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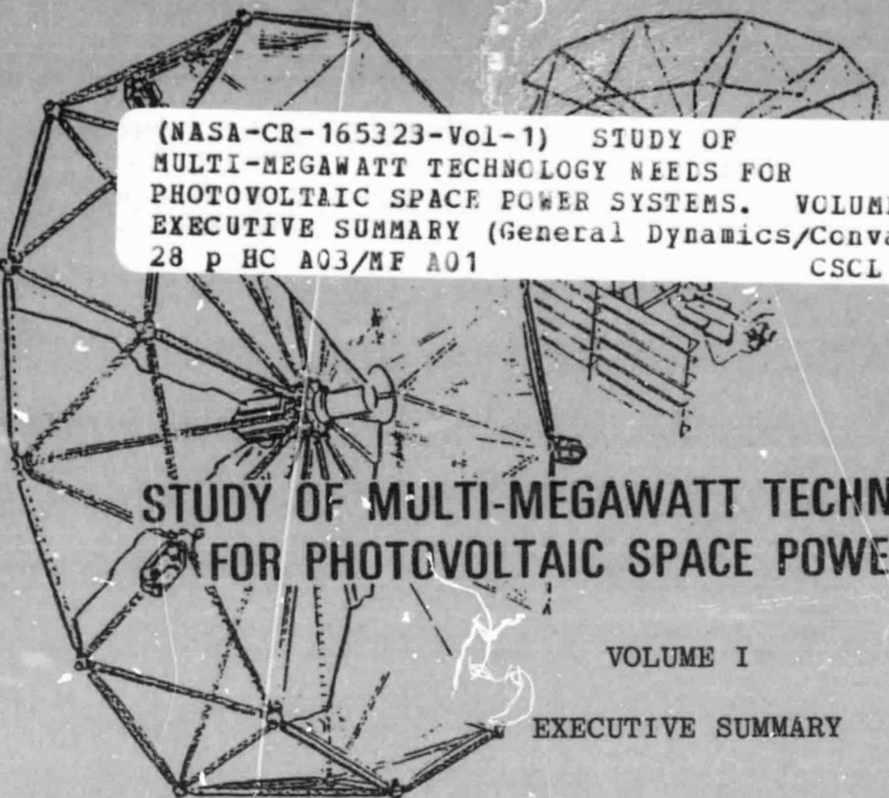

STUDY OF MULTI-MEGAWATT TECHNOLOGY NEEDS FOR PHOTOVOLTAIC SPACE POWER SYSTEMS

VOLUME I

EXECUTIVE SUMMARY

AUGUST 1981

FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER

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16. Abstract

This study examines possible beneficial missions requiring multi-megawatt photovoltaic space power systems in the 1990s time frame and the power system technology needs associated with these missions.

To develop the required technology plan, LEO and GEO missions are postulated, along with various orbital constraints and operational alternatives. Representative GEO Radar and LEO Construction Facility missions are selected for further study and the power requirements defined.

Concepts for photovoltaic power approaches are considered, including planar arrays, concentrating arrays, hybrid systems using Rankine engines, thermophotovoltaic approaches; all with various photovoltaic cell component technologies. AC and DC power management approaches, and battery, fuel cell, and flywheel energy storage concepts are evaluated. Interactions with the electrical ion engine injection and stationkeeping system are considered.

The levels of modularity for efficient, safe, constructable, serviceable, and cost effective system design are analyzed, and the benefits of alternate approaches developed. A technology plan for technology development which would not otherwise occur is presented. Also, technology developments applicable to power systems which appear to have benefits independent of the absolute power level are suggested.

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FOREWORD

This final report was prepared by General Dynamics Convair Division for NASA Lewis Research Center in compliance with Contract NAS3-21951.

The principal results were developed throughout 1980 with reviews at LeRC on 7 May 1980, 4 September 1980, and 17 December 1980.

Because of the scope of the study, many individuals contributed technical assistance. General Dynamics Convair personnel who significantly contributed to the study include:

Study Manager	D.M. Peterson
Mission Orbital Constraints	L.A. Cowgill
Systems Thermal Analyses	R.L. Pleasant
Cost Analysis	R.C. Risley
Component Design Analysis	T.G. Stern J.W. Mildice C.G. Foster A.T. Wells
Concept Design and Trade Analysis Studies	D.M. Peterson T.G. Stern J.W. Mildice
Dynamics Analysis	R.V. Haltzenberg
Technical Review	M. Cornwall J.G. Fisher

In addition to the General Dynamics personnel involved, information pertaining to advanced photovoltaic cell projections was developed by T.J. Maloney and B.R. Cairns of Varian. They provided Appendix III to this report and their data were used for portions of the projections in Volumes I and II.

The study was conducted in Convair's Advanced Space Programs Department, directed by W. Rector. The NASA Project Manager is M. Valgora of the LeRC Space Propulsion Division.

For further information contact:

M. Valgora	D.M. Peterson
NASA/LeRC	General Dynamics Convair Division
Cleveland, Ohio	San Diego, CA 92117
(216) 433-4000 ext. 5186	(714) 277-8900 ext. 2204

This Executive Summary is the first of two volumes comprising the total report. Volume Two is a detailed discussion of the study results.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION 1
INTRODUCTION

The ability of man to exploit space will be a function of the power and energy available there at an affordable cost. Programs such as the 25 KW power system are underway to develop and orbit space power in the tens of kilowatts, and studies are now pursuing hundreds of kilowatts. It is envisioned that megawatt capability will enable some higher power missions which could offer significant benefits to society by the end of the century. This study was constructed to survey possible beneficial missions and identify the crucial technologies that must be developed to enable multi-megawatt photovoltaic space power systems.

Both manned Low Earth Orbit (LEO) and unmanned Geosynchronous Earth Orbit (GEO) applications were examined. LEO orbits offered the obvious advantage of lower insertion costs and initial manned serviceability and constructability, while GEO orbits enable single or dual satellites to support services tied to one terrestial area.

This study assumed that power levels in the low megawatt range could be realized by the year 2000 if technology development started early enough to permit an orderly, well-planned, development approach. Such an approach would also be used to aid in making programmatic decisions on current and near-term technology efforts in such a way as to direct those tecynologies toward multi-megawatt capability. In particular, orbital constraints such as drag were considered, along with the use of electrical and chemical propulsion for insertion and stationkeeping.

By contractual groundrule, a photovoltaic source was selected for the baseline power generation system, rather than solar thermodynamics or nuclear systems. However, to assure that possible beneficial solutions were not overlooked, two alternates employing hybrid photovoltaic/thermodynamic approaches were included for completeness.

The study was divided into four separate tasks:

a. Identification of potential beneficial multi-megawatt missions which require multi-megawatt power.

b. Comparison of alternative power system concepts and operating options, including alternative component technologies.

c. Concept refinement considering environmental interactions and modularity, to establish technology goals and benefits.

d. Technology plan development. This Executive Summary attempts only to highlight the study outputs - the reader is referred to Volume II for detailed results.

