PROCEEDINGS OF THE 18th

IECEC '83

INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE

VOLUME

3

OF 5 VOLUMES

ELECTRICAL POWER SYSTEMS

18th INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE

PROCEEDINGS
IN 5 VOLUMES

VOLUME 3
ELECTRICAL POWER SYSTEMS

"Energy for the Marketplace"

SHERATON-TWIN TOWERS
ORLANDO, FLORIDA

Participating Societies

The Engineering Resource For Advancing Mobility

Intersociety Energy Conversion Engineering Conference

PURPOSE:

To reduce the overlapping and duplicative effort of the sponsoring societies in the field of advanced or non-conventional energy conversion. This conference is concerned with the engineering and application aspects of non-conventional energy conversion systems and devices as opposed to the details that are presented at various specialist conferences. Papers are screened for technical competence, clarity and brevity.

ORGANIZATION:

A standing IECEC Steering Committee consisting of two members from each society coordinates all conference activities. Each year a society (this year AIChE) sponsors the conference. Session Organizers are appointed by the General Chairman and the Program Chairman. Session Organizers invite abstracts and receive abstracts from a general solicitation through the Program Chairman. Within limits set by the General and the Program Chairman the Session Organizers are responsible for the content of their sessions and appoint appropriate Session Chairmen.

SPONSORING SOCIETIES:

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(1976 Conference)

American Nuclear Society
(1977 Conference, Washington, D.C.)

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(1978 Conference, San Diego, CA)

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(1979 Conference, Boston, MA)

American Institute of Aeronautics and Astronautics
(1980 Conference, Seattle, WA)

American Society of Mechanical Engineers
(1981 Conference)

Institute of Electrical and Electronic Engineers
(1982 Conference)

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Message from the Program Chairman

This year's conference is the 18th in the series. Reflection on the changing national energy interests and priorities reveals that the energy conversion field has evolved from one of strong orientation toward military and aerospace applications to one of greater breadth that recognizes a wide spectrum of terrestrial and private-sector requirements. This shift has brought with it greater concern for the economics of the marketplace. Hence this year's theme "Energy for the Marketplace."

Superimposed on the shift discussed above is the present federal policy of emphasis on longer-range R&D, coupled with a de-emphasis of government-funded demonstration and commercialization projects. These added constraints have placed new and difficult challenges before the energy conversion engineering field. It is in this new atmosphere of difficult financial and policy constraints that we present the 18th IECEC.

The program in this Proceedings shows the areas of current interest, many of which lie in the private sector. I think that the spectrum of topics represents a healthy balance among the technical fields, and among the potential markets. Some of them are in healthy competition; others complement one another. Frank McLarnon and I hope that you find this program interesting and informative. Thank you for joining us for a successful 18th IECEC.

Elton J. Cairns
Technical Program Chairman

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FUTURE MILITARY SPACE POWER SYSTEMS AND TECHNOLOGY

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ABSTRACT

The challenge of the next decade in electrical power systems for spacecraft will be to provide larger amounts of electrical power with dramatically improved power system performance. Reliability, survivability, adaptability, scaleability, spaceability and endurability will continue to be important power system technology considerations for military missions. This paper (a) addresses increasing power trends seen for future DOD missions (b) describes the current Air Force space power advanced development program and (c) assesses the overall impact of advanced technology in achieving enhanced electrical power system performance capabilities.

INTRODUCTION

The future of spacecraft power will be dominated by the Space Shuttle/Space Transportation System and possible future Heavy Lift Launch Vehicle Systems. These systems will enable routine launching of sophisticated payloads into low earth orbit thus opening up new dimensions for both manned and unmanned space operations. As these new capabilities are developed, so will requirements for much larger spacecraft and power systems. Near term emphasis on higher mission power requirements will focus on the 5 KW_e to 30KW_e steady state power regime. Both solar and nuclear power sources with photovoltaic and thermoelectric power conversion are viable options for meeting these requirements. With fixed chemical propulsion capability to higher orbits of principal interest, increases in electrical power system (EPS) specific power (watts/lb) is of particular importance. Even for improved chemical propulsion upper stages and future electric propulsion transfer stages, increased EPS specific power is crucial to maximize available power on station. Thus, this paper's major emphasis is on near term needs for higher steady state power levels and those Air Force exploratory and advanced development programs either in progress or planned to meet this challenge.

This emphasis should not be construed as diminution of the importance of emerging requirements in the areas of high level pulsed and burst power systems. Such requirements have constituted the basis for extensive in-house studies of exotic chemical, electrochemical and nuclear driven systems leading to a contractual Integrated Spacecraft Total Energy System Analysis program and a comprehensive, new initiative Technology Program Plan for Weapon Systems Power advanced development.

INCREASING STEADY STATE POWER TRENDS

Present DOD mission steady state power requirements fall in the 1-2 KW_e range. Near-term (1985-1990) missions are expected to require power in the 2-12 KW_e range. In the mid-term (1990-1995), some missions are likely to require 12-30 KW_e while in the far-term, power levels of 30 KW_e to 100 KW_e are envisioned. These power requirements will be met by a combination of advanced solar array/battery and nuclear power system technologies. The principal direction of Air Force research, development, test and evaluation (RDT&E) will focus on meeting near-term to mid-term power needs. Solar arrays used in conjunction with rechargeable batteries can fulfill these requirements in a timely and cost effective manner. A system technology demonstration approach will be followed which exploits high performance capabilities of radiation tolerant solar arrays, advanced electrochemical energy storage and efficient power control/power conditioning electronics. Higher generation/distribution voltages (140-270 volts DC) will result in improved electrical power system efficiencies as well as lower weight and volume for power conditioning equipment. Thus, with emphasis on solar array/battery power system demonstrations using advanced component technologies of the 1980s, the majority of the DOD mission power needs of the 1990s, can be met.

