ELECTROCHEMICAL ORBITAL ENERGY STORAGE (ECOES) TECHNOLOGY PROGRAM

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Since the earliest days of manned space flight utilizing fuel cell power systems, the potential for increased mission duration, which may be made possible by recycling reactants, has been a strong attraction to advanced mission planners and technologists. Studies have been conducted since the mid-60's geared toward assessing this potential in light of the missions in vogue at the time. This concept is generally referred to as a Regenerative Fuel Cell System. The concept will now be reviewed by describing salient features, study history, study results, technology base, and an overview of the on-going technology program. Finally, several illustrations will be given depicting the versatility and flexibility of a Regenerative Fuel Cell Power and Energy Storage System.

The principal elements of a Regenerative Fuel Cell System combine the fuel cell and electrolysis cell with a photovoltaic solar cell array, along with fluid storage and transfer equipment. The power output of the array (for LEO) must be roughly triple the load requirements of the vehicle since the electrolyzers must receive about double the fuel cell output power in order to regenerate the reactants (2/3 of the array power) while 1/3 of the array power supplies the vehicle base load. The working fluids are essentially recycled indefinitely. Any resupply requirements necessitated by leakage or inefficient reclamation is water - an ideal material to handle and transport. Any variation in energy storage capacity impacts only the fluid storage portion, and the system is insensitive to use of reserve reactant capacity.

CONCEPT FEATURES - REGENERATIVE FUEL CELL SYSTEM

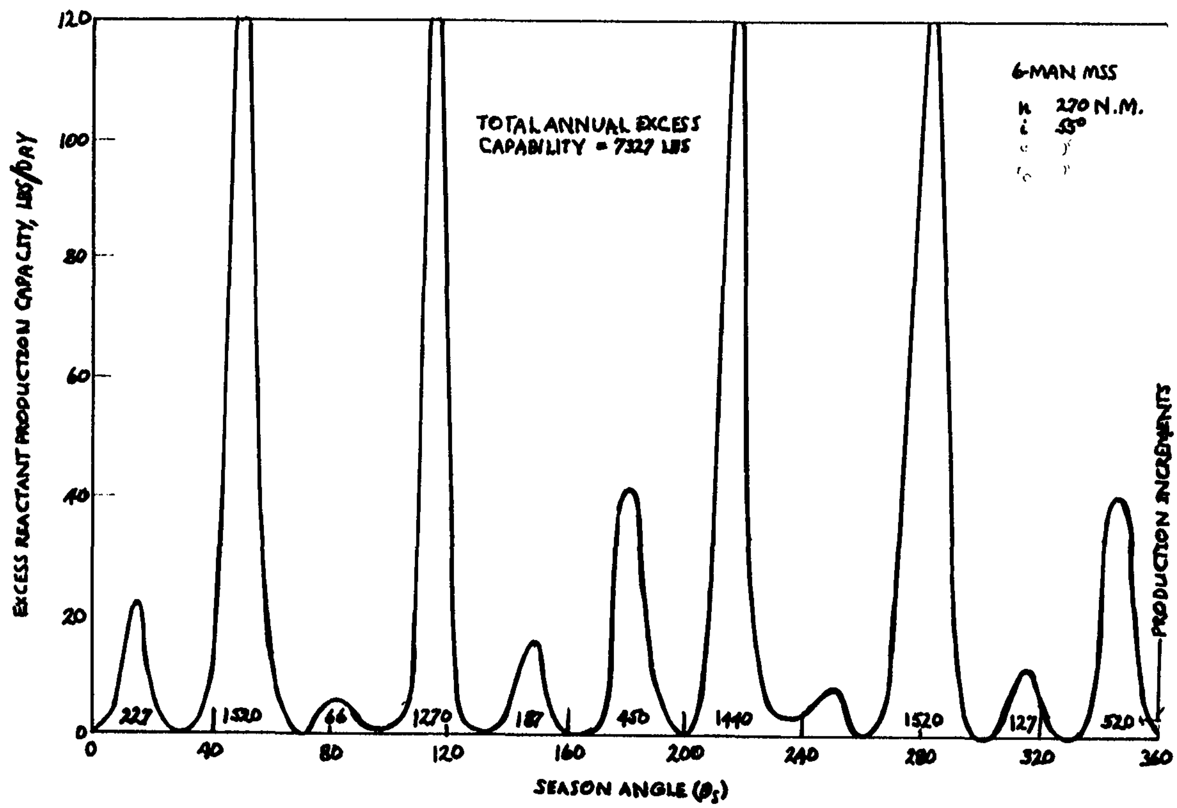
- O MATES H_2/O_2 FUEL CELLS AND ELECTROLYSIS CELLS WITH PHOTOVOLTAIC SOLAR CELL ARRAYS.
- O RECYCLES WORKING FLUIDS ($H_2O/H_2/O_2$) INDEFINITELY.
- O RESUPPLY REQUIREMENTS - WATER.
- O ENERGY STORAGE CAPACITY VARIATIONS - FLUID TANKS.
- O DEEP DISCHARGE INSENSITIVITY - USE OF RESERVE CAPACITY.

In addition to several analyses conducted within the Agency, four specific studies were contracted for. The first was conducted by NAR as an add-on task for the Modular Space Station Study to compare the concept with a NiCd battery system for a 6-man, 25 kW vehicle. Lockheed and Life Systems then performed detailed design analyses of the approach and produced Design Data Handbooks. The most recent effort was a McDonnel-Douglas Space Construction Base Study requiring a 100 kW_e power system.