SECTION 2

STUDY RESULTS

2.1 TASK 1, BASELINE MISSION IDENTIFICATION

2.1.1 SPACE-BASED RADAR ILLUMINATOR. The selected mission with high potential benefit is a space-based radar illuminator (Figure 2-1). A space radar transmitter operating in a bistatic mode would sequentially illuminate the area surrounding up to 1,000 airports. Surrounding the airport, several bistatic receivers would use inexpensive high-speed data processors which will be available in the 1990s, along with techniques from modern information theory to establish the location of the airplanes within error interval. The redundant set of ground system radars would be redistributed to other airports; the space radar thus provides redundancy to protect against random or overtly caused failures of the ground radar or power systems. The ground system would provide redundancy in the event of hostile action against the space radar, or some highly improbable catastrophic failure. Airplane transponders would not be required.

In the baseline approach, the radar transmitter itself could be configured as a phased array using techniques under development at General Dynamics and Grumman to mount radar transmitter modules on a membrane which provides the array substrate.

2.1.2 2.5 MW LEO SPACE CONSTRUCTION FACILITY (Figure 2-2). There are two major thrusts that encourage the development of space construction capability. The first arises from the results of many studies that are concluding that the Shuttle System payload capability to LEO is volume-limited rather than weight-limited. This implies that more efficient use of STS will result from the ability to load the cargo bay with a dense array of raw materials and then to construct and deploy basic building blocks, using an orbiting construction facility. This will allow a variety of structures to be fabricated and assembled without incurring the penalty of transporting a separate deployment mechanism into orbit for each. The beams of the planar structure of Figure 2-1 are an example, as their mass is cut in half because they are fabricated in space. This would be especially true as Shuttle performance increases in the 1990s.

The second thrust is the fact that structurs which have a significant depth as well as length and width can be more maneuverable and transportable because of their load-bearing capability. Perhaps they can be erected in LEO, fully tested, and then deployed intact more easily with this facility. Later in this study, concentrating arrays are shown to have greater benefits (lower cost, higher efficiency) than planar arrays. This also may be true at lower power levels for different missions. The technology for assembly may be significantly aided by utilizing space-aided construction.