AIR FORCE ADVANCED COMPONENT/POWER SYSTEM TECHNOLOGY DEVELOPMENT

Nickel Hydrogen Battery:

The Ni/H_2 battery is being developed as a replacement energy storage subsystem for Ni/Cd batteries. Figure 1 shows the development sequence of the Air Force Ni/H_2 battery program which began in 1972. All Ni/H_2 battery cells developed so far have been 3.5 inch diameter cells in which each cell is packaged within its own individual pressure vessel. (IPV). IPV packaging is low risk because it avoids problems associated with electrolyte bridging between cells, but it is inefficient with respect to weight, volume and cost. Exploratory development has shown the feasibility of packaging a group of cells in a common pressure vessel (CPV). This greatly increases packaging efficiency with attendent volume reductions of up to 50 percent. Additional benefits are Ni/H_2 battery weight reduction of 20 percent and cost reduction of 50 percent. The current approach is to design, build and test 4.5 inch diameter CPV modules containing from 4 to 6 cells. The 4.5 inch diameter allows capacity growth to 150 ampere hours. Since the CPV approach involves new technology issues, higher risk and four years of development time; there is a technology gap between the small (3.5 inch diameter, 60 ampere hour) IPV cells available now and the large CPV modules which will be available later. To fill this gap at low risk and low cost, a task has been included in the CPV program to fabricate and test a small number of 4.5 inch diameter IPV cells. This will make high capacity IPV cells available in 1984, several years before CPV modules have been adequately tested to warrant their transition.

Advanced Silicon, Gallium Arsenide and Gallium Arsenide Derived (Galicon and Multibandgap) Solar Cell Technology:

The Air Force High Efficiency Solar Panel (HESP) advanced development program was initiated in 1975. Effort to date has been predominantly in the areas of advanced silicon and gallium arsenide solar cell and panel technology. Early silicon solar cell development resulted in thin, shallow junction devices which provided approximately 15 percent greater end-of-life power per unit area when compared with traditional (circa 1970) silicon solar cells. Parallel gallium arsenide cell development completed in 1981 has demonstrated yet another 15 percent increase in end-of-life power per unit area relative to advanced silicon cell technology. Galicon and Multibandgap cell technologies are being pursued under Air Force basic research and exploratory development programs to achieve further reductions in solar panel area and weight to meet a given end-of-life power requirement. Table 1 summarizes present and advanced solar panel technology projections for five, seven and ten year geostationary mission lifetimes. Table 2 presents similar data for a high radiation 5600 NM polar orbit for mission lifetimes of three, five and seven years. In developing this data, cell electrical performance and temperature coefficients have been traded off against shielding requirements to obtain end-of-life watts/ft^2 and lbs/ft^2 capabilities. GaAs solar cells developed during the course of the HESP program have demonstrated measured cell efficiencies ranging from 16% to 19%. This new cell technology has been extensively evaluated in the laboratory and improved efficiency and radiation tolerance documented. Experimental cells have been delivered for flight test on the NASA GSFC San Marco D/L satellite and the Navy Living Plume Shield (LIPS) experiment. Three additional flight tests of GaAs cells are planned for the 1986/1987 time period.

High Energy Density Rechargeable Battery:

While IPV Ni/H_2 batteries with their longer lifetimes and higher energy densities are starting to find their way into the inventory, weight limitations and higher power levels of future satellites will require rechargeable batteries with still higher energy densities. For baseload mission power requirements of 5 to 30 KW_e, the energy storage subsystem will continue to be the heaviest component of the electrical power system. The Air Force High Energy Density Rechargeable Battery (HEDRB) program is structured to be responsive to the need for ultra-high performance rechargeable batteries. Studies sponsored by the Aero Propulsion Laboratory conclude that a HEDRB with an energy density of 50 watt hours per pound (watt hrs/lb) can be developed. Figure 2 shows the weights of Ni/Cd, Ni/H_2 and HEDRB batteries as a function of electrical power system output. The HEDRB is capable of reducing battery weight by 80 percent when compared to Ni/Cd batteries, a savings of over 3000 pounds for a 30 KW_e power system and 60 percent when compared to Ni/H_2 batteries. Candidate cell technologies for the planned HEDRB program include sodium sulfur and lithium alloy-iron sulfide. For individual cells, sodium sulfur has demonstrated superior cycle life (1100 cycles for sodium sulfur vs. 430 cycles for lithium alloy-iron sulfide) and higher energy densities than lithium alloy-iron sulfide (55 vs. 36 watt hrs/lb). The HEDRB program objective is to design, build and flight qualify batteries with energy densities of 50 watt hrs/lb and cycle lifetimes compatible with 10 year mid-altitude and geosynchronous orbit requirements - 15,000 and 1,000 cycles respectively.

Survivable Solar Concentrator Panel:

Emphasis being placed on satellite survivability and endurability has led to the investigation of alternative solar array concepts. The concentrating photovoltaic panel is one such concept. Concentrating photovoltaic concepts, originally investigated by the Air Force in the 1960's and new concepts recently studied by NASA, show good prospects of low cost as well as survivability. Figure 3 illustrates the basic unit concentrator cell and how a multitude of unit cells are modularly integrated into a Cassegrainian Concentrating Array. Focused sunlight increases cell efficiency up to 10 percent providing areal power density (watts/ft^2) equivalent to planar array configurations. Active cell area is reduced in approximate proportion to concentration ratio thus providing a vehicle for transitioning new high efficiency, high cost solar cells. The concept provides a substantial increase in overall shielding from the radiation environment while clever heat rejection design permits cell operating temperatures much lower than one might expect.

