N87-26426

THE AIR FORCE CONCENTRATING PHOTOVOLTAIC ARRAY PROGRAM

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The history of the Air Force solar concentrator project goes back to FY77 when an initial concentrator study program was conducted with Rockwell International Space Systems. The conclusions drawn from the study were that solar concentrator arrays have the potential to survive severe nuclear, particulate, and laser radiation environments which no planar solar array of comparable weight could tolerate. Concentrator arrays also offer the advantage over planar arrays of higher power per unit area than conventional planar array designs because the higher photovoltaic efficiency of the concentrator cells more than offsets the optical loss of the concentrator system.

Cell costs can be reduced significantly compared to costs for planar cells because a concentrator designed at a given Concentration Ratio (CR) will require approximately 1/CR the area of solar cells to produce the same electrical power output. Because concentrator cells operate at higher efficiency and degrade less in hazardous nuclear environments (concentrator shielding protects cells), the required End-Of-Life (EOL) array size can be 30-60% smaller than that required by planar solar cell arrays.

Satellite vehicles requiring high efficiency, low life cycle cost and maximum W/m^2 capability, and which must operate in high intensity natural radiation belts, could profitably use concentrator array systems. The high performance, high radiation resistance, but high cost gallium arsenide solar cell will find a natural application in the concentrating photovoltaic array where the cost of the solar cells themselves becomes secondary to other system costs.

AFWAL/ML funded TRW systems on the Satellite Materials Hardening Programs (SMATH). Although the major effort under SMATH IV in the power hardening area was to explore and develop techniques for hardening planar solar cell array power systems to the combined nuclear and laser radiation threat environments, a portion of the program dollars was devoted to developing a preliminary design for a hardened solar concentrator. The TRW design that was selected was a Cassagrainian configuration that utilized a narrow light acceptance angle to advantage for front side laser protection, and a deployable metal foil shutter for backside protection. The AFWAL/APL (Aero Propulsion Laboratory), as a result of the SMATH program, initiated several efforts to design, fabricate, and test concentrating photovoltaic devices which are survivable to hazardous nuclear and radiation environments. The first contract was awarded to TRW Systems, Inc., "Multi-Threat Hardened Concentrating Development" (F33615-81C-2055). The Laboratory has also sponsored concentrator feasibility and development work with General Dynamics Corporation on contract F33615-83C-2319, "SLATS Concentrator Development Program," and on contract F33615-84C-2420, "SLATS PHASE II."

More recently efforts have been directed toward transitioning the exploratory development efforts to advanced development through the initiation of the "Survivable Concentrating Photovoltaic Array" (SCOPA) program. This program, which is expected to begin in FY87, will result in the design, fabrication, test, flight qualification, and subsequent flying of a 500 watt concentrator panel in a low-altitude orbit. This paper discusses the general program objectives and overall performance goals of the program.

THE SURVIVABLE CONCENTRATING PHOTOVOLTAIC ARRAY (SCOPA) PROGRAM

Concentrator development has progressed substantially under the above mentioned contracts with TRW systems and the general Dynamics Corporation. Estimated performance capabilities for low to moderately hardened configurations are shown in Table I (General Dynamics Corporation briefing to AFWAL/POOC April, 1984). Subsequent designs to meet increasingly higher laser irradiation threats will reduce concentrator specific power and weight values due to higher mass density optical and thermal radiator components, and higher temperatures for the concentrator cells. It should also be noted here that post-laser irradiation performance levels of planar arrays under low to moderate laser irradiation levels may decrease drastically, or the array may fail catastrophically, compared to concentrators. The objectives of the two Air Force sponsored programs were to develop designs that are survivable to high level laser weapon, nuclear weapon, and background particulate irradiations, while maintaining reasonable electrical performance.

Air Force plans for FY87 and beyond are to initiate a five-year, multi-million dollar program to transition hardened concentrator elemental and modular technology from exploratory development to advanced development, and subsequent flight test of a hardened 500W concentrator panel. The program is divided into four phases: Phase I - Critical Hardened Component Development and Preliminary Panel Design; Phase IIA - Design, Fabrication, and Flight Qualification of Hardened Concentrator Panel; Phase IIB - Hardened Flight Panel Acceptance Testing and Spacecraft Integration; and Phase IIC - Flight Support of Hardened Concentrator Panel.