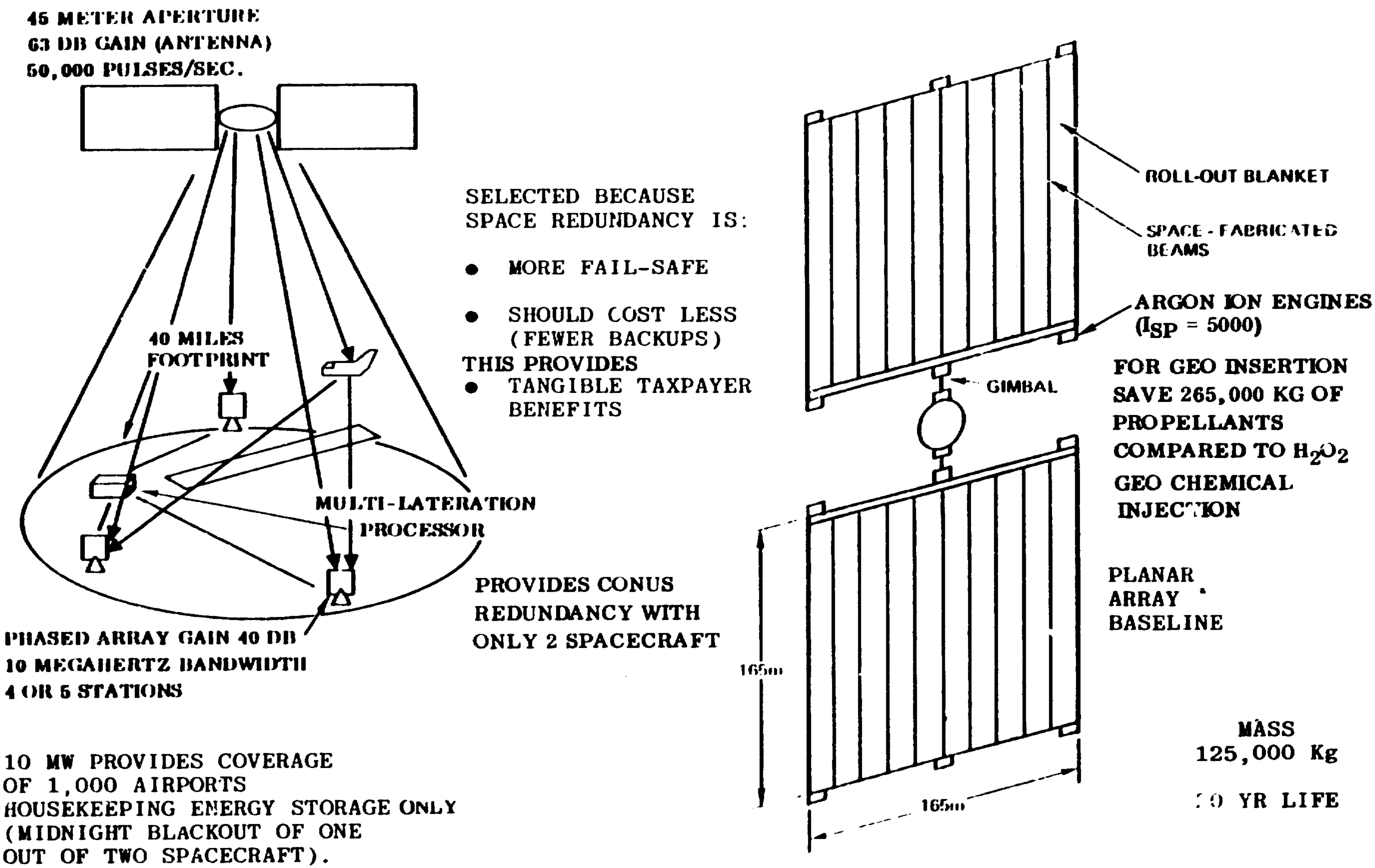

Figure 2-1. GEO Mission Concept - Air Traffic Control Radar Illuminator

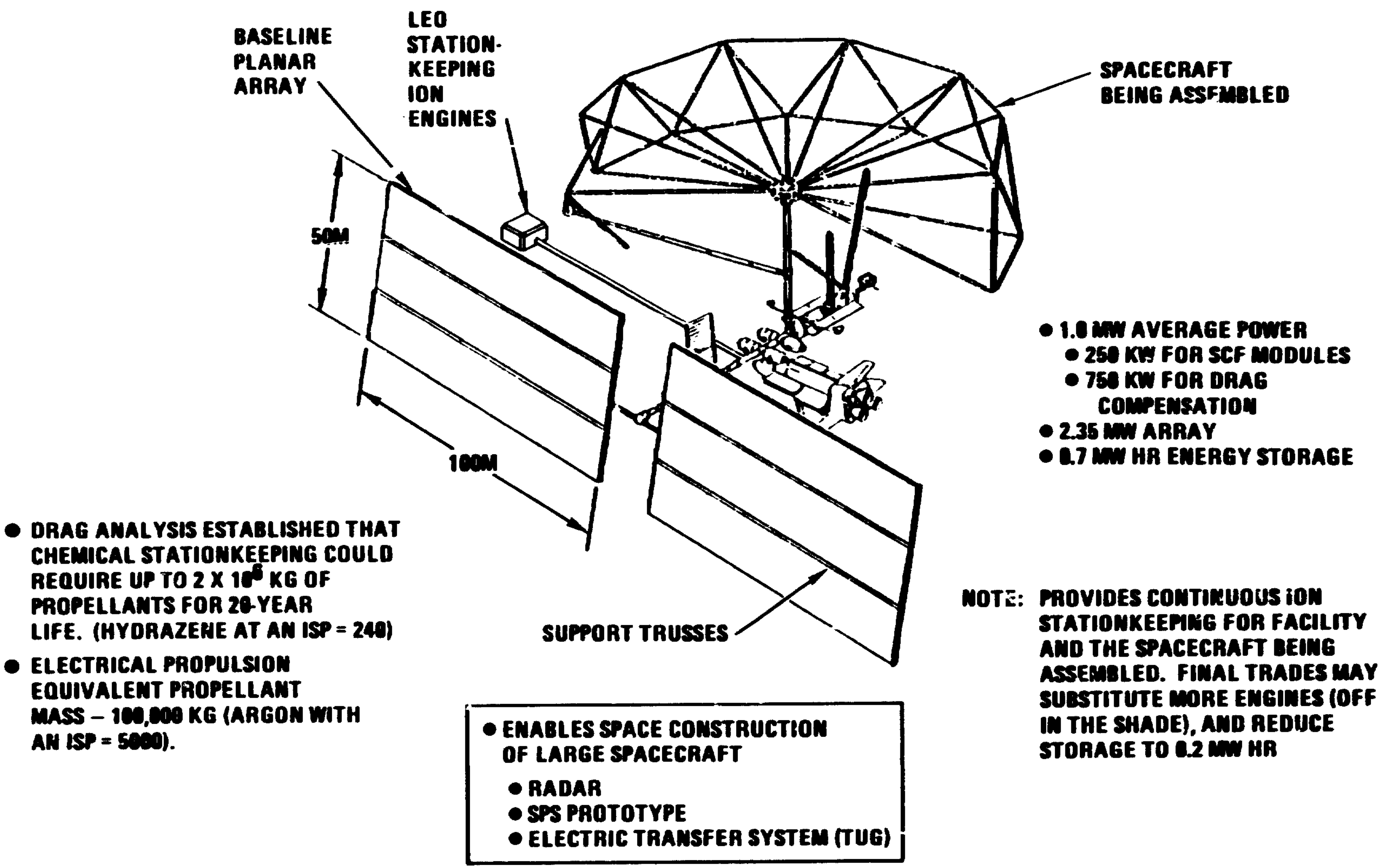

Figure 2-2. LEO Mission Concept - Space Construction Facility

Because of these issues, a space construction facility was selected as the baseline LEO mission. Since the facility would be used to assemble larger spacecarft, such as those eventually to be stationed at GEO, the baseline design includes electrical propulsion ion engines and their propellants, and solar arrays and batteries required for stationkeeping of both the space construction facility and the GEO radar illuminator. Final trades could substitute more engines and array than included in the baseline, these would fire only when the spacecraft is insolated by sunlight, and the energy storage requirement would be decreased accordingly. Nonetheless, some energy storage will certainly be needed to keep processes and activity going during eclipsed periods.

2.1.3 <u>POWER GENERATION OPTIONS CONSIDERED</u>. Planar arrays which are large-scale versions of today's spacecraft photovoltaic systems were considered. Planar cells considered included:

a. Silicon cells (η = 0.16, 50 μm [2 mils] width)

b. Gallium arsenide cells (η = 0.18)

c. Multi-band cells (η = 0.27)

d. Low-cost silicon (η = 0.10)

Concentrators which used mirrors to concentrate sunlight on Gallium Arsenide, multi-band cells, and dual-band cells were also considered. Figure 2-3 indicates some of the concentrator geometries, which range from very large parabolic cylindrical and spherical sections to miniconcentrators whose unit cell dimension is only one to two inches. The very large concentrator configurations also considered a thermophotovoltaic approach and a Rankine turbine hybrid to ensure that possible efficiency improvement approaches were not overlooked.

Figure 2-4 shows the most effective approach developed, which has the following benefits:

a. Good for a wide range of power levels.

b. Cell area and cost reduced by concentration ratios of 30 to 50.

c. Large pointing angle tolerance along pitch axis.

d. Low light loss (no secondary mirror).

e. Thin cross-section enhances Shuttle packaging.

f. Adaptable to two cells (early 1980s IOC available).

g. Compatible with I^2R annealing.

h. Single-array gimbal (one gimbal eliminated).

i. Compatible with both missions.

j. Low aperature for high efficiency.

