE - 60 KW**
 PEAK - TBD
 EMERGENCY - SEPARATE SYSTEM.

CONFIGURATION:

- 6, 10-KW MODULES
- 2 MODULES ON EACH OF 3 BUSES
- 4 MODULES, ABLE TO CARRY FULL POWER (15 KW/MODULE)

VOLTAGE: **120V**

ORBIT: **NOMINAL - 270 N.M.**
 RANGE - 200-300 N.M.

TIME: **CHARGE - 58.8 MIN.**
 DISCHARGE - 35.7 MIN.

LIFE: **10 YEARS**

Figure 6. 60-KW point design comparison of nickel-cadmium, bi-polar nickel-hydrogen and regenerative fuel cell energy storage subsystems.

DESIGN RESULTS

<u>CHARACTERISTIC</u>	<u>Ni/Cd</u>	<u>B. P. Ni/H₂</u>	<u>RFC</u>
EFFECTIVE ENERGY DENSITY	3.3 wh/kg	14.9 wh/kg	17.8 wh/kg
ROUND TRIP ELECTRICAL EFFICIENCY (END OF LIFE)	70%	70%	56%
TOTAL STORAGE SUBSYSTEM WEIGHT	11 050 kg	2408 kg	2023 kg
TOTAL STORAGE SUBSYSTEM VOLUME	120 ft ³	115 ft ³	203 ft ³
REQUIRED STORAGE SUBSYSTEM REPLACEMENTS FOR 10-YEAR LIFE	1	2	1
HEAT REJECTION: REQUIREMENT (MAXIMUM) TEMPERATURE	27 kW 10 ⁰ C	30 kW 30 ⁰ C	38 kW 60 ⁰ C
NUMBER OF CONTROLLABLE UNITS	4320	6	F.C. 6 E. 6

Figure 7. 60-KW point design comparison of nickel-cadmium, bipolar nickel-hydrogen and regenerative fuel cell energy storage subsystems.

RFC parameters selected were 140° F operating temperature, a full cell current density of 135 ASF, and an electrolyzer current density of 150 ASF.

From the standpoint of overall system autonomous control, the number of controllable units greatly favor the RFC and bipolar Ni/H₂ battery storage systems. The level of autonomous control is greatly simplified in controlling 6 to 12 subsystems as compared to 4320 individual 50 ampere/hour Ni/Cd cells.

Concluding Remarks

Fuel cells have found application in space since Gemini. Over the years technology advances have been factored into the mainstream hardware programs. Performance levels and service lives have been gradually improving. More recently, the storage application for fuel cell-electrolyzer combinations has been receiving considerable emphasis. The regenerative system application described here is part of a NASA Fuel Cell Program which has been developed to advance the fuel cell and electrolyzer technology required to satisfy the identified power generation and energy storage need of the Agency for space transportation and orbital applications to the year 2000.

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4. "Analysis of Regenerative Fuel Cells", Contract NAS 9-16151, Report D180-27160-1, Boeing Aerospace Co., August 1982.

Q. McDermott, Martin Marietta: On the Shuttle and on the Gemini you showed 2 and 3 fuel cells. Is that a redundancy system we're looking at there?

A. Gonzalez, NASA/Lewis Research Center: For the Shuttle? Yes.

Q. McDermott, Martin Marietta: I noticed first it was 2, then it went to 3. Is that because of increased load requirements or is it that they have gone from having 2 redundant fuel cells.

A. Gonzalez, NASA/Lewis Research Center: They've gone up for redundancy.

COMMENT

Gross, Boeing: I'd like to make a couple of comments on things that came out of our looking at this regenerative fuel cell system. There are two very interesting attributes of regenerative fuel cell systems. One is that, though I noticed in this study that you showed - you had a separate emergency power system, but, as it turns out, the regenerative fuel cell system has a very excellent capability to provide emergency power because you already have the fuel cells you already have all the hardware. All you need to do to provide emergency power is to increase the size of the hydrogen and oxygen tanks and the gasses, and this can come fairly inexpensively, and for manned space applications you can easily convince yourself that you ought to have a very large emergency power capability. The second point is that when you design the regenerative fuel cell system for high energy efficiency and for long life, you operate at relatively low current densities. Now, this allows a fair number of failures before you run into any trouble. You can merely increase the current density on the non-failed units when this happens and it can operate and tolerate a fairly large number of failures very successfully.

COMMENT

Gonzalez, NASA/Lewis Research Center: You're right. With the emergency system which was not included in this study, this requirement came from the space station office and they still haven't determined what peak emergency requirements will be. That's why they were not included. But it could be included in a fuel cell system without really increasing the weight of the system or the volume of the system too much.