PHASE I - CRITICAL HARDENED COMPONENT DEVELOPMENT AND PRELIMINARY PANEL DESIGN

The intent is to award dual contracts for this 1 1/2 - 2 year effort. SCOPA performance and survivability objectives have been discussed through numerous meetings with various Satellite Program Offices (SPO's). As a result of these meetings, there has arisen a general understanding of the need for near-term development of space power systems that will be survivable to natural threats that may exist in space in the 1990's and beyond. SCOPA can meet these threats, and has been defined as a enabling space power technology.

Stringent and demanding threat requirements support the development of two competing concepts for Phase I to maximize the probability of program success. Concepts proposed for SCOPA by the various bidders on this multi-source procurement vary greatly in design, and each has its own strengths and weaknesses.

The major objectives of Phase I will be to establish confidence in concentrator designs and fabrication/manufacturing processes necessary to meet the program performance and survivability requirements and goals. Concentrator elements and modules will be subjected to vacuum chamber irradiation exposures from continuous wave and pulsed wave laser sources that simulate irradiation intensities and exposure times of ground-based and space-based lasers. Modules will also be subjected to thermal cycling, proton, electron, and space plasma environments such as might be encountered in Mid-Earth-Orbit (MEO) and Low-Earth-Orbit (LEO). A 500 W panel preliminary design will be accomplished near the end of Phase I. At the end of Phase I the best concentrator concept will be carried into Phase II A.

PHASE IIA - DESIGN, FABRICATION, AND FLIGHT QUALIFICATION OF HARDENED CONCENTRATOR PANEL

Under Phase IIA the contractor will fabricate at least one hardened 500 W panel, based on the test results and preliminary design work of Phase I. The panel will represent structurally and thermally the characteristics of a multi-kilowatt concentrator array. The contractor will conduct ground-based qualification of the 500 W panel. Qualification test guidelines will be based on a possible future space shuttle launch with subsequent deployment in a LEO orbit for a one-year (nominal) operation. Tests will include but not be limited to thermal, vibration, deployment and dynamic/static loading, and electrical performance verification tests.

PHASE IIB - HARDENED FLIGHT PANEL ACCEPTANCE TESTING AND SPACECRAFT INTEGRATION

Under Phase IIB, the contractor will refurbish the hardened concentrator panel developed and tested under Phase IIA, or build another unit and perform flight acceptance tests in accordance with acceptance test guidelines.

PHASE IIC - FLIGHT SUPPORT OF HARDENED CONCENTRATOR PANEL

The final phase of the program will be involved with providing the necessary supporting personnel for experiment data collection, reduction, and analysis resulting from a low-altitude "proof-of-concept" flight experiment. The experiment will be designed to determine the operational envelope of hardened concentrating photovoltaic arrays operating in space. Table II lists the Survivable Concentrating Photovoltaic Array Performance Verification Flight Experiment (AFWAL - 501) characteristics, (AFWAL/POOC briefing to Space Test Program Tri-Service panel, June, 1986).

HARDENED CONCENTRATOR DESIGN

REQUIREMENTS AND GOALS

The achievement of the concentrator design requirements and goals will permit the development of high performance, survivable, multi-kilowatt concentrator arrays for operation in hazardous natural and artificial space environments. In addition, the achievement of these requirements and goals will demonstrate significant survivability and performance improvements compared to conventionally hardened planar solar arrays, and will satisfy the requirements of several Air Force satellite systems.

In addition to continuous and pulsed wave laser, nuclear, and pellet threat hardening requirements and goals, the concentrator must be survivable to natural background radiation and space plasma environments as shown in Table III (AFWAL/POOC SCOPA Requirements and Goals, 1986).

SCOPA requires that a concentrator system be capable of surviving, with no more than 20% electrical power degradation, one exposure from each of the background radiations described in Table III. The tests represent five-year fluences in a 5600 NMI orbit at 60% inclination. The test exposures are not to be cumulative.