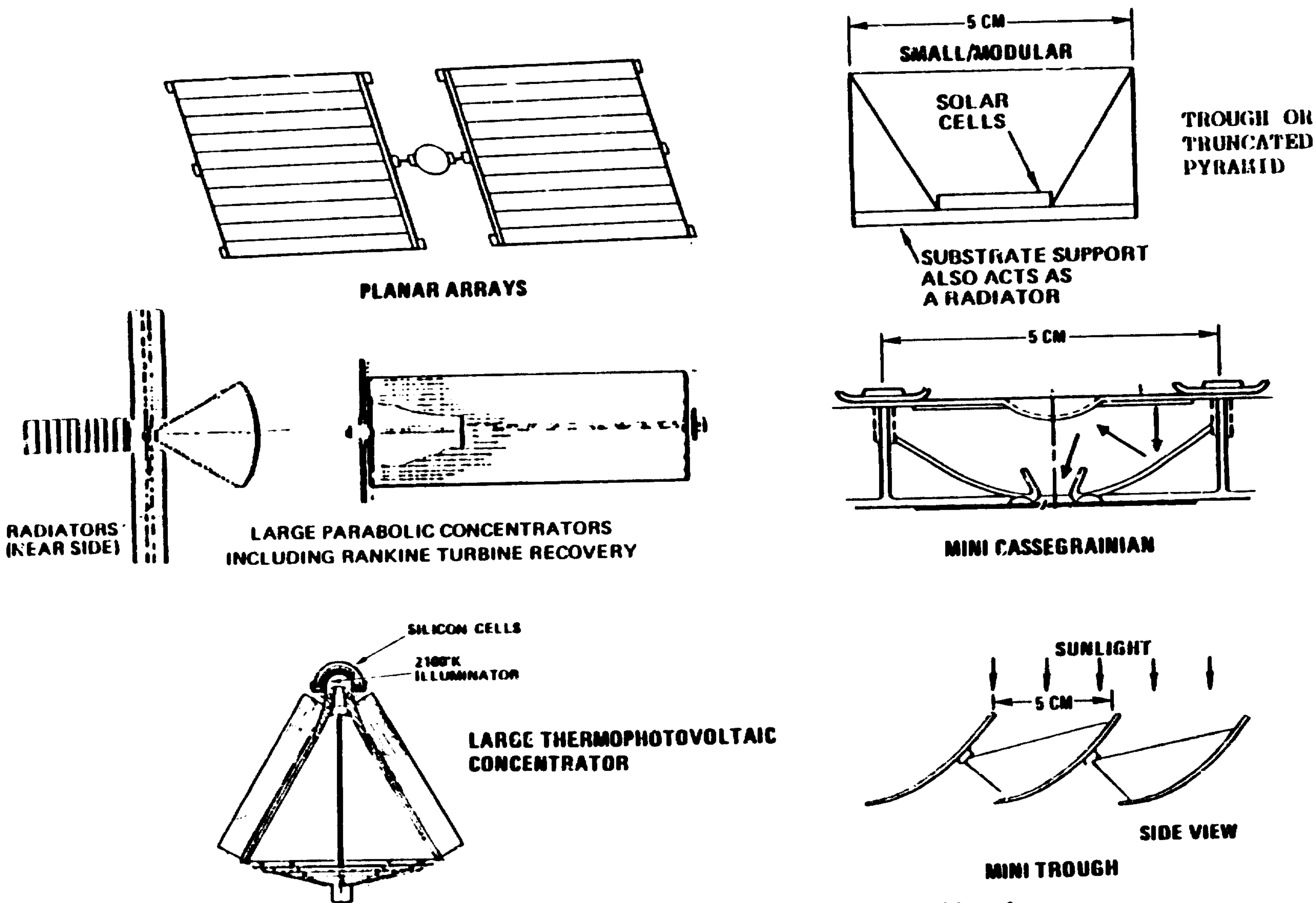

Figure 2-3. Alternate Power Generation Options Considered

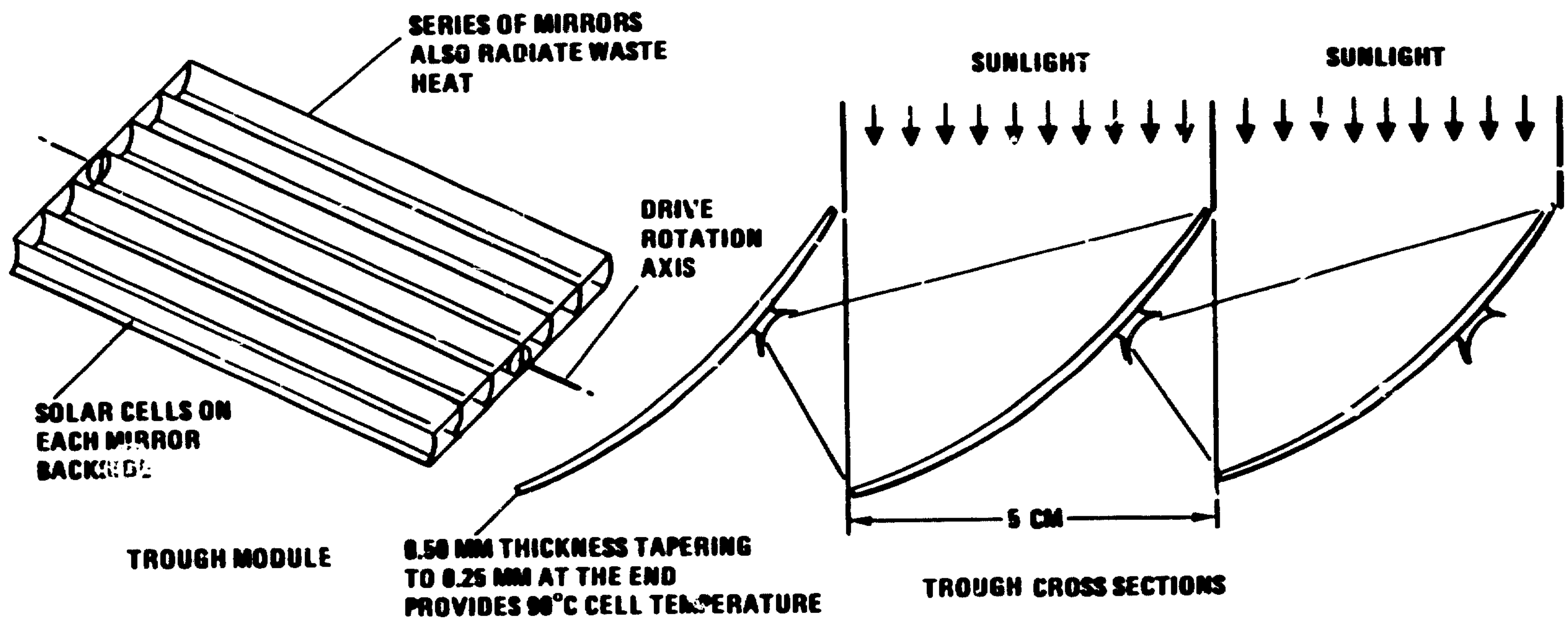

Figure 2-4. A Small, Modular Trough Assembly

Apparent disadvantages are:

a. It is heavier than thin-cell blankets.

b. It imposes an operational requirement of 0 ±1° pointing control about the drive rotation axis.

The apparent disadvantages are not particularly significant since:

a. Lighter weight planar gallium arsenide arrays could only be deployed at much greater expense, the greater weight of the concentrator will not be as significant in the area of the Shuttle, and the reduced area lowers drag.

b. Accurate, smooth, well-controlled pointing of such large structures will be the norm. It would be highly undesirable for large-step motions to be injected into the system.

Of these benefits, most are self-explanatory; however, some additional explanation of the mini-trough large pointing angle tolerance is warranted.

2.1.3.1 Concentrator Pointing Strategies. The geometric design of a concentrating solar array must be compatible with the spacecraft orbital geometry and its overall relationship to the ecliptic plane and the direction of the sun. Since this geometry changes with the seasons, the approach to the overall design should be compatible with this seasonal change. Figure 2-5 shows the relationship of the sun to the earth during winter. For a spacecraft with a rotary solar array joint in GEO or LEO, three options which could accommodate the geometric variations are possible:

a. Option 1 - A single rotary joint can be utilized, with its axis (the spacecraft pitch axis) oriented normal to the plane of the orbit. Then the array counter-rotation compensates for spacecraft rotation and the array remains facing the sun. Depending on the season, it will be from the direction of the sun by an angle of from 0° (during the spring and autumn equinoxes) to up to 23.5° for GEO in July and December when the tilt angle of 23.5° causes the effective insolation incident upon the array plane to be decreased by cos 23.5 (8%). This loss is compensated for by the fact that problems associated with the other two strategies are avoided. The control and coordinate strategy of many three-axis-stabilized satellites launched today (specifically, FLTSATCOM, INTELSAT V, RCA Satcoms, Canadian Technology Satellite, and European OTS) utilizes this single rotary joint approach.

b. Option 2 - The array can be designed with two gimbals and two rotary joints so that, as the seasons change, the second gimbal and joint compensate for the change in tilt angle. This strategy has obvious mass penalties, momentum interaction penalties, and reliability disadvantages (extra rotary joint). Non-trough concentrators having a high concentration ratio require these two gimbals.