Advanced Light Weight Solar Array Blanket:

Requirements governing the evolution of planar solar array blanket technology include the need for higher power levels, lower power system weight and improved survivability to the radiation environment. The Air Force Advanced Light Weight Solar Array Blanket program will optimize the electrical performance, weight and survivability of array blankets for planar array configurations. The 2 mil multibandgap cell technology presently being pursued under basic research and exploratory development, the thin (2 mil) Galicon cell and thin (2 mil) advanced silicon solar cell are candidates for achieving substantial weight reductions and improvements in radiation tolerance. Figure 4 illustrates one of several possible approaches to optimizing solar array blanket weight. An important aspect of the lightweight blanket program is development of technology for handling and assembly of large quantities of very thin advanced cell types into array segments for test and evaluation.

High Voltage Power System:

Solar arrays used in conjunction with rechargeable electrochemical batteries are and will continue to be the principal source of electrical power for DOD space systems. Solar array/battery power systems can fulfill many of the projected power needs in the 5 to 30 KW_e power range. The High Voltage Power System (HVPS) advanced development program is fully responsive to requirements for improved solar array/battery power system performance, survivability and autonomy. Figure 5 is an artist's rendition of the High Voltage Power System concept. The program integrates related Air Force and NASA advanced component technologies into a high performance demonstration power system. The Aero Propulsion Laboratory has conducted in-house power system studies for the load power range from 5 to 50 KW_e for low earth polar, mid-altitude, geosynchronous and 2 times geosynchronous orbits. Results of these studies, as well as results of supporting contractual studies, indicate that by employing advanced solar cells, high energy batteries, and advanced structures technology forecast for the 1985-1987 time period, increases in power system performance from 4-5 watts/lb to 8-10 watts/lb are possible. The power subsystem level benefits are illustrated in Figure 6. Thus, the objective of HVPS development is to design, build and conclusively demonstrate advanced solar array/battery technology capable of 8-10 watts/lb and also demonstrate survivable and autonomous capabilities. This program will also provide advanced component and power subsystems technology spinoffs useful to present systems. These spinoffs will be particularly valuable in the critical areas of reliability, survivability, autonomous operations and advanced high voltage power distribution and conditioning technologies.

ADVANCED COMPONENT, SUBSYSTEM AND SYSTEM LEVEL TECHNOLOGY PROJECTIONS

The foregoing discussions pertain primarily to the Air Force Advanced Space Power Supply Technology program which emphasizes near term needs. Overall Air Force interests are not restricted to solar array/battery power systems. Basic research, exploratory development and in-house analysis programs are addressing all facets of power and energy systems technology for space applications. These facets include for example, the electrical power system components (present status/future projections) shown in Table 3. Some of this data has been used for recent in-house studies of specialized prime power generation systems including (a) chemical combustion and nuclear driven turboalternators and MHD, (b) high power density fuel cells, and (c) high energy density primary and rechargeable electrochemical batteries. Important power system issues to be resolved include: (a) losses from source to load, (b) power form, power quality and duty cycle, (c) prime power generation system channelization (power module size) versus power level and energy conversion system voltage, (d) closed cycle versus open cycle operation and the rationale for selection of one over the other, (d) chemical stores provision and maintenance in the space environment (refrigeration versus resupply of cryogenic fluids), (e) electrical power system thermal management and rejection of waste heat, (f) electrical power system effluent management for protection of sensitive space platform optical and thermal control coatings and (g) attitude control and stabilization during power system operation. Principle objectives of prime power generation system parametric design studies and analyses are development of scaling laws for size, weight and volume of candidate systems and a realistic determination of power level/energy level handoff from chemical (or electrochemical) source energy to nuclear source energy. Table 4 summarizes projected improvements in specific power for steady state electrical power systems for the 5 to 100 KW_e power range.

IMPACT OF ADVANCED SOLAR ARRAY/ BATTERY POWER SYSTEM TECHNOLOGY

Table 5 shows the increased power capability which advanced solar array/battery technology offers for future geosynchronous orbit (GEO) missions. With Inertial Upper Stage and Wide Body Centaur propulsion capabilities of approximately 5,000 pounds and 10,600 pounds respectively to GEO, and assuming a 30 percent weight fraction for electrical power, increased power capabilities indicated may be realized.

It should be noted that advanced silicon solar cells with 2 mil thickness and 3 mil shields plus IPV Ni/H_2 (14 watt hrs/ lb) energy storage provides power capability equivalent to "thick" (8 mil) gallium arsenide solar cells with 6 mil shields plus CPV Ni/H_2 (17 watt hr/lb) energy storage. The gallium arsenide solar array area however is only 64 percent of the advanced silicon solar array area (850 ft^2 versus 1,320 ft^2). In comparison, the projected power capability gain offered by developmental 2 mil Galicon and multibandgap solar cells with HEDRB energy storage, is dramatic. Table 6 presents similar information to that contained in Table 5 for a high radiation environment mid-altitude (MAO) orbit.

SUMMARY

This paper has briefly described the objectives, current status and future direction of the Air Force program in space power technology. Primary emphasis is on advanced component, subsystem and system level technologies to meet near-term to mid-term steady state power requirements of 5 to 30 KW_e. Thus advanced solar cell, electrochemical energy storage and high voltage power generation, distribution and power conditioning technologies will be emphasized. Emerging requirements in the area of pulsed power and burst power systems are being addressed through basic research, exploratory development component demonstrations and system level in-house and contractual integrated total energy system studies, analyses and conceptual designs. Solar, chemical and nuclear power sources along with all known energy conversion and advanced energy storage options will continue to be investigated. The need for unique approaches to thermal control, heat transport and thermal rejection has clearly surfaced as an important technological challenge. High voltage power conditioning technology to match unique power source characteristics to specialized load requirements warrants and will receive greater emphasis. Finally, manufacturing technology programs such as those currently in progress on gallium arsenide solar cells and IPV Ni/H_2 battery cells, will be utilized to ensure availability and affordability of advanced power system components.