HISTORY - RFC SYSTEM STUDIES

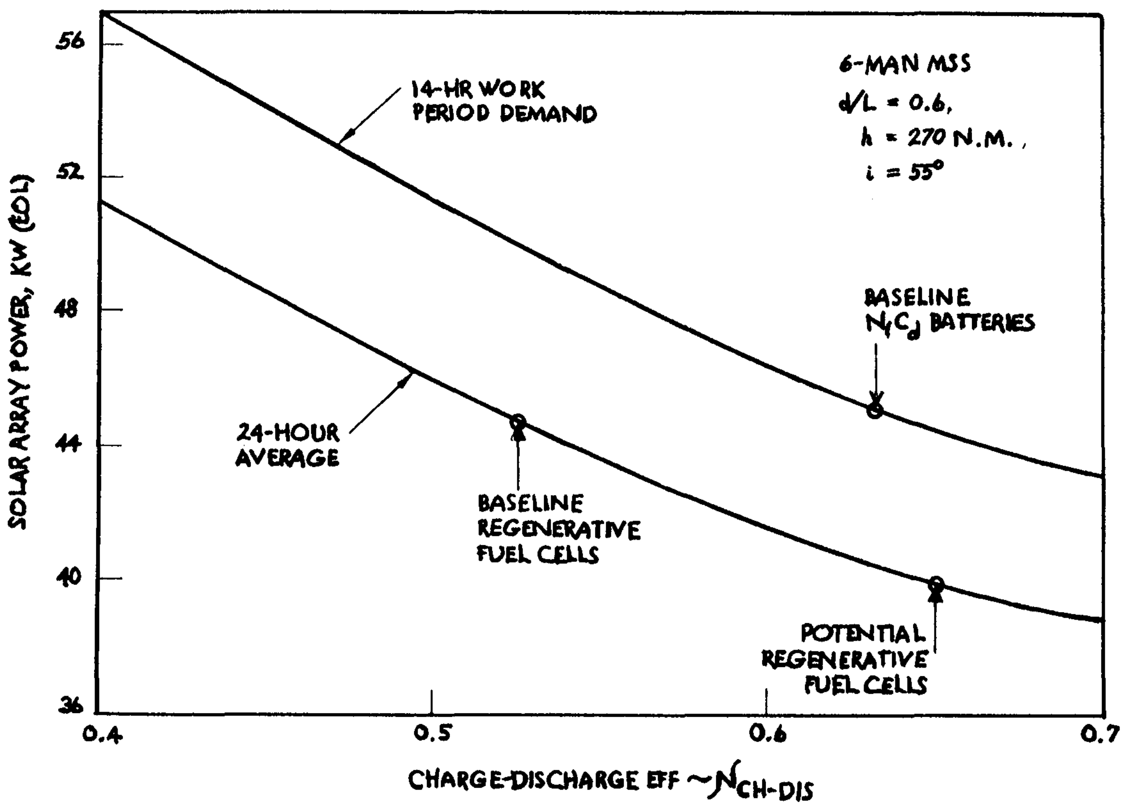
- O NAR - 1972, MODULAR SPACE STATION, PHASE B EXTENSION
  6-MAN, 25 KW, 10 YEAR LIFE
- O LMSD - 1972, DETAILED SYSTEM DESIGN DATA HANDBOOK
- O LSI -1972, DETAILED SYSTEM DESIGN DATA HANDBOOK
- O MDAC - 1977, SPACE CONSTRUCTION BASE SYSTEMS ANALYSIS
  100 KW, 10 YEAR LIFE

The analysis was performed in the Rockwell study as to how the seasonal solar angle may relate to the RFC System. This is plotted in terms of excess reactant production capability. It is shown that the total annual excess rate is 7,327 pounds for the basic 25 kW (net) system. Thus by sizing storage tank capacity to store the excess, the array size can be proportionately reduced.



EPS Excess Reactant Production Versus Season Angle

The 24-hour day was divided into a 14-hour work (high activity) period and a 10-hour sleep (low activity) period. By optimizing the reactant storage capacity and sizing the array for a 24-hour average day, it is seen that at a fixed charge-discharge efficiency, the array power (size) may be reduced by about 10%.



Effect of Energy Storage on Solar Array Size

The effect of this is shown for the RFC vs. the NiCd battery system. Case 1 is for the 14/10 hour work/sleep design, and case 2 is is for the 24-hour average. The RFC weight adjusts downward slightly, while the battery system, because of the linear relationship of weight vs. capacity, must increase by approximately 2700 pounds.