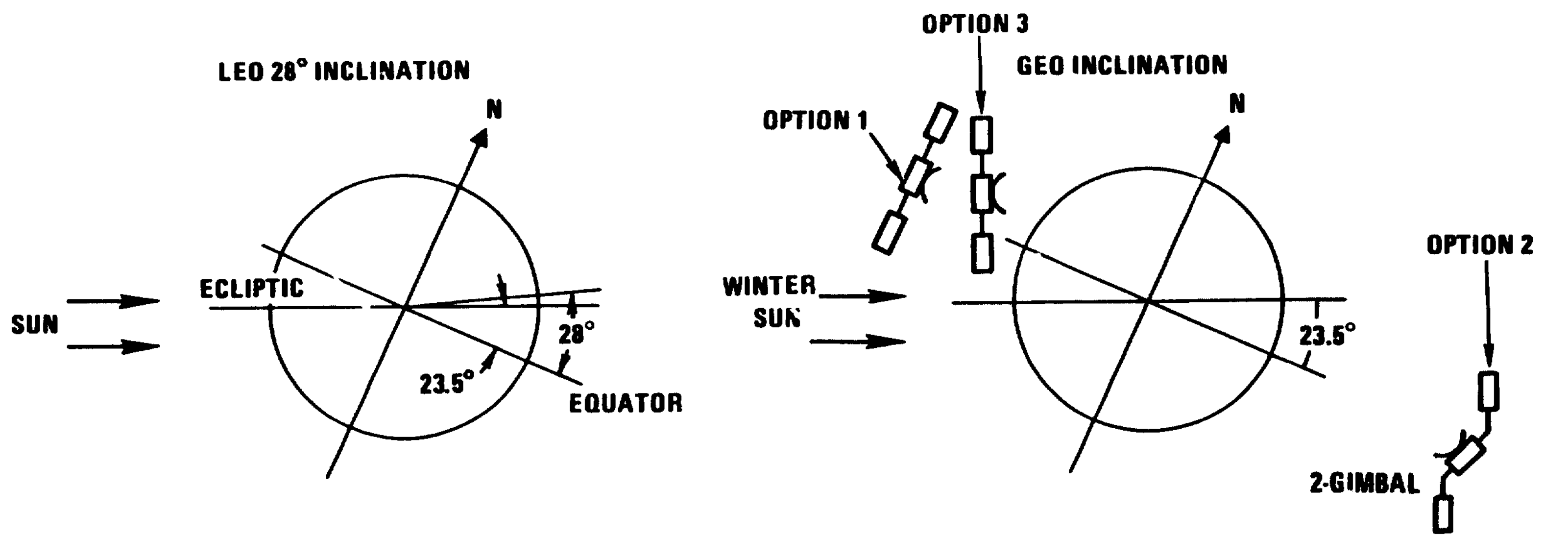

Figure 2-5. Solar Declination Strategies

c. Option 3 - The spacecraft can be positioned so that its single rotary joint axis is aligned normal to the plane of the ecliptic.

There are several penalties associated with Option 3:

a. The daily antenna pointing shift over the orbit.

b. The requirement for extra antenna gimbals and their momentum/angle, interactions/rotary joints, etc.

c. The requirement that the total angular momentum vector must be adjusted so that it is normal to the plane of the orbit, which implies the need for extra momentum storage.

For LEO orbits inclined at 28°, the same alternative strategies can be considered; i.e., one earth-pointing gimbal, two gimbals, and one sun-pointing gimbal (see Figure 2-5).

The two-gimbal systems have the same penalties at LEO that they have at GEO: extra mass and momentum interactions, which are undesirable.

Of the single-gimbal systems, an earth-pointing spacecraft system has advantages, since gravity gradients remain constant, and the system is neutrally stabilized, if the larger masses hang down from the array (toward the earth).

Since an infinite number of 28° inclinations are possible, the 28° inclination closest to the ecliptic should be considered first. This constrains the launch time but does not impact performance. It also suggests that a 4.5° pointing angle (28°-23.5°) tolerance along the array axis is desirable.

Now, consider the mini-trough geometry. If the single rotary joint axis is aligned along the trough axis, as shown in Figure 2-4, and the axis of the rotary joint is aligned normal to the orbital plane, the rotary joint can keep the array properly pointed as the spacecraft orbits, even if the body of the spacecraft points toward earth. The LEO ±4.5° pointing error and GEO ±23° pointing error will cause the light to fall on different cells along the trough, with losses due to edge loss, defocusing, and non-normal (cosine) pointing. Since these should be less than 10%, the mini-trough accommodates these pointing errors with only one gimbal, without the extra mass of two gimbals and without constraining the spacecraft pointing. Both the GEO and LEO systems can work in the same simple fashion utilized by today's spacecraft with single-gimbal axes.

2.1.3.2 Power Generation Conclusions Summarized. Table 2-1 summarizes the projected mass, area, and cost for the Space Construction Facility using the various alternative approaches. Although the concentrator mass is twice the mass of the planar array mass, its cost is still significantly less, because of the reduced cell area required. Even if multi-band gap cells are not developed by the time the facility is deployed, two-band systems can be substituted for

Table 2-1. Cost Comparison LEO Power Generation

2.5 MW SPACE CONSTRUCTION FACILITY

	MASS OF POWER GENERATION SYSTEMS (kg)	AREA (M^2)	CELL AREA (M^2)	COST ($M)	COST TO ORBIT ($M)	COST OF ROUTINE MAINTENANCE	TOTAL COST ($M)
PLANAR ARRAYS							
• SILICON	8,900	15,300	15,300	139	12	$15M IN	168
• GALLIUM ARSENSIDE	9,700	11,950	11,950	215	13	10 YEARS	230
• LC SILICON	39,790	30,600	30,600	194	52	$15M IN	267
• MGB**	15,100	10,300	10,300	295	20	10 YEARS	320
LARGE TROUGH							
MULTIBAND GAP**	55,000	10,000	200	135	85	$10M 5 YEARS	230
RANKINE HYBRID	50,900	8,400	170	100	66	$10M 5 YEARS	196
LARGE SPHERICAL THERMO PHOTOVOLTAIC*	26,900	5,000	500	50	35	$25M 5 YEARS	160
SMALL MODULAR CONCENTRATORS							
TRUNDATED PYRAMID							
TWO CELL	40,700	10,200	2,000	60	52	—	112
MULTIBAND GAP**	34,000	8,600	1,700	44	44	—	88
MINI CASSEGRAIN							
TWO CELL	48,400	13,200	132	42	63	—	105
MULTIBAND GAP**	40,300	11,100	111	32	53	—	85
MINI TROUGH							
TWO CELL	22,100	11,500	230-600	40	29	—	69
MULTIBAND GAP**	18,200	9,300	230	40	24	—	64

*SAFETY PROBLEMS LIQUID COOLING HIGH RISK.

LOWER COST OF CONCENTRATORS WILL INCREASE SPACE ACTIVITY

**HIGH RISK TECHNICAL BREAKTHROUGH REQUIRED.

a small cost increase. Two-band system drag is one-half that of single bandgap planar systems. It should be noted that since cost is the primary driver favoring the mini-trough, development should be started in the early eighties. This would ensure that more costly planar arrays would not continue to be used merely because of the higher risk associated with the concentrator technology development.

Table 2-2 summarizes the mass, area required, and costs of the various approaches for a 10 MW Space Radar Illuminator. The benefits of using a mini-trough for this configuration are more significant, because of the radiation degradation which silicon arrays would suffer if they were used for the electrically-propelled insertion from LEO to GEO.

For all the systems considered, the use of space fabricated trusses to support the solar cells or mirrors reduces system mass approximately 5%, compared to deployable space trusses.

To summarize, technologies which do not appear to be as beneficial for multi-megawatt systems are:

a. Planar Arrays

b. Large Parabolic Concentrators, including hybrids with Rankine turbines

c. Planar Silicon Arrays.

Arrays are the mainstay of today's technology and will be more expensive than concentrators because of their increased cell area and lower efficiency. They are inferior when compared to concentrators for the self-injected GEO spacecraft because of their susceptibility to radiation.