Table 1 - SOLAR PANEL TECHNOLOGY

$$P_{out/unit\ area} = H_o\ N_{c_{25\ ^oC}}\ K_p\ K_w\ K_r\ K_t\ K_{uv}\ K_{dm}$$

\- 19,323 NM EQUATORIAL -

SOLAR PANEL PARAMETER	SOTA Si (8 MIL)	ADV Si (2 MIL)	GaAs (8 MIL)	GALICON (2 MIL)	MULTIBANDGAP (2 MIL)
Mission Lifetime (Yrs)	5/7/10	5/7/10	5/7/10	5/7/10	5/7/10
Shield Thickness (Mils)	6	3	6	6	6
H_o = 125.7 Watts/Ft^2	-	-	-	-	-
N_c, 25^{o}C, BOL (%/100)	.123	.136	.17	.17	.25
K_p (Packing Factor)	.88	.88	.88	.88	.88
K_w (Wiring Loss Factor)	.95	.95	.95	.95	.95
K_r (Rad Damage Factor)	.74/.71/.67	.67/.63/.60	.77/.73/.68	.79/.75/.70	.79/.75/.70
K_t (Temp Loss Factor)	.86	.86	.93	.93	.93
K_{uv} (UV Darkening Factor)	.97	.97	.97	.97	.97
K_{dm} (Design Margin Factor)	.98	.98	.98	.98	.98
EOL Watts/Ft^2	8/7.5/7.0	8/7.4/7.1	12/11.5/11	12.5/12/11	18.5/17.5/16.3
Solar Panel Lbs/Ft^2	.15	.07	.27	.09	.09

Table 2 - SOLAR PANEL TECHNOLOGY

$$P_{out/unit\ area} = H_o\ N_{c_{25\ ^oC}}\ K_p\ K_w\ K_r\ K_t\ K_{uv}\ K_{dm}$$

\- 5600 NM POLAR -

SOLAR PANEL PARAMETER	SOTA Si (8 MIL)	ADV Si (2 MIL)	GaAs (8 MIL)	GALICON (2 MIL)	MULTIBANDGAP (2 MIL)
Mission Lifetime (Yrs)	3/5/7	3/5/7	3/5/7	3/5/7	3/5/7
Shield Thickness (Mils)	12	12	12	12	12
H_o = 125.7 Watts/Ft^2	-	-	-	-	-
N_c, 25^{o}C, BOL (%/100)	.123	.136	.17	.17	.25
K_p (Packing Factor)	.88	.88	.88	.88	.88
K_w (Wiring Loss Factor)	.95	.95	.95	.95	.95
K_r (Rad Damage Factor)	.65/.60/.57	.62/.56/.53	.64/.56/.53	.66/.58/.55	.66/.58/.55
K_t (Temp Loss Factor)	.84	.84	.92	.92	.92
K_{uv} (UV Darkening Factor)	.99/.98/.97	.99/.98/.97	.99/.98/.97	.99/.98/.97	.99/.98/.97
K_{dm} (Design Margin Factor)	.98	.98	.98	.98	.98
EOL Watts/Ft^2	7/6.3/6.0	7.2/6.5/6.0	10.2/8.8/8.3	10.5/9.2/8.6	15.5/13.5/12.6
Solar Panel Lbs/Ft^2	.22	.15	.33	.15	.15

Table 3

ELECTRICAL POWER SYSTEM COMPONENTS

(PRESENT STATUS/FUTURE PROJECTIONS)

COMPONENT/SUBSYSTEM	PRESENT SOTA	1990 PROJECTION	2000 PROJECTION	COMMENTS
1. Primary Batteries (High Rate)	10 W·Hrs/Lb (Reserve Ag Zn; Automatically Activated; 20 W·Hrs per Lb @ 500 Sec)	30 W·Hrs/Lb (Lithium Only)	60 W·Hrs/Lb (Lithium Only)	o Ag Zn or Lithium o No Effluent o Modular o Low Development Cost o Low Development Risk o Good Lifetime
2. Rechargeable Batteries (LEO)	4 W·Hrs/Lb (Ni Cd)	8 W·Hrs/Lb (Ni Cd)	10 W·Hrs Lb (Ni Cd)	o Base Load, 3-5 Yr Life
	20 W·Hrs/Lb (Ag Zn)	20 W·Hrs/Lb (Ag Zn)		o Base Load, 6 Mos Life
			30 W·Hrs/Lb (Lithium)	o Base Load, 1 Yr Life
3. High Energy Density Rechargeable Batteries (LEO)	----	30 W·Hrs/Lb (Sodium Sulfur or Lithium Metal Sulfide; 1 Yr Life)	50 W·Hrs/Lb (Sodium Sulfur or Lithium Metal Sulfide; 3-5 Yr Life	o Sodium Sulfur = 350°C o Lithium Metal Sulfide = 400°C o Base Load
4. Metal Gas Batteries (LEO)	9 W·Hrs/Lb (3 Yr Life)	16 W·Hrs/Lb (5 Yr Life)	20 W·Hrs/Lb (5 Yr Life)	o Base Load or Pulse Load
5. High Energy Density Primary Fuel Cell	1500 W·Hrs/Lb	2000 W·Hrs/Lb	2500 W·Hrs/Lb	o Includes Power Section & Plumbing o Fuel, Tankage, Thermal Mgmt, & Pwr. Cond. Not Included
6. Inertial (Flywheel) Energy Storage	10 W·Hrs/Lb	20 W·Hrs/Lb	30 W·Hrs/Lb	o Vehicle Altitude Disturbance o Use Requires Shallow Energy Extraction for Generator Drive o Clutch/Gearbox Required o Bearing Lifetime an Issue

Table 3 (Cont'd)