The hardened arrays are to be designed for Beginning-Of-Life (BOL) performance goals of 15W/kg (including pointing and tracking mechanism), and 120W/m². Although the performance design goals are very conservative, the laser and nuclear requirements and goals are not! The severe threat conditions imposed on the design result in a relatively heavy system, but the hardened design requirements and goals, if achieved, will permit the future development of multi-kilowatt concentrating photovoltaic arrays that will be survivable to artificial threat environments projected for the 1990's and beyond, and to natural threat environments that may be encountered in MEO missions and which cannot be accomplished with planar solar cell arrays. Projections of performance improvements possible with concentrator systems, when compared to planar array systems, are shown in Figure 1 and Figure 2 (Reference 1).

CONCLUDING REMARKS

The SCOPA program is very ambitious, especially from a survivability standpoint. However, a successful program will enable the Air Force to provide a survivable space power system that will have the capability of performing a variety of missions in hazardous environments, including those missions previously thought incapable of being accomplished by photovoltaic arrays (e.g., 5600 NMI missions). In addition, the concentrator will be capable of being designed as a lightweight system (50-100W/kg) through the use of thinner, low mass density materials and configurations, and may find applications in such missions as high power, lightweight electric propulsion orbital transfer where weight is a critical factor.

REFERENCES

1. Spacecraft Subsystem Survivability, R. M. Kurland, J. S. Archer, W. R. Hardgrove, TRW Systems, Inc., 30 March 1986.

TABLE I - EFFECT OF IMPROVED EFFICIENCY ON OVERALL CONCENTRATOR PERFORMANCE

Parameter	Planar *	Cassegrainian	SLATS	SLATS W/DUAL-BANDGAP
Optical Efficiency	.98%	.80%	.92%	.92%
Cell Efficiency	.10% @ 65°C	.20% @ 85°C	.18% @ 85°C	.25% @ 85°C
Packing Factor	.86	.85	.95	.9
Radiation Deg (5 yr, 600 NMi, 60°)	.76	.92	.92	.86
Net Array EOL Effic.	6.4%	12.5%	14.5%	17.8%
Specific Power	87 W/m²	169 W/m²	196 W/m²	240 W/m²
Specific Weight	18.8 W/kg	24.8 W/kg	48.8 W/kg	59.9 W/kg

* INSAT ARRAY

Note: Data presented are for 1984 concentrator designs, based on survivability background radiation environment, and moderate laser irradiation threat environment only.

TABLE II - SURVIVABLE CONCENTRATING PHOTOVOLTAIC ARRAY PERFORMANCE VERIFICATION FLIGHT EXPERIMENT (AFWAL-501) CHARACTERISTICS

- Experiment only, free flyer out-of-space shuttle bay, or on another spacecraft, up to 12 month in LEO
- 3-axis spacecraft stabiliation to within ±1°
- -20°C to +125°C, nominal thermal environment
- 500 W panel, 35 kg nominal, 454 X 92 cm
- Panel pointing and tracking (± 1½°)
- Temperature, current/voltage measurements
- Sun sensor
- Mirror/cell degradation sensor

TABLE III
GEOMAGNETICALLY TRAPPED PROTONS AND ELECTRONS
(OMNIDIRECTIONAL FLUENCES), AND
SPACE CHARGE/SPACE PLASMA EFFECTS CONDITIONS

- o 1 Mev, 1 X 10^{15} protons/cm^2
- o 5 Mev, 8.6 X 10^{12} protons/cm^2
- o 10 Mev, 5 X 10^{11} protons/cm^2
- o These tests represent 5-year fluences in a 5600 NMi orbit at 60° inclination

(a) PROTON TEST CONDITIONS

- o 1 Mev, 7.5 X 10^{13} electrons/cm^2
- o 3 Mev, 7.5 X 10^{12} electrons/cm^2
- o 5 Mev, 7.4 X 10^{11} electrons/cm^2
- o These tests represent 5-year fluences in a 5600 NMi orbit at 60° inclination

(b) ELECTRON TEST CONDITIONS

- o 10^3 - 10^6 electrons, and nitrogen (or argon) ions per cm^3
- o 0.1 - 1.0 volt, individual particle energies
- o Test to be performed in 10^{-7} torn, with test article biased + 500V relative to tank