Large parabolic concentrators, including hybrids with Rankine turbine, are ineffective because of the massive radiators required to dispose of the waste heat generated by the cell inefficiencies. These radiator systems are more massive than small modular concentrators, because the radiators require heat carrying fluids, tubes, and heat pipes to distribute the heat out to the fins in the redundant manner required for micrometeoroid survivability.

2.2 OPERATING OPTIONS

2.2.1 PROPULSION FOR INJECTION AND STATIONKEEPING. This study considered both chemical and electrical propulsion (Argon, Isp = 5000) for injecting the radar illuminator from LEO into GEO orbit and for LEO stationkeeping. LEO to GEO injection using chemical propulsion (H_2O_2, Isp = 450) required 300,000 kg additional mass lifted to GEO, 12 extra Shuttle flights, and cost approximately $400M more (1980 dollars). Stationkeeping using ion engines in LEO paid for itself in six months and thereafter was less costly compared to hydrazine, Isp = 235. Therefore, ion propulsion was recommended for both missions.

Table 2-2. A Comparison of Estimates for the Power Generation Options

10 MW SPACE RADAR

	MASS OF POWER GENERATION SYSTEMS (kg)	AREA (m^2)	SOLAR CELL AREA (m^2)	COST ($M)	COST TO LOW EARTH ORBIT ($M)	COST OF ROUTINE MAINTENANCE (RADIATION)	LIFE CYCLE TOTAL ($M)
PLANAR ARRAYS							
GaAlAs	31,100	49,000	49,000	423	40	SMALL	473
SILICON	81,300	104,000	104,000	348	105	$30M EVERY 5 YEARS	453
MULTIBAND GAP**	61,200	36,000	36,200	585	80	SMALL	665
LARGE TROUGH							
MULTIBAND GAP**	220,000	40,500		298	286	SMALL	584
RANKINE HYBRID[1]	DATA NOT GENERATED - ELIMINATED BECAUSE OF LEO SCF CALCULATIONS						
LARGE SPHERICAL THERMO-PHOTOVOLTAIC	109,000	20,000	1,000	200	142	$342 5-10 YRS	684
SMALL MODULAR CONCENTRATORS							
TRUNCATED PYRAMID							
TWO CELL	160,000	40,800	8,200	180	210	SMALL	390
MULTIBAND GAP**	136,000	34,000	6,800	150	172	SMALL	322
MINI CASSEGRAIN							
TWO CELL	192,000	53,000	530	90	250	SMALL	340
MULTIBAND GAP**	160,000	44,500	440	80	210	SMALL	290
MINI TROUGH							
TWO CELL	101,000	51,000	1,020/ 2,400	90	132	SMALL	222
MULTIBAND GAP**	79,500	41,500	830	100	103	SMALL	203

LOWER COST OF CONCENTRATORS INCREASES MISSION CAPTURE PROBABILITY AND SPACE ACTIVITY

**HIGH RISK — REQUIRES TECHNOLOGY BREAKTHROUGH

2.2.2 ENERGY STORAGE. Six energy storage components were considered as possible concepts for meeting the LEO SCF energy storage requirements (see Table 2-3). Batteries with solid anode and cathode plate materials typically have limited cycle lives more suitable to higher orbits, including GEO; in LEO, they must be restocked at varying intervals. Fuel cells are less efficient, requiring more array area and larger radiators for waste heat rejection. Flywheels are efficient and promise very long life; however, their specific energy is limited because the energy stored cannot exceed the elastic limit of the material or catastrophic failure occurs.

One battery technology not limited by solid plate problems is the Sodium Sulfur High Temperature battery, in which the anode and cathode materials (sodium and sulfur) are liquid and separated by Beta Alumina separators. This liquid phase mode of operation, when controlled, should enable significant LEO battery cycle life (see Table 2-4). In studies of No. 5 batteries by Hughes and Ford, "bare" battery specific energies as high as 250 W-Hr/kg have been predicted for designs with 1 mm separators and parallel plate type designs. Allowing for control system mass and some safety factor in the separator thickness, an energy goal of 100 W-Hr/kg was predicted.

To meet the cycle goal, corrosion problems which currently cause increased cell resistance must be solved, this study recommends attacking these problems in parallel to actively pursue increased cycle life along with designing cells to meet the 10-35 kW-Hr power requirements. Table 2-4 shows the projected improvements in life cycle cost.

Table 2-4 also indicates energy storage technologies which were predicted to be less beneficial. These include:

a. Hydrogen-oxygen fuel cells.

b. Current solid plate batteries (NiCd, NiH).

c. Less-developed high energy density systems (ZnBr, LiMS).

Hydrogen-oxygen fuel cells, with electrolysis units for storage have about the highest theoretical specific energy (joules/kg); but, in practice, the system is massive and inefficient. The surrounding hardware, with provisions for electrolysis with phase changes, and survivability of the fluids and gas systems when exposed to micrometeoroids, decreases achievable specific energies to 60 W-Hr/kg, and efficiencies are less than 50% (including the electrolysis). The added solar arrays also have undesirable increased drag and this is reflected in the cost of the fuel cell system.

The current systems (NiCd, NiH) all have shorter cycle life and would require significant on-orbit battery restocking for the LEO mission with its 100,000 cycle-life need.

Table 2-3. Six Energy Storage Technologies Were Considered

TECHNOLOGY	CHARACTERISTICS	REMARKS	RISKS
FLYWHEELS	40 W-HR/kg @ 2:1 SPEED RED. POTENTIALLY UNLIMITED CYCLE LIFE.	SHARED FUNCTIONS: CMG AND LARGE STRUCTURE BENDING MODE DAMPING.	HIGH MOTOR/GENERATOR RUNAWAY AND ROTOR BALANCING AND SPACECRAFT INTEGRATION.
SODIUM-SULFUR	150 W-HR/kg BECAUSE OF LIQUID ELECTROLYTES 6,000-30,000 CYCLES DEPENDS ON DEVELOPMENT ACTIVITY.	CYCLE LIFE LIMITED BY CORROSION. POOR PEAK POWER CAPABILITY.	HIGH CORROSION PROTECTION VALIDATION REQUIRED
NICKEL HYDROGEN	30 W-HR/kg 50 kWh/m^3 30,000 CYCLES @ 50% DOD	SUPERIOR TO NiCd IN SOME APPLICATIONS. EASY TO CONTROL BY PRESSURE SENSING.	MEDIUM HIGH PRESSURE GAS. ANY PUNCTURE/TEAR CAUSES IMMEDIATE CELL FAILURE.
NICKEL CADMIUM (ADVANCED)	20 W-HR/kg 100 kWh/m^3 30,000 CYCLES @ 30% DOD	HIGH CONFIDENCE SYSTEM WITH LITTLE ROOM FOR IMPROVEMENT.	LOW TERRESTRIAL IMPACT OF CADMIUM.
FUEL CELLS (W/ELECTROLYZER)	60 W-HR/kg 50 kWH/m^3 60,000 HOUR LIFE	SEPARATE CHARGE/DISCHARGE SUBSYSTEMS MAY BE AN ADVANTAGE AS MAY BE ALTERNATIVE USE OF WATER, H_2 GAS, AND O_2 GAS.	MEDIUM LOW COST CELLS MAY NOT BE ABLE TO RETAIN HIGH RELIABILITY, EFFICIENCY LIFETIME.
SILVER HYDROGEN	50 W-HR/kg 200 kWH/m^3 6,000 CYCLES @ 40% DOD	GOOD CELL WEIGHT VS. POOR CYCLE LIFE. CALENDAR LIFE 2 YEARS.	MEDIUM