COMPONENT/SUBSYSTEM	PRESENT SOTA	1990 PROJECTION	2000 PROJECTION	COMMENTS
7. Superconducting Energy Storage	----	15 W·Hrs/Lb (?)	30 W·Hrs/Lb (?)	o Needs Further Definition
8. Conventional Turbomachinery	5000 W/Lb	6000 W/Lb	7000 W/Lb	o Wire Wound Alternator o Includes Turbine, Combustor & Alternator o Excludes Fuel, Tankage & Pwr. Cond. o 1220 W·Hrs/Lb (Includes Everything Except Cooling/Radiator) o Efficiency = 95% o 3Ø, 3 KV Line to Line
9. Permanent Magnet Generator	5000 Watts/Lb	5500 Watts/Lb	6000 Watts/Lb	o Limited to 5 MW_e Per Machine
10. Superconducting Turboalternator	5300 Watts/Lb	6000 Watts/Lb	9000 Watts/Lb	o Includes Combustor, Turbine, Liquid He Coolant, & Alternator o Excludes Pwr. Cond., Tankage and Fuel o Efficiency = 98%
11. High Power Fast Start Turbine Power Unit	17000 Watts/Lb			o Excludes Fuel o Hydrazine = 1400 Watt·Hrs/Lb o Capable of Accelerating .255 Slug Ft^2 Inertial Load to 29,000 RPM at 6000 Shaft Hp within .85 Sec
12. Magnetohydrodynamic Generator	4000 Watts/Lb	8000 Watts/Lb	10000 Watts/Lb	o Includes Prime Power Generation System o Excludes Pwr. Cond., Tankage and Fuel

Table 4

STEADY STATE ELECTRICAL POWER SYSTEMS

(PRESENT STATUS/FUTURE PROJECTIONS)

POWER RANGE: 5 KW_e TO 100 KW_e EOL

ELECTRICAL POWER SYSTEM	PRESENT SOTA	1990 PROJECTION	2000 PROJECTION
1. SOLAR ARRAY/BATTERIES	3 - 5 WATTS/LB	6 - 8 WATTS/LB	10 - 12 WATTS/LB
2. NUCLEAR STATIC (TE)	1 - 2 WATTS/LB	15 WATTS/LB	20 WATTS/LB
3. SPACE POWER ADVANCED REACTOR (THERMIONIC, BRAYTON OR STIRLING POWER CONVERSION)	------	20 WATTS/LB	30 WATTS/LB
4. RADIOISOTOPE STATIC (TE)	1 - 2 WATTS/LB	2 - 3 WATTS/LB	3 - 5 WATTS/LB
5. RADIOISOTOPE DYNAMIC (ORGANIC RANKINE)	------	3 WATTS/LB	5 WATTS/LB

Table 5

POWER CAPABILITY VERSUS PAYLOAD CAPABILITY TO GEO

- 19,323 NM, EQUATORIAL ORBIT -

(BASED ON 30% EPS WEIGHT FRACTION)

	POWER CAPABILITY (KW_e, 10 YRS EOL)				
PROPULSION SYSTEM	SOTA Si + Ni/Cd	ADV Si + IPV Ni/H_2	GaAs + CPV Ni/H_2	GALICON + HEDRB	MULTIBANDGAP + HEDRB
IUS (5000 LBS TO GEO) 1500 LBS ALLOCATED TO EPS	5	8	8	18	21
WIDE BODY CENTAUR (10,600 LBS TO GEO) 3180 LBS ALLOCATED TO EPS	10	17	17	38	43

Table 6

POWER CAPABILITY VERSUS PAYLOAD CAPABILITY TO MAO

- 5600 NM, POLAR ORBIT -

(BASED ON 30% EPS WEIGHT FRACTION)

	POWER CAPABILITY (KW_e, 5 YRS EOL)				
PROPULSION SYSTEM	SOTA Si + Ni/Cd	ADV Si + IPV Ni/H_2	GaAs + CPV Ni/H_2	GALICON + HEDRB	MULTIBANDGAP + HEDRB
IUS (8000 LBS TO MAO) 2400 LBS ALLOCATED TO EPS	8	12	13	26	33
WIDE BODY CENTAUR (13,800 LBS TO MAO) 4140 LBS ALLOCATED TO EPS	13	21	23	46	56