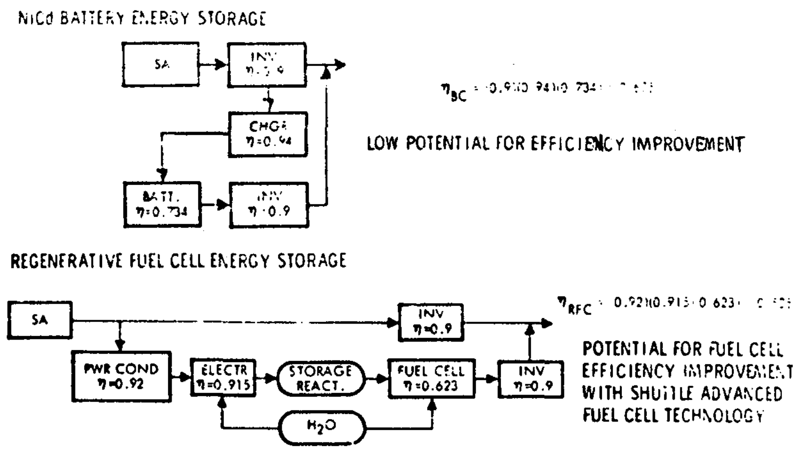


Figure 6-40. EPS Energy Storage Efficiency Analyses

Table 6-19. Solar Array Area Comparison

SOLAR ARRAY AREA SENSITIVE TO
- ENERGY STORAGE CONCEPT EFFICIENCY
- ENERGY STORAGE CAPACITY

ENERGY STORAGE CONCEPT	NiCd BATTERIES	REGENERATIVE FUEL CELLS
CHARGE/DISCH EFFICIENCY	0.625	0.525
CASE 1 SOLAR ARRAY SIZED TO 14 HR WORK DAY		
LOAD + ENERGY STORAGE	31.21 KW	31.21 KW
TOTAL EPS LOSSES	13.64	17.79
SOLAR ARRAY POWER *	44.85	49.00
SOLAR ARRAY AREA, FT²	7,780	8,500
ENERGY STORAGE WEIGHT LB	9,17[illegible]	2,50[illegible]
EPS SUBSYSTEM WEIGHT LB	22,932 ←	16,815
CASE 2 SOLAR ARRAY SIZED TO 24 HOUR AVERAGE		
LOAD + ENERGY STORAGE	27.85 KW	27.85 KW
TOTAL EPS LOSSES	11.75	15.65
SOLAR ARRAY POWER *	39.6	43.50
SOLAR ARRAY AREA (FT²)	6,980	7,540
ENERGY STORAGE WEIGHT (LB)	12,61[illegible]	7,81[illegible]
EPS SUBSYSTEM WEIGHT, (LB)	25,620	16,351 ←

*END OF LIFE POWER, 36% DEGRADATION ASSUMED

DECREASED SOLAR ARRAY AREA FOR REGENERATIVE FUEL CELL ENERGY STORAGE

The MDAC Study results compare the four energy storage systems studied. The RFC ranges from 25% lighter to less than 1/2 the weight of competitors. Ten year resupply weight is even more pronounced as is energy density. And, as alluded to earlier, deep discharge (depleting the reactant supply) has no adverse effect upon the Regenerative Fuel Cell System.

ENERGY STORAGE CHARACTERISTICS SUMMARY*

	NiCd	ADVANCED NiCd	NiH_2	REGENERATIVE FUEL CELLS
ARRAY OUTPUT, BOL, KWe				
• TYPICAL	214.7	209.0	217.1	230.7
• SOLAR ORIENTED	233.4	227.2	236.0	250.8
ARRAY AREA, M^2	2,407	2,343	2,434	2,587
STORAGE EFFICIENCY, %	62	65.7	60.8	54.1
DEPTH OF DISCHARGE, %	14.5	14.5	18.6	33
ENERGY DENSITY(2), W-H/KG	3.93/27.08	6.39/44.1	9.49/51	25.0/75.1 ←
EXPECTED LIFE, YEAR				
• DEMONSTRATED	3.33	NONE	~1	5+/3+(1)
• DESIGN	3.33	3.33	3.33	5
• POTENTIAL	5	5	10	10
PEAK LOAD CAPABILITY	~10X	~10X	2-10X	~4X
LOAD AVERAGING POTENTIAL	FAIR	FAIR	FAIR	GOOD
LAUNCH WEIGHT, KG	34,763	25,868	21,450	16,083 ←
RESUPPLY WEIGHT (10 YR), KG	41,919	25,746	17,356	2,994 ←

*100 KWe AVERAGE AT INVERTER OUTPUT; FAB AND ASSEMBLY POWER PLATFORM
(1) FUEL CELL/ELECTROLYSIS CELL
(2) BATTERY: USEABLE/ABSOLUTE

A weight summary of a study conducted by JSC in 1979 is shown for a 35, 100, and 250 kW system. Capacity was sized for a 2-hour period. Thus, for a 100 kW system, the 10-year weight to orbit, 200,000 WH, yields an energy density of 15.5 WH/lb. For direct comparison with a battery system, it may be necessary to subtract out those elements not normally included in the energy density figure.

H_2-O_2 (DEDICATED UNITS) WEIGHTS, kg

ITEM	POWER LEVEL-kW		
	35	100	250
Fuel Cell Unit (FCU)	196	487	1,118
Electolysis Unit (EU)	522	949	2,373
Hydrogen Tank	51	111	280
Oxygen Tank	31	63	137
Water Tank, Low Press.	2	4	7
Water Tank, High Press.	2	4	7
Power Supply to EU	90	257	643
Regulator	80	230	574
Piping	23	34	57
Pipe Fittings and Valves	23	34	57
Pump, Water Circ. and Press.	9	18	34
Structure*	97	211	524
Reactant	8	22	55
Incremental Solar Array**	348	995	2,484
Incremental Radiator	180	515	1,287
Total Weight	1,662	3,934	9,737
Ten-Year Weight to Orbit; 5-Year Life	2,559	5,857	14,579

*Structure weight assumed as 10% of combined weights of FCU, EU, tanks, power supply and regulator.

**Increment of array above that for equivalent battery system.

The technology base for the Regenerative Fuel Cell dates from 1962 with the solid polymer electrolyte fuel cell for the Gemini Program. The Apollo Program provided for a different technology - the Bacon-type cell - in parallel with the SPE. Several technology programs are listed which led up to the present Shuttle fuel cell - the alkaline capillary matrix type.