(c) SPACE CHARGE/SPACE PLASMA EFFECTS TEST CONDITIONS

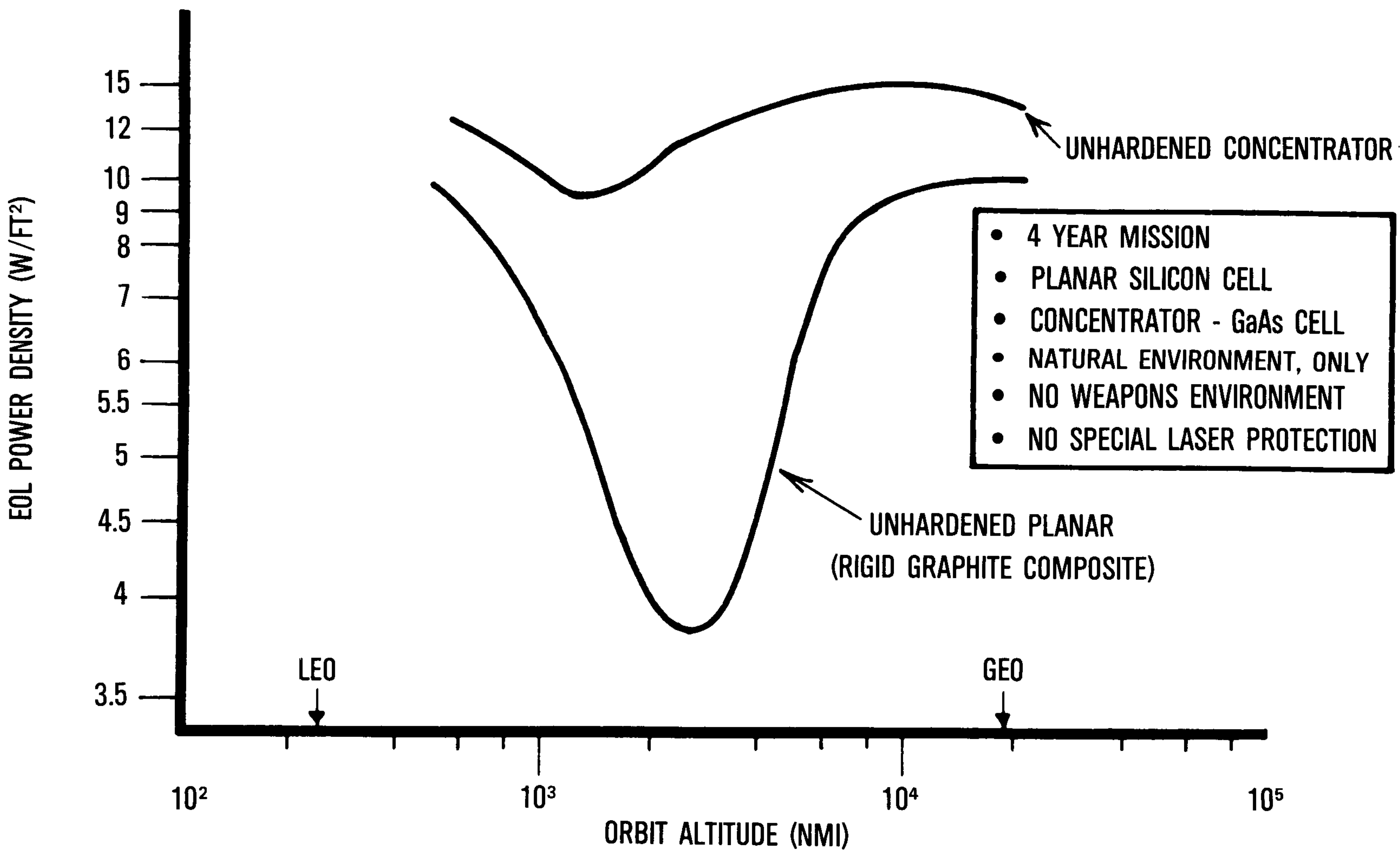

FIGURE 1. EOL PLANAR AND CONCENTRATOR PERFORMANCE