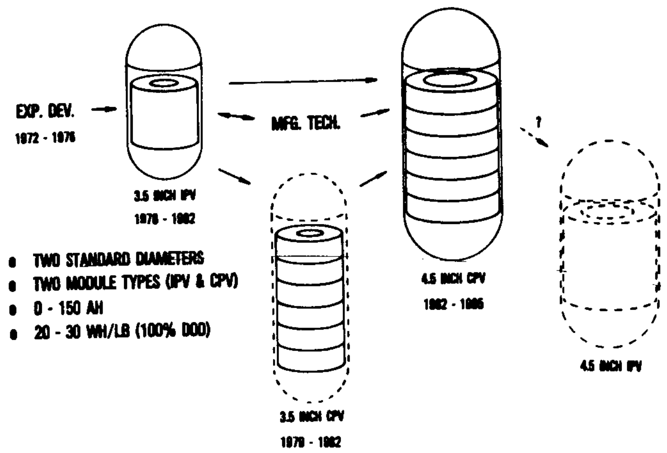

Figure 1 - Ni/H_2 Development Sequence and Standard Components

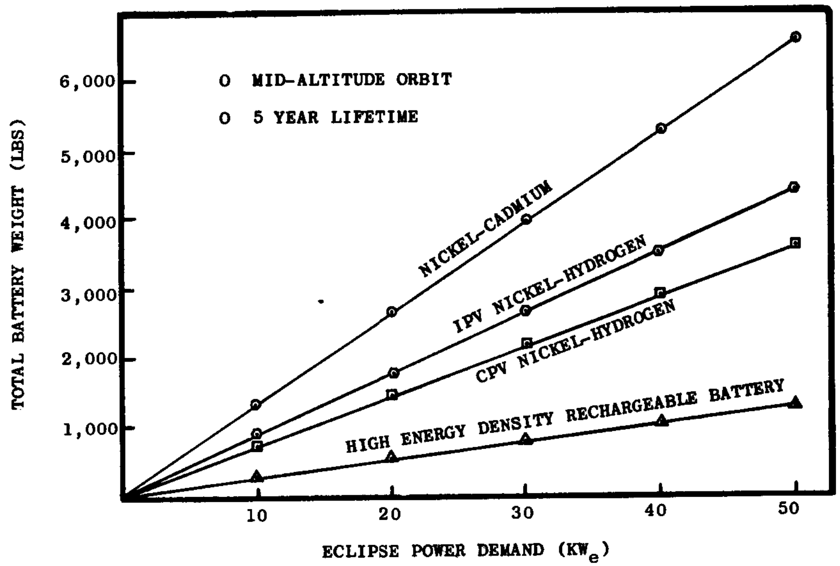

Figure 2 - Total Battery Weight Versus Eclipse Power Demand

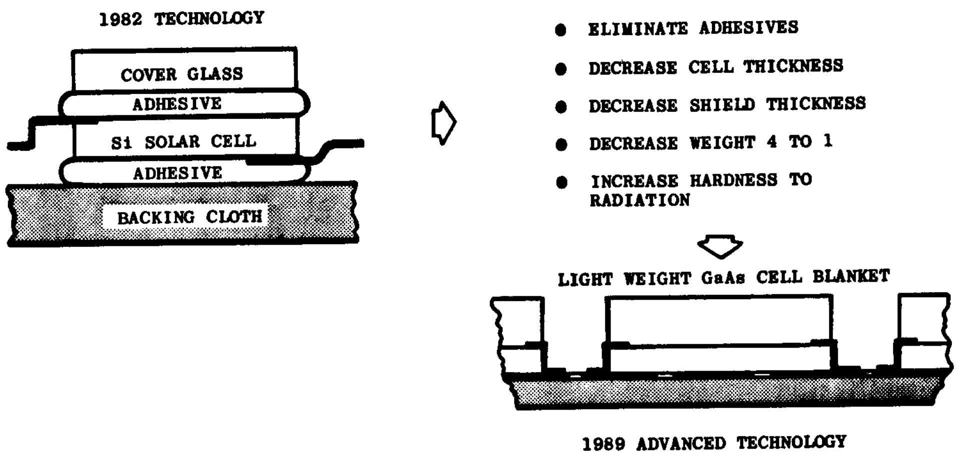

Figure 4 - Advanced Light Weight Solar Array Blanket Technology

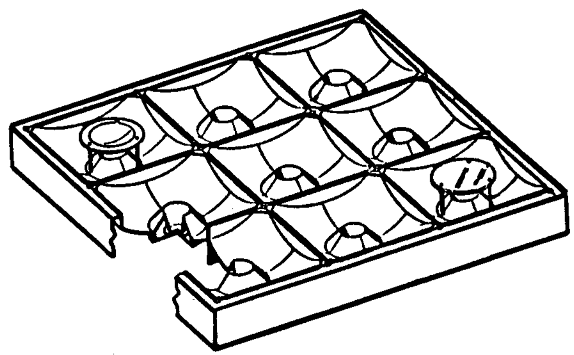

Figure 3 - Photovoltaic Cassegrainian Concentrator Module

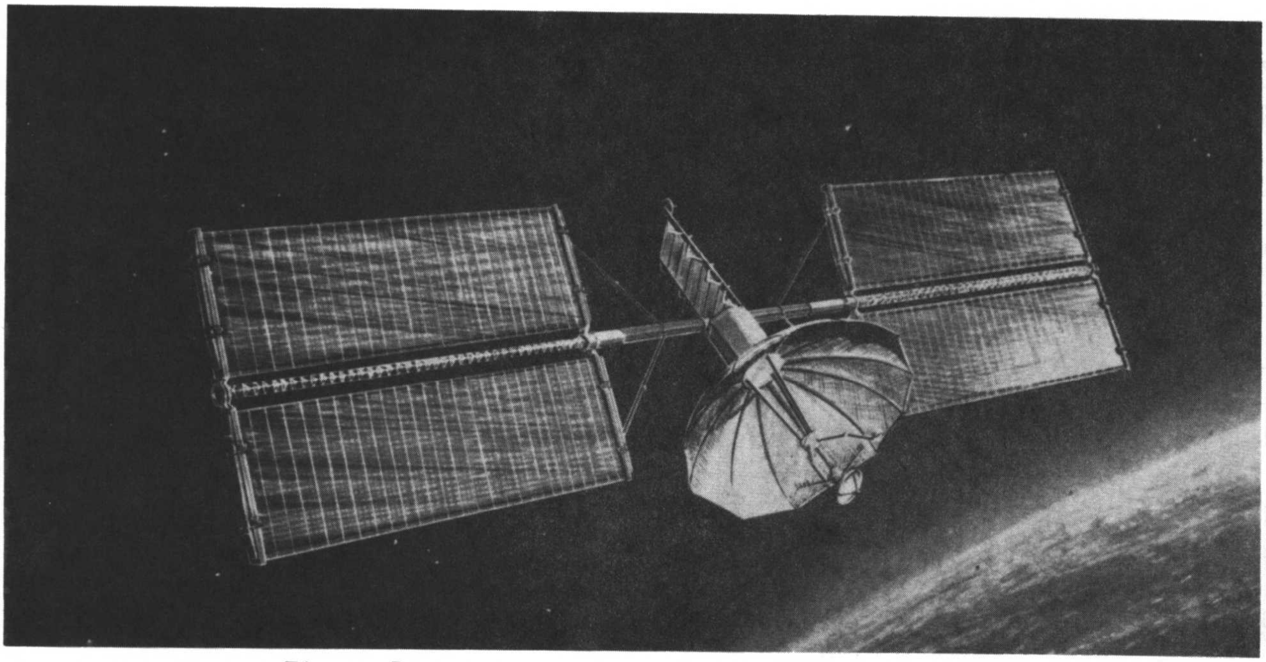

Figure 5 Artist's Concept of High Voltage Power System

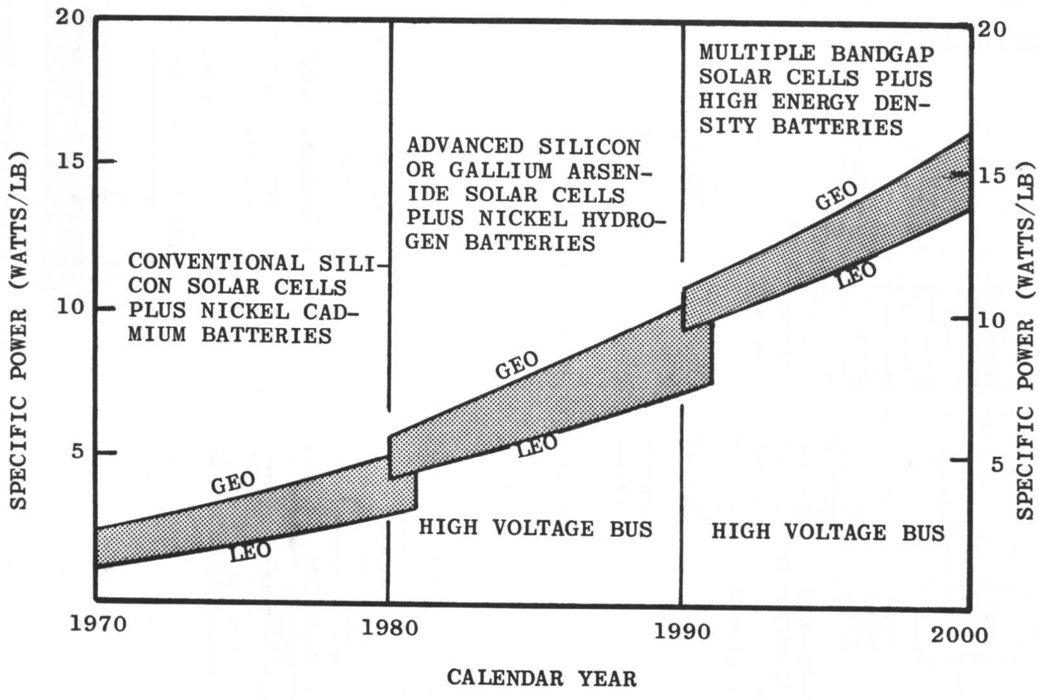

Figure 6 - Projected Improvement in Solar Array/Battery Power System Specific Power (Watts/Lb)

839154

ELECTRICAL POWER SUBSYSTEM DESIGNS FOR AN INITIAL LOW-COST FACILITY (LCF) SPACE STATION

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ABSTRACT

Over the past years, a great deal of effort was invested by the government and industry into defining space station concepts to meet scientific and experimentation mission requirements. More recently, attention has been given to other mission requirements, e.g., low earth orbital staging and operational base. Rockwell's studies have identified a number of key subsystem issues which impact system design in development of such an evolutionary growth space station. This paper discusses some of the electrical power subsystem (EPS) highlights and significant findings from these studies. Three low-cost facility (LCF) approaches were evaluated for an initial space station capability. This paper will discuss these approaches, with special emphasis given to a "super cheapy" LCF concept utilizing Shuttle hardware to the maximum extent.

This work was performed under Rockwell-sponsored IR&D (1).

INTRODUCTION

The objective of this paper is to show a low-cost approach to obtaining an early manned space station driven by the requirement for minimum risk and low cost, yet evolutionary in hardware, software, and operational procedures.

Three concepts were selected for final consideration: (a) Concept B, Stefan Standard (new technology); (b) Concept C, Modified Spacelab (Shuttle-derived technology); and (c) Concept D, Super Cheapy (Shuttle technology). Subsystems were studied using the following specific requirements: four-man crew; early IOC; low development cost; maximum benefits from Shuttle bay operational experience; and maximum utilization of Shuttle equipment.