TECHNOLOGY BASE - FUEL CELLS

0 GEMINI - SOLID POLYMER ELECTROLYTE (ACIDIC SPE)
- 1962 - 1966
- 1 KW MODULES
- 400 HOURS LIFE (> 1000)
- 75 - 125°F
- 30 PSI

0 APOLLO/SKYLAB - BACON-TYPE (ALKALINE KOH)
- 1962 - 1974
- 1.4 KW MODULES
- 400 HOURS LIFE (>1000)
- 385 - 430°F
- 60 PSI

0 TECHNOLOGY (APOLLO-X, AAP) - ALKALINE CAPILLARY MATRIX
- 1964 - 1970
- 2 KW MODULES
- 2500 HOURS DEV. TEST LIFE
- 180°F
- 45 PSI

0 TECHNOLOGY (PRE-SHUTTLE) PROGRAMS

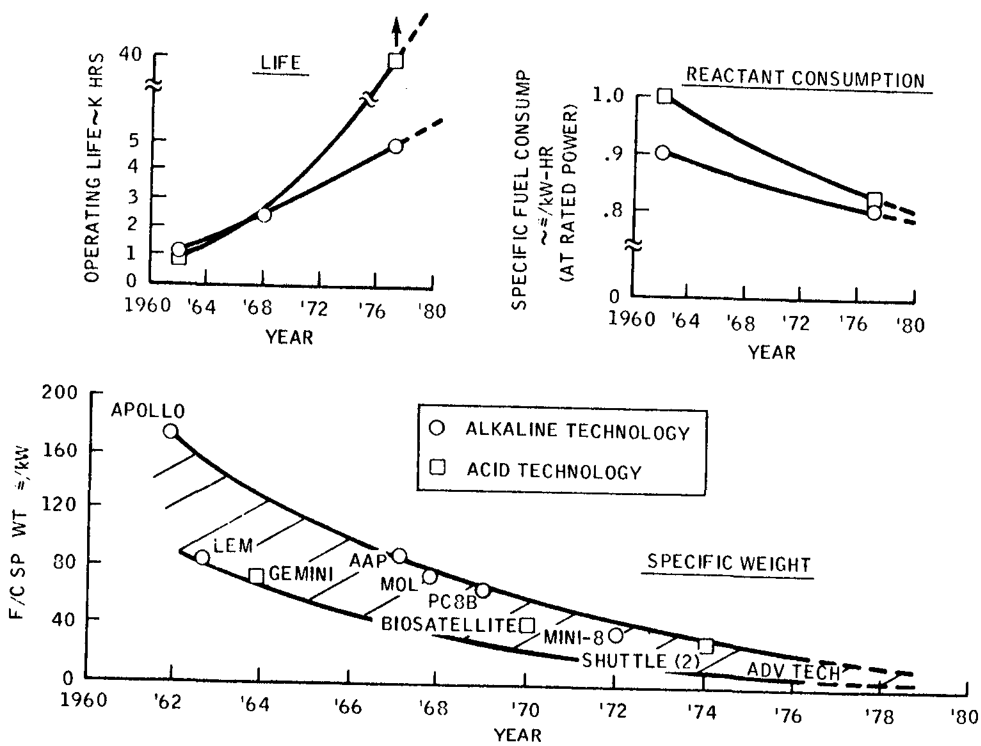
CAPILLARY MATRIX (KOH)	SPE (ACIDIC)
1970 - 1974	1970 - 1979
5 KW MODULE	2.5 KW STACK
5000 HOURS	5000 HOURS
180°F	180°F
60 PSI	60 PSI

0 VARIOUS ELECTROLYSIS PROGRAMS FOR LIFE SUPPORT AND H_2 PRODUCTION.
0 TUG FUEL CELL DEVELOPMENT CAPILLARY MATRIX.
0 "LIGHTWEIGHT" FUEL CELL TECHNOLOGY.
0 MATRIX, ELECTRODE/CATALYST, MATERIALS TECHNOLOGY.

Substantial weight reduction has been realized. The Apollo fuel cell weighed in at about 185 pounds/kW. The Shuttle fuel cell weighs about 30 pounds. Advanced technology indicated a weight of less than 20 pounds kW.

Operating lifetimes also show a marked increase. The Gemini and Apollo fuel cells were required to operate approximately 400 hours and under certain conditions could go to 1000 hours. Shuttle development hardware has operated in excess of 5000 hours, and advanced technology test hardware is operating in excess of 40,000 hours.

FUEL CELL TECHNOLOGY EVOLUTION



The program now in progress has been in planning since 1977. It is oriented toward producing technology capable of providing large incremental increases in orbital power availability from about 35 kW (the approximate Shuttle limit) to about 500 kW

OVERVIEW OF PROGRAM

O OBJECTIVE: TO MAKE READY A H_2/O_2 ELECTROCHEMICAL CELL TECHNOLOGY BY 1985-86 TIME PERIOD SUITABLE FOR SELECTION FOR LARGE (100-500 KW), LONG-TERM (5-10 YEARS) ORBITAL ENERGY STORAGE REQUIREMENTS.

O APPROACH: TO BE ACCOMPLISHED OVER A PERIOD OF APPROXIMATELY 7 YEARS THROUGH A SERIES OF CONTRACTED EFFORTS AND SUPPORTED BY THE AGENCY THROUGH ANALYSES, FIELD BREADBOARD FEASIBILITY TESTING, AND INTEGRATED TESTING OF ENGINEERING MODELS TO DEMONSTRATE TECHNOLOGY READINESS.

The schedule for the 7-year program is shown with major milestones. The reversible type cell is not showing and appreciable advantage over the dedicated cell approach, and that task will be terminated in a few months when present testing is completed. Cell commonality is being phased into other appropriate tasks with the next contract increment. The State-of-the-Art analysis was completed, but will be updated as the program moves ahead.