Table 2-4. Life Cycle Cost and Weight are a Strong Function of Achievable Useful Life

OPTION	MAXIMUM USEFUL LIFE	RELATIVE LIFE CYCLE COST*	RELATIVE LIFE CYCLE WEIGHT	REMARKS
FLYWHEELS	20	0.36	0.17	SPACECRAFT DYNAMIC INTERACTION AND VALUE OF ATTITUDE CONTROL SHOULD BE STUDIED
LONG-LIFE NA/S	5	0.48	0.24	NEEDS AGGRESSIVE DEVELOPMENT TO ACHIEVE THIS LIFETIME.
NI-H	7	0.68	0.51	NI-H DURABILITY AND RELIABILITY MUST BE DEMONSTRATED.
NI-CD	5	1.00	1.00	CURRENT BASELINE
H_2/O_2 FUEL CELLS	7	1.04	0.27	LONG-LIFE SPACE QUALIFIED CELLS NEED DEMONSTRATION. INEFFICIENCY A LIMITATION.
CURRENT NA/S	1	1.72	0.99	EMPHASIS HAS BEEN PLACED ON TERRESTRIAL APPLICATION.
AG-H	1	3.2	1.93	SHORT LEO CYCLE LIFETIME IS A SEVERE CONSTRAINT.

*TIME VALUE OF MONEY NOT INCLUDED.
BASED ON 20-YEAR MISSION.

Of the other two high-energy/density systems, ZnBr requires pumps and fluid loops and appears to be less efficient and less capable than the NaS alternative recommended. The LiMS approach does not have active loops but does have probable penalties for lower efficiency. Both of these systems have a solid-plate electrode, which is perhaps more vulnerable to life-cycle degradation than the liquid NaS system.

2.2.3 10-MEGAWATT RADAR POWER MANAGEMENT AND DISTRIBUTION SYSTEM SYNTHESIS. The 10-megawatt radar system required power supplies, power conditioning for the ion engines, and power conditioning on the radar phased array to convert the high voltage from the photovoltaic system to the low voltages required by the radar transmitter modules. Three alternate configurations were considered for the system (Table 2-5). They were:

a. An all-dc system with power for the ion engine beam voltage and discharge currents provided by dc-to-dc converters, and with power for the radar modules provided by a separate set of dc-to-dc converters.

b. A split-inverter ac system, with one set of dc/ac drivers which delivers ac to the radar at low voltages, and with another set of ac/dc converters for the ion engine supplies.

c. A hybrid approach (Figure 2-6) which uses dc/dc on-array regulation for ion engine beam power, and a single, time-shared dc/ac resonant converter to drive either the ion engine discharge ac/dc low voltage supplies or the ac/dc radar module low voltage supplies, depending on the mission phase. The system, thus, saves significant amounts of converter mass.

The results of this analysis activity were that the approach with 900-Vdc beam power supplied with on-array regulation appears to be more attractive than the others, from a mass and cost standpoint.

Table 2-6 summarizes the analytical results and the effect of four other alternative topologies on system mass.

a. Alternative 1 uses ac distribution on the array and requires 7.2 MW of extra converter hardware to provide regulation beam voltage and power (an extra mass of 14,500 kg for the radar, 2600 kg for the SCF).

b. Alternative 2 uses 900-Vdc distribution and dc-dc converters for the radar and discharge supplies. For the radar, it is more massive because of the extra dc-ac converter on the array.

c. Alternative 3 is the all-dc system without on-array regulation. The extra mass of beam converters is required.

d. Alternative 4 is a larger power converter module for the 10 MW radar. Mass saving is not significant.

Table 2-5. Power Conversion Options Considered

APPROACH	RADAR MISSION CONVERTERS	SCF MISSION CONVERTERS
ALL AC	ON ARRAY DC/AC CONVERTERS ON ARRAY ION ENGINE AC/DC CONVERTERS (BEAM & DISCHARGE) AC/DC CONVERTERS (RADAR)	ON ARRAY DC/AC CONVERTERS ION ENGINE AND USER AC/DC CONVERTERS
ALL DC	ION ENGINE DC/DC CONVERTERS RADAR DC/DC CONVERTERS	DC/DC CONVERTERS AT USERS
HYBRID	DIRECT BEAM SUPPLY (900 VDC) AC APPROACH FOR THE REST OF THE SYSTEM	DIRECT BEAM SUPPLY (900 VDC) AC APPROACH FOR THE TEST OF THE SYSTEM

HYBRID SYSTEM (900 VDC) REQUIRES

- ACCEPTABLE ARRAY ARCING PROBABILITY
- ACCEPTABILITY OF SYSTEM SAFETY

It should be emphasized that the safety issue associated with 900-Vdc power distribution and array voltages must be resolved satisfactorily, and that the ion engines themselves must be able to accept delta regulation of the beam voltage (switched banks of solar cells) with a step-size of approximately 10-20 volts or with a small linear delta regulator which regulates the final voltage within a small range. Also, plasma losses must be acceptable, which requires their more exact modeling.

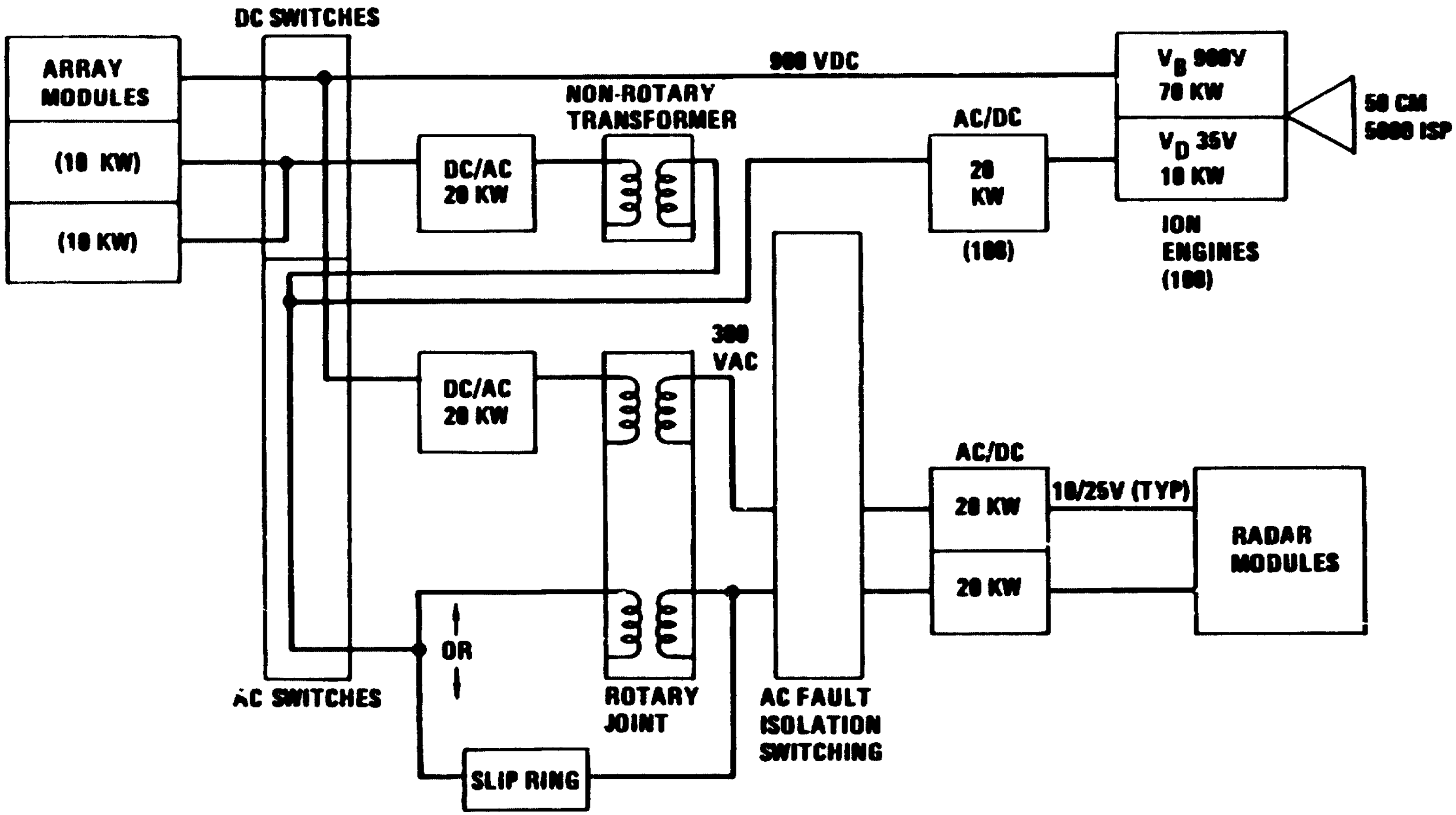

Figure 2-6. Hybrid Power Management and Control Block Diagram - GEO Radar System

Table 2-6. AC versus DC Comparison

TOPOLOGY	LEO SPACE CONSTRUCTION FACILITY	GEO 10 MW SPACE RADAR
HYBRID AC-DC		
SPLIT INVERTER MASS*	1770 Kg	43,200 Kg
NO. OF MODULES/SUBWINGS	10 + 1 SPARE	27 + 2 SPARES
NO. OF SUBWINGS/WING	1	9
NO. OF WINGS	2	2
P.M. MODULE SIZE(S)	20 KW	20 KW
ARRAY MODULE SIZE	10 KW	10 KW
MASS OF TRANSMISSION LINES	60 Kg	2040
ARRAY MASS FOR LINE LOSSES	30	2410
TOTAL MASS	1860 Kg	47,650 Kg

OTHER ALTERNATIVES	IMPACT ON SYSTEM MASS	IMPACT ON SYSTEM MASS
1. ALL AC (900 VAC) WITH ION BEAM CONVERTERS	+ Δ 2600	+ Δ 14,500 Kg
2. ALL DC (900 VDC) WITH DISCHARGE CONVERTERS ONLY	SMALL DELTA	+ Δ 4,100 Kg
3. ALL DC WITH BEAM CONVERTERS	+ Δ 2600	+ Δ 29,000 Kg
4. WITH 250 KW MODULE SIZE AND MULTIPLE LOADS	NOT APPLICABLE	- Δ 500 Kg

*SPLIT INVERTER MASS INCLUDES ARRAY MASS FOR INVERTER LOSSES AND ARRAY SWITCHING.

SECTION 3

CONCLUSIONS, GOALS, AND PLANS

This study looked at the technology needs for the 1990s which might require multi-megawatt power levels.

3.1 MISSION SELECTION

Two missions were selected for study: a GEO air traffic control radar illuminator, and a LEO space construction facility. The GEO radar appears to be beneficial because of its ability to provide a terminal region redundancy at low cost. One system with a moderate amount of additional capacity can back up the entire CONUS and, with two satellites, the entire United States is redundantly covered using the minimum number of orbit slots. The LEO space construction facility provides a base for assembly and test of the two radar satellites, as well as the potential for assembling an electrical orbital transfer vehicle. For both missions, argon ion engines were found to have significant benefits for stationkeeping (LEO) and orbital injection (LEO to GEO).

3.2 PHOTOVOLTAIC CONCENTRATORS

The study also developed beneficial approaches for concentrating photovoltaic systems. The concentrating photovoltaic system, using small, backlit semi-parabolic troughs, has low light loss and supports the GEO and LEO missions with only one gimbal per array wing. It is tolerant of array pointing errors up to 25° about the yaw axis. Pitch error tolerance is 1°, an error tolerance easily achieved by today's GEO spacecraft.

3.3 GaAlAs PLANAR ARRAYS

Though GaAlAs planar arrays are projected to cost more than the modular concentrator, their low mass makes them attractive for missions such as the electrical orbital transfer vehicle (TUG).

3.4 DEVELOPMENT PLANS

Plans were made for development of power generation, energy storage, and power management. Considerably more detail on these recommendations is provided in Volume II of this report.

3.4.1 POWER GENERATION. To implement the power generation recommendations, technology development plans are required in six areas:

a. Early two-cell concentrator development

b. Multiband gap cell process development

c. Prototype trough module development

d. Environmental tests of mirrors/cells

e. I^2R annealing tests

f. Structure/fabrication system development.

3.4.2 ENERGY STORAGE. Energy storage technology development recommendations are corrosion-resistant sodium-sulfur batteries and flywheel backup systems.

3.4.3 POWER MANAGEMENT. Four power management technology development recommendations emerged from the study.

a. Power Management Topology: The development of power management topology to accommodate the ion engines by time-sharing portions of the power conversion equipment which can be shared, thus minimizing mass. Ion engine on-array dc control with discrete delta voltage regulation saves significant converter mass.

b. AC and DC rotary joint power transfer: The need for a maintainable, low friction, high efficiency, and space-survivable approach for ac and dc rotary joint power transfer.

c. AC and DC power distribution switching: The need for the development of fault-isolating, fault-tolerant, efficient switching for ac and dc power distribution systems. The ac problem is more amenable to solution, because ac current is automatically zero at the crossover point each half-cycle; therefore, the probability of a thermal runaway in a half-cycle at 20 kHz is small if efficient thyristors are used as the control device. DC distribution will require fast-actuating electromechanical devices sized to accommodate maximum short-circuit currents during their activation interval.

d. High power dc transistors: The development of high power dc transistors will be necessary if ac development is not accomplished and a dc system is required.

3.5 RECOMMENDATIONS

This study found three developments which are very significant, because each can be considered for utilization at power levels below 1 MW. In fact, they appear to offer significant benefits at power levels significantly below the scope of the study, down to the 35 kW range.

a. The semiparabolic mini-trough can be modularized below the 1 kW level, and the modularity should produce cost reduction, array aperture reduction, and mass savings at this level, too. Specific power will decrease slightly because of on-orbit deployment, but should still be higher than most other arrays.

b. Sodium sulfur batteries should at least double the specific energy of other cells now available, at least for loads without significant peaks.

c. AC power management should be versatile and enable arcless magnetically coupled power transfer across interfaces.