The three concepts are illustrated in Figure 1. The concepts differ in two principal areas: (a) the station buildup; and (b) the electrical power subsystem and its integration with other subsystems. All concepts had the following modules: (a) core section, (b) logistic module, (c) airlock, and (d) cargo bay module. In addition, Concepts B and C had an energy section. Concept D utilized a remote manipulator system (RMS) and eliminated the need for an energy module. Subsystems for each concept are different; for example, power module type of solar arrays is used for Concepts B and C, and the power extension package (PEP) solar array is used for Concept D. The same planar silicon array technology is utilized for all three concepts, but there is a major difference in area requirement.

SUBSYSTEM ELECTRICAL LOADS COMPARISON

A summary of the electrical loads and how they are distributed among subsystems is presented in Figure 2. Also indicated in the figure is a comparison of the electrical loads for the LCF concepts and the Shuttle orbiter. The space station electrical power stationkeeping loads for the four-man crew are in the range of from 9,141 to 14,251 W. The average emergency electrical load is 3,902 W.

Power requirements for payload support are shown in Figure 3. An estimate of 96 kWh per day and 9 kW (average) appears adequate for the early space station traffic and system requirements shown in Table 1 [i.e., sufficient to support a Rockwell-developed medium activity mission model (2)]. Illustrated are science and application pallet experiments, and GEO staging and servicing operations taking place on the station's payload support assembly (PSA). The pallet experiments are shown to require 2 kW continuously, and an additional 3 kW during manned operations. The corresponding requirements for flight support and servicing operations are 0.5 kW continuous, and an average of 3.5 kW during manned operations. The manned operations involve power required for lights, the RMS specialized end effectors, checkout consoles, and spacecraft and orbital transfer vehicle (OTV) servicing.

ELECTRICAL POWER SUBSYSTEM (EPS)

The EPS design drivers are the 200 to 243 nmi altitude orbit period of 92 minutes, of which the space station is eclipsed by the earth for 36 minutes. The LCF space station mission is at 28° inclination.