Q. Orin, Ford: For the design that you're showing for the fuel cell system, you're showing that the efficiency is about 56% and there is an added heat rejection requirement. How much mass is associated with those two factors?

- A. Gonzalez, NASA/Lewis Research Center: With the heat rejection requirement? I really cannot tell you.
- Q. Van Ommering, Ford: How about the efficiency reduction compared to nickel cadmium and nickel hydrogen.
- A. Gonzalez, NASA/Lewis Research Center: No. This is the power system only. When you go to the total energy storage system then the efficiency will play a role in it because it will affect the size of the power array system and the fuel consumption for keeping it in orbit. But this is only the energy storage system and it doesn't include any other subsystem with it. These numbers will have to be included into further studies which include the total power system instead of the energy storage system which is what this includes in it. So that's why it doesn't reflect it.
- Q. Roth, NASA HQ: With regard to the technical problems that you mentioned before going through the membrane and so on - just how significant are these problems and what does it really take to resolve them so that this becomes a truly useable system?
- A. Gonzalez, NASA/Lewis Research Center: It is a useable system. The SB system has gas diffusion through the membrane. This decreases the overall efficiency of the system. But, if you operate it at a low pressure like this system has been operated - up to 120 PSI then you won't really suffer any great penalty in the overall efficiency and you can still achieve your 60% efficiency of the total energy storage system. For the alkaline subsystem, the carbonation problem is with the frame materials and these are trying to be replaced. The matrix instability is already being taken care of. The asbestos is being replaced with PKT separator.
- Q. Rodriguez, GSFC: Could you comment on the voltage regulation of the regenerative fuel cell perhaps in the percentage of the charge and discharge?
- A. Gonzalez, NASA/Lewis Research Center: I don't understand the question.
- Q. Rodriguez, GSFC: Well, does the fuel cell voltage vary as it's being charged or discharged?
- A. Gonzalez, NASA/Lewis Research Center: No.
- Q. Rodriguez, GSFC: It does not vary at all?
- A. Gonzalez, NASA/Lewis Research Center: No. It varies with life. That's the voltage variance that you would see, less than one microvolt per hour, but not during the cycle.

- A. Rodriguez, GSFC: Thank you.
- Q. Yen, JPL: You mentioned about you have this hydrogen embarkment of a nyobium phylactis. How serious is this problem and do you have any idea what is the chemical nature of this problem?
- A. Gonzalez, NASA/Lewis Research Center: The seriousness of the problem, I already mentioned that, over the 40,000 hours, it didn't show up but it is known that it will happen with time. I cannot really tell you what the chemical mechanism for it is.
- A. Yen, JPL: I see.
- A. Gonzalez, NASA/Lewis Research Center: I can give you the contacts to find it out.
- A. Yen, JPL: Alright, thank you.

COMMENT

Ford, GSFC: Just to make a couple of comments. When you're talking about advanced energy storage systems, in looking at the next ten years, one of the things that's going to become very important is not just the life but the life cycle cost. And I think just to make the point that as you think of these systems you have to look at that. If you talk about life cycle cost, you talk about the initial investment plus the cost to replace it and that replacement cost is a function of the ultimate life and one of the things that I think we've got to face is that the present systems that we've been using in the past, while they perform quite nicely for most of the applications, do not seem consistent with the long life that we are being asked to look into for the future systems. This is one of the things that prompted us to start looking elsewhere - the flywheel. Other cost factors that came out of these - and these studies are very difficult as Sid can vouch for as other people have tried to undertake these things, it's very difficult to get your arms around all these parameters and compare apples and apples. In most cases we find out the technologist in a given field advocates his technology and out of lack of total knowledge of the other areas tends to sell short the other technologies - not intentionally but just the fact that in some cases the information is not available. I think it behooves us though, to realize that we've got to look at the system aspect. We're no longer just talking about component technology as with the flywheel. The flywheel will get across at least every major subsystem. The solar array will be impacted by the round-trip efficiency, provided we use solar arrays for power generation. So a 10% loss in round trip efficiency will have significant impact on the size of the array. The size of the

Ford, GSFC (Con't): array affects the amount of fuel it takes to keep it in-orbit because of drag. What we're really saying is that we're going to have to become more system oriented rather than component technologist, which we still have to be. We're going to have to start considering the system related problem. And that's really how the future is going to be met would it be an electrolysis fuel cell, flywheel, batteries or something out there we haven't even talked about yet. So I challenge you to put on your hats and start thinking system - related problems as well as component related problems. And with that, unless there are any comments or further comments we will close this session. Are there any other comments? Would anybody like to make any additional statements at this time?