PROGRAM GOALS

- O STATE OF THE ART ANALYSIS
  - O INITIAL REPORT - 11/79
  - O ANNUAL UPDATE REFLECTING TECHNOLOGY IMPROVEMENTS
- O BREADBOARD FEASIBILITY TESTING
  - O CONTRACTOR CHECKOUT AND DELIVERY - 5/82
  - O FIELD TESTING - 5/82 - 12/82
  - O ACIDIC/ALKALINE SELECTION - 5/83
- O ENGINEERING MODEL HARDWARE TESTING
  - O CONTRACTOR CHECKOUT AND DELIVERY - 10/85
  - O "TECHNOLOGY READINESS" DEMONSTRATION - 10/85 - 5/86

1980 PROGRAM STATUS

JSC

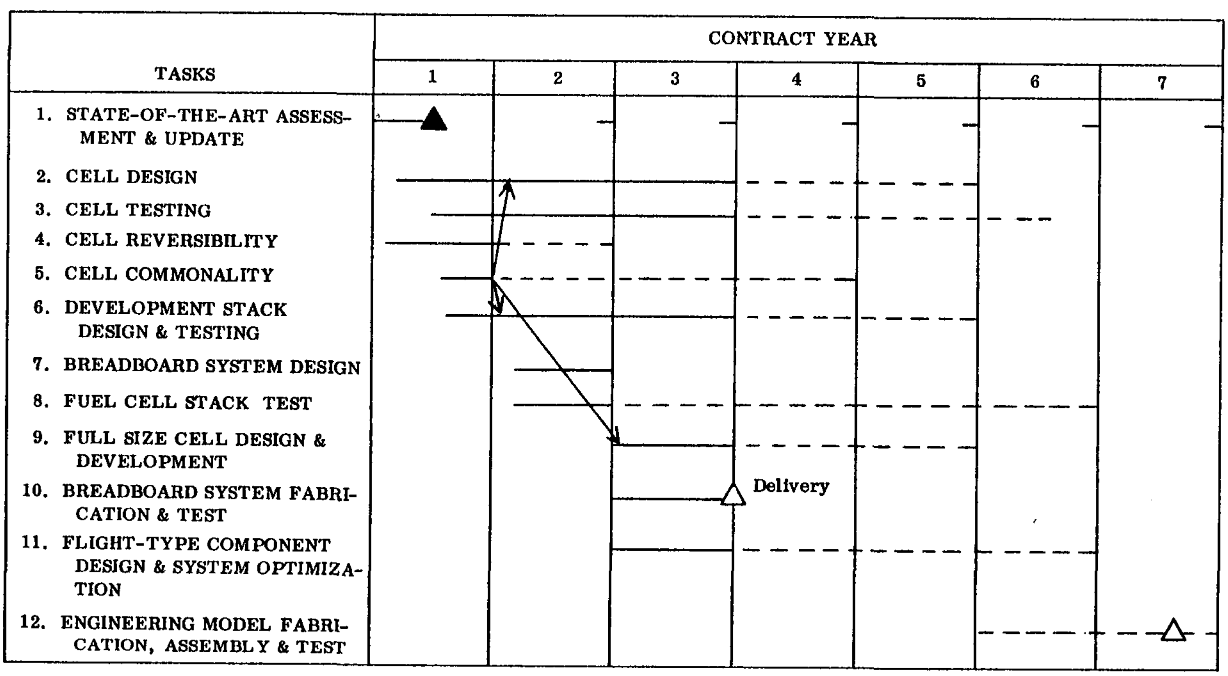
- 0 CONTRACT - 5/1/79 - G.E. SPE TECHNOLOGY
  - 0 SOA ANALYSIS
  - 0 CELL AND MATERIALS DEVELOPMENT
  - 0 ADVANCED DESIGN CONCEPTS

LeRC

- 0 CONTRACT - 8/1/79 - LSI ALKALINE O_2 ELECTRODES
  - 0 2 - "SUPER" } (CELL TESTS)
  - o 2 - "ADVANCED" } (CELL TESTS)
- 0 CONTRACT - 8/31/79 - UTC ALKALINE CAPILLARY MATRIX
  - 0 LONG-DURATION, LO TEMP. CELL TEST
  - 0 3 KW TUG STACK TEST
  - 0 ADVANCED ORBITER-TYPE ELECTRODE TEST

PROCUREMENT ACTION FOR CONTRACT RENEWAL IN PROGRESS.

ELECTROCHEMICAL CELL TECHNOLOGY
DEVELOPMENT FOR ORBITAL ENERGY STORAGE



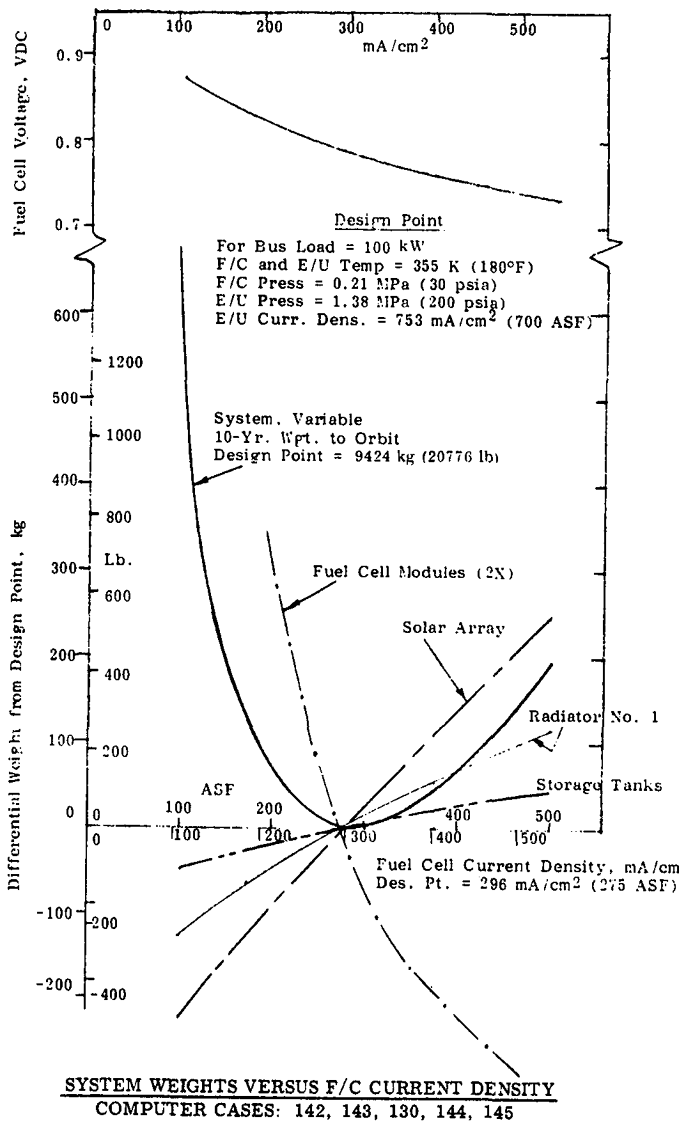
An example of the SOA analysis is shown. This is a computer optimization of the various parameters affecting the overall weight. Total system energy density based upon 200,000 WH of stored energy is 9.62 WH/lb. Subtracting out the solar array weight yields an energy density figure of 24 WH/lb, 10-year weight to orbit.

ECOD-1   1144   10/26/79   CASE 330 DESIGN POINT

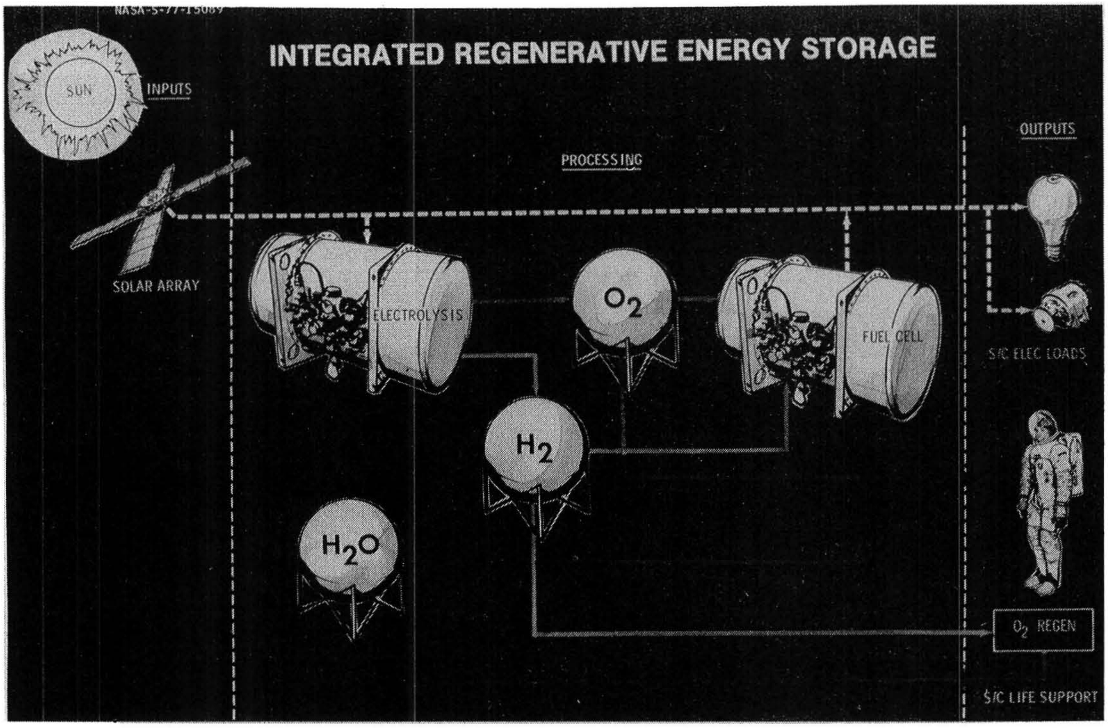
DEDICATED ELECTROLYSIS/FUEL CELL SUMMARY

BUS POWER	100.0	KW
BUS VOLTAGE	108.0	VOLTS
FUEL CELL OPERATING CONDITIONS		
MEAN CELL PRESSURE	30.0	PSIA
MEAN CELL TEMPERATURE	180.0	DEG F
CELL CURRENT DENSITY	275.0	AMP/SQ FT
CELL VOLTAGE	.7896	VOLTS
NO. OF CELLS PER MODULE	137.0	
NUMBER OF MODULES	4.0	
INDIVIDUAL CELL AREA	.88	SQ FT
TOTAL AREA OF CELLS	484.78	SQ FT
MODULE SPECIFIC WEIGHT	1.73	LB/SQFT
CELL CURRENT, PARALLEL MODULES	243.27	AMP
MODULES OUTPUT POWER	105.263	KW
CELL CURRENT EFFICIENCY	.9921	
PERMEABILITY LOSS(EQUIV)	2.182	AMP/SQ FT
MODULES HEAT GEN. RATE(DARK)	92.480	KW
MODULES HEAT GEN. RATE(LIGHT)	1.842	KW
ELECTROLYSIS UNIT OPERATING CONDITIONS		
MEAN CELL PRESSURE	200.0	PSIA
MEAN CELL TEMPERATURE	180.0	DEG F
CELL CURRENT DENSITY	700.0	AMP/SQ FT
CELL VOLTAGE	1.7705	VOLTS
NO. OF CELLS PER MODULE	59.0	
NUMBER OF MODULES	5.0	
INDIVIDUAL CELL AREA	.45	SQ FT
TOTAL AREA OF CELLS	132.01	SQ FT
MODULE SPECIFIC WEIGHT	3.34	LB/SQFT
CELL CURRENT, PARALLEL MODULES	313.24	AMP
MODULES INPUT POWER(LIGHT)	171.781	KW
POWER CONDITIONER INPUT POWER	182.746	KW
STANDBY INPUT POWER(DARK)	.0002	KW
STANDBY INPUT CURRENT(DARK)	.0006	AMP
CELL CURRENT EFFICIENCY	.9842	
PERMEABILITY LOSS(EQUIV)	11.051	AMP/SQ FT
MODULES HEAT GEN. RATE(LIGHT)	29.763	KW
MODULES HEAT GEN. RATE(DARK)	.251	KW
SYSTEM OPERATING CONDITIONS		
SOLAR ARRAY OUTPUT POWER	288.009	KW
IDEAL REGEN FUEL CELL EFF.	.4355	
SYSTEM ENERGY STORAGE EFF.	.3648	
WATER PRODUCED (2 HR)	199.134	LB
MINIMUM BOTTLE PRESSURE (2 HR)	40.000	PSIA
H2 STORAGE BOTTLE VOLUME	418.866	CU FT
H2 BOTTLE DIAMETER	111.40	IN.
WEIGHT SUMMARY		
SOLAR ARRAY WEIGHT	13018.73	LB
RADIATOR NO 1 WEIGHT	1788.49	LB
RADIATOR NO 2 WEIGHT	70.09	LB
H2,O2,&H20 BOTTLE WGTS	1346.62	LB
PRIMARY HEAT EXCHANGER WGT	118.33	LB
REGENERATIVE HEAT EXCH. WGT	32.32	LB
CONDENSER WEIGHT	15.34	LB
PRODUCT H20 HEAT EXCH. WGT	2.90	LB
FUEL CELL MODULES WEIGHT	837.22	LB
ELECTROLYSIS MODULES WEIGHT	440.86	LB
POWER CONDITIONER WEIGHT	913.73	LB
SYSTEM VARIABLE LAUNCH WEIGHT	18584.63	LB
SYSTEM VARIABLE 10-YR ORB. WGT	20776.44	LB

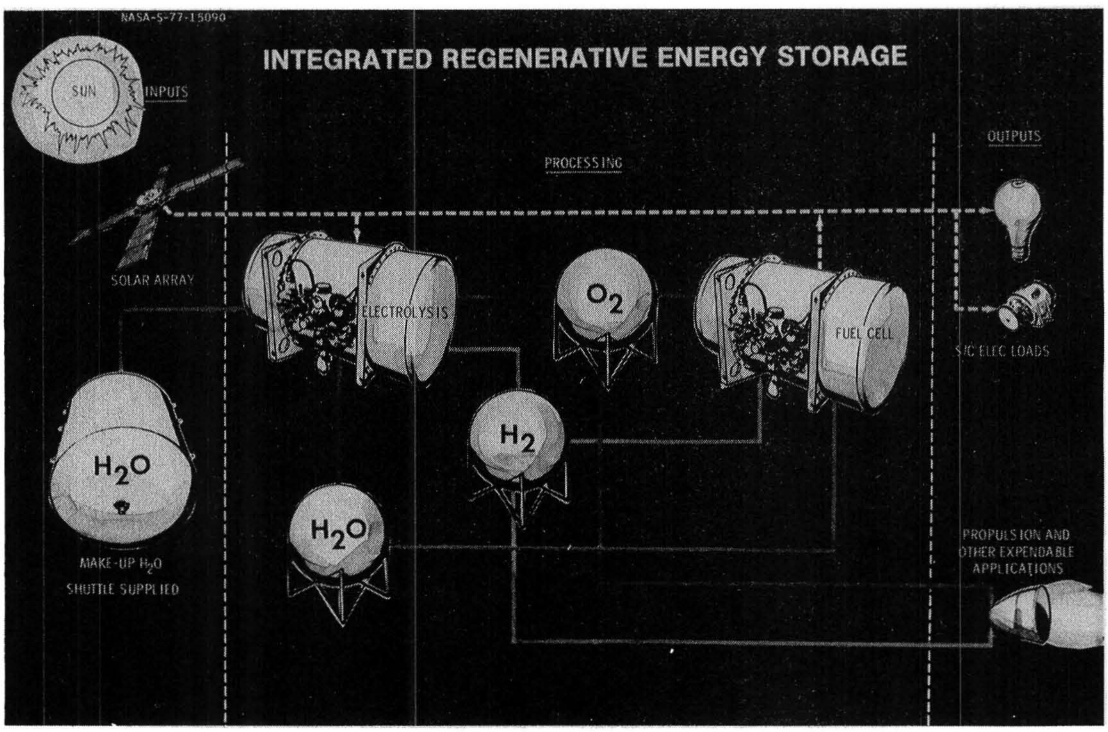
An illustration of how the various elements of a system are impacted by varying one parameter is shown. In this case the fuel cell current density design point was 275 ASF. For example, if current density is reduced the solar array area (and weight) is reduced. However, total system weight is increased. Other elements are affected also which can be traced similarly.



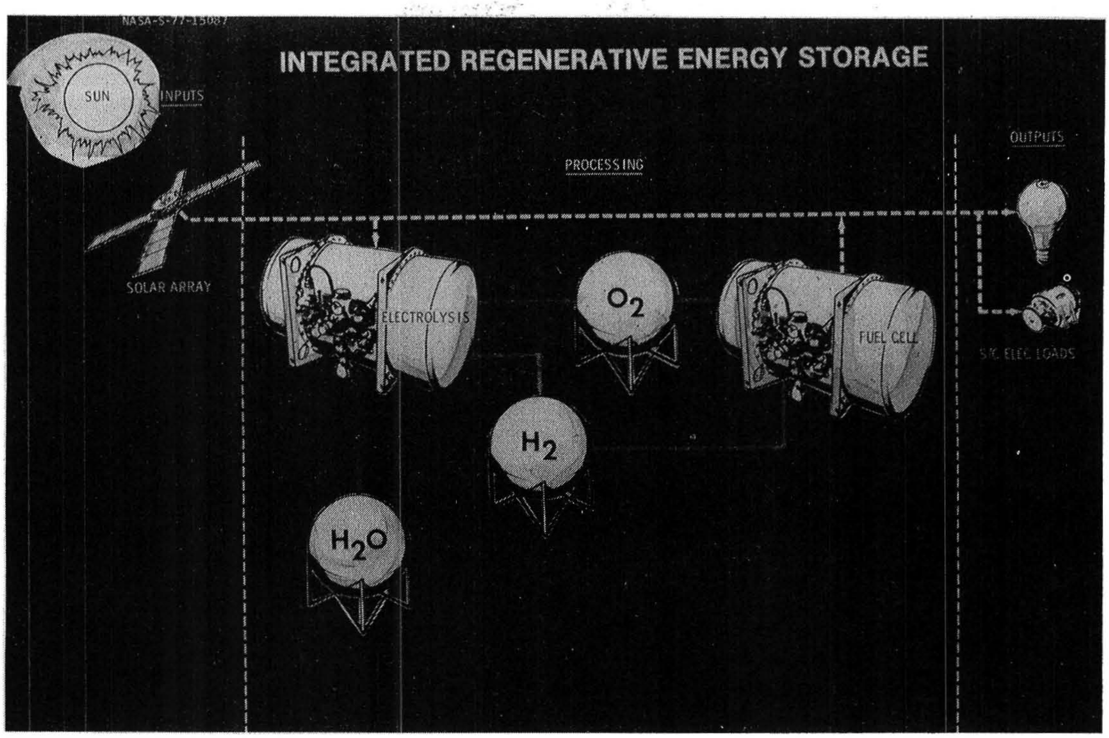
SYSTEM WEIGHTS VERSUS F/C CURRENT DENSITY
COMPUTER CASES: 142, 143, 130, 144, 145

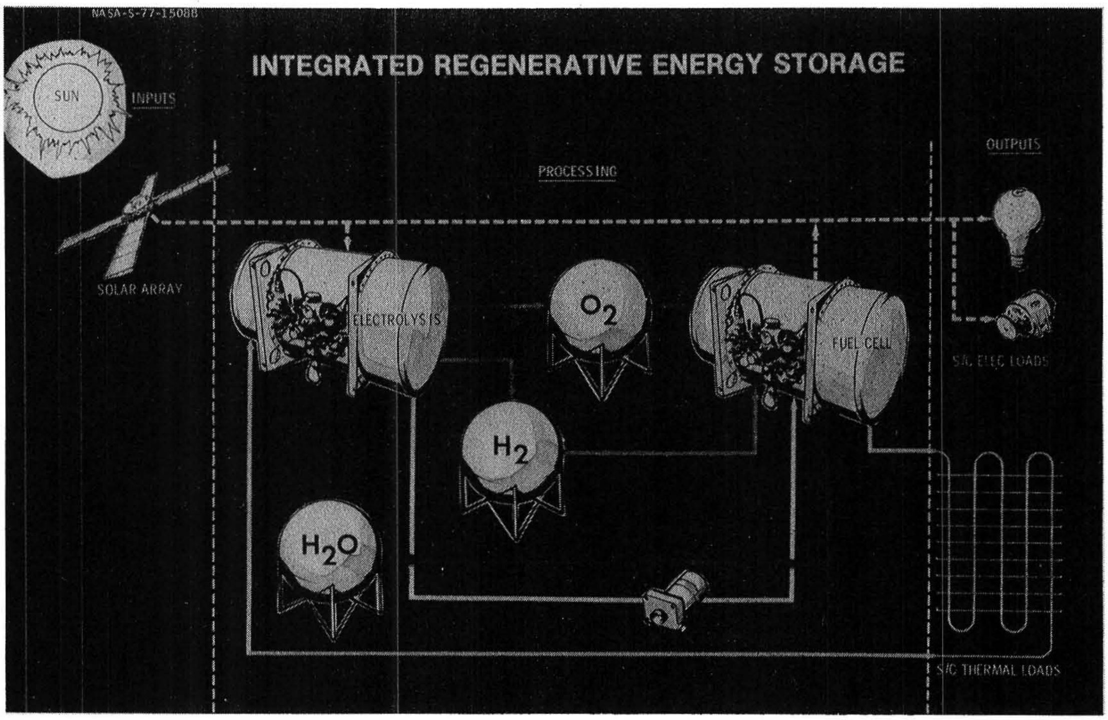


NASA-S-77-15089
INTEGRATED REGENERATIVE ENERGY STORAGE
SUN
INPUTS
SOLAR ARRAY
PROCESSING
ELECTROLYSIS
O_2
H_2
H_2O
FUEL CELL
OUTPUTS
S/C ELEC LOADS
O_2 REGEN
S/C LIFE SUPPORT



NASA-S-77-15090
INTEGRATED REGENERATIVE ENERGY STORAGE
SUN
INPUTS
SOLAR ARRAY
H_2O
MAKE-UP H_2O
SHUTTLE SUPPLIED
PROCESSING
ELECTROLYSIS
O_2
H_2
H_2O
FUEL CELL
OUTPUTS
S/C ELEC LOADS
PROPULSION AND
OTHER EXPENDABLE
APPLICATIONS


NASA-S-77-15087
INTEGRATED REGENERATIVE ENERGY STORAGE
SUN
INPUTS
PROCESSING
OUTPUTS
SOLAR ARRAY
ELECTROLYSIS
O2
FUEL CELL
S/C ELEC LOADS
H2
H2O


NASA-S-77-15088
INTEGRATED REGENERATIVE ENERGY STORAGE
SUN
INPUTS
PROCESSING
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SOLAR ARRAY
ELECTROLYSIS
O2
FUEL CELL
S/C ELEC LOADS
H2
H2O
S/C THERMAL LOADS