The EPS must perform its function from Shuttle launch to end-of-mission in all station configurations and operating modes. The on-orbit operating mode is the driver in EPS sizing. The solar array size and battery/fuel cell capacity determined for the on-orbit mode are ample for all other modes.

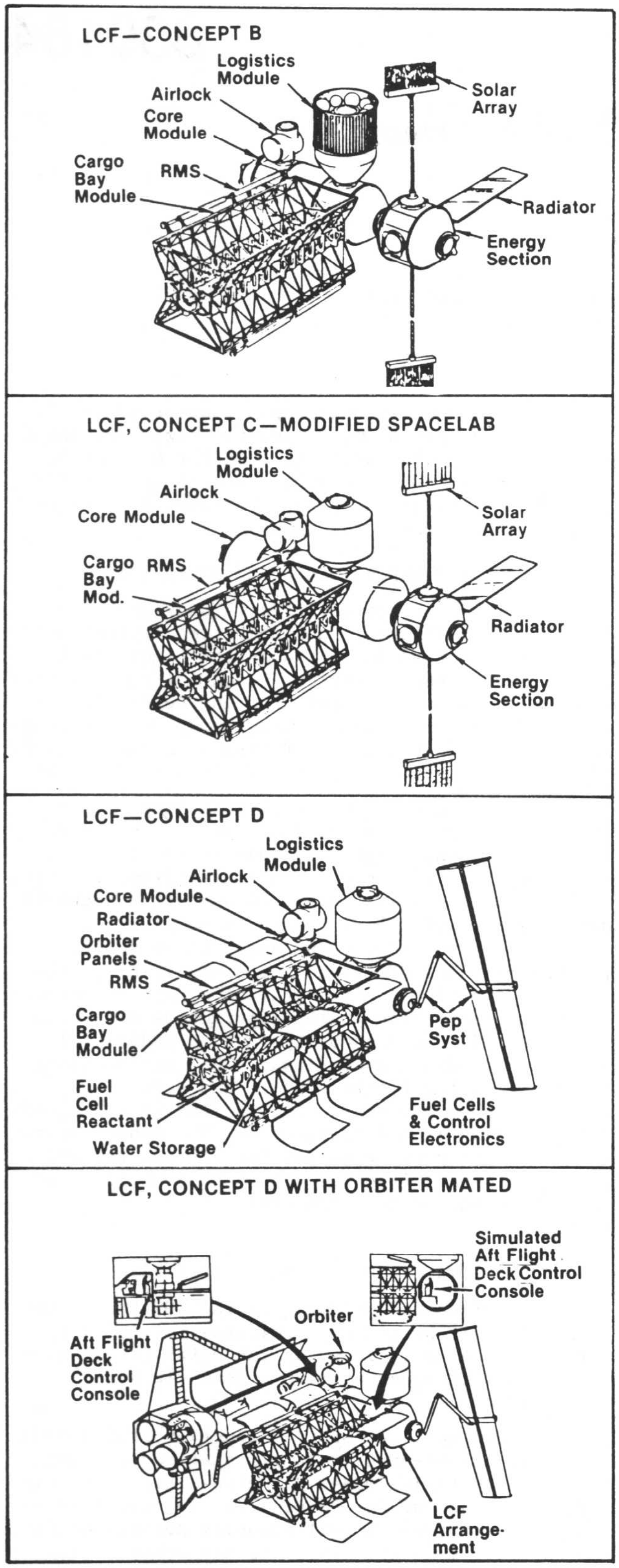


Figure 1. LCF Configurations

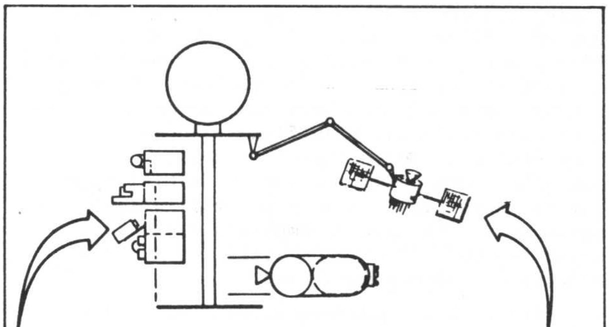
• Orbiter Elect. Loads

Load	kW
• Avionics	11.0
• Thermal	3.0
• Payloads	1.0
• Dev Flt Instr	3.0
Total	18.0

• LCF Space Station Electrical Power Loads

Load	Average Standard	Average Spacelab	Average Concept D	Average Emergency
• ECLSS	3,706	3,072	3,131	1,747
• Comm Data Management	4,000	4,000	3,000	500
• Propulsion	100	100	100	100
• Thermal Control	1,500	1,500	960	300
• Attitude Control	250	250	250	250
• Lighting/Instrumentation	1,800	1,800	1,200	400
• Crew Provisions	1,600	1,600	500	250
Subtotal	12,956	12,322	9,141	3,547
Contingency	1,295	1,232	914	355
Total	14,251	13,554	10,055	3,902

Figure 2. Electrical Loads Comparison



PALLET EXPERIMENTS

2 kW continuous
+
3 kW during manned operations

FLIGHT SUPPORT/ SERVICING OPERATIONS

0.5 kW continuous
+
2-4.5 kW (3.5 avg.) during manned*operations*

- Lights
- RMS
- Cherrypicker
- Checkout console
- Satellite/OTV

(2.5 x 24) + (3.6 x 10) = 96 kWh/DAY

*Utilization factor—60%

Figure 3. Power Requirements for Project Operations

Table 1. Traffic and System Requirements Summary

	1990	1991	1992	1993
NUMBER OF PAYLOADS	26	38	41	34
STATION RESUPPLY	6	6	6	6
NUMBER OF OTVs	8	10	12	10
NUMBER OF SHUTTLE FLIGHTS	19	22	25	21
EQUIV. MANNING LEVEL	2.2	2.9	3.4	2.5
ELECT. POWER FOR PROJECT OPERATIONS (KWH PER DAY)	80	90	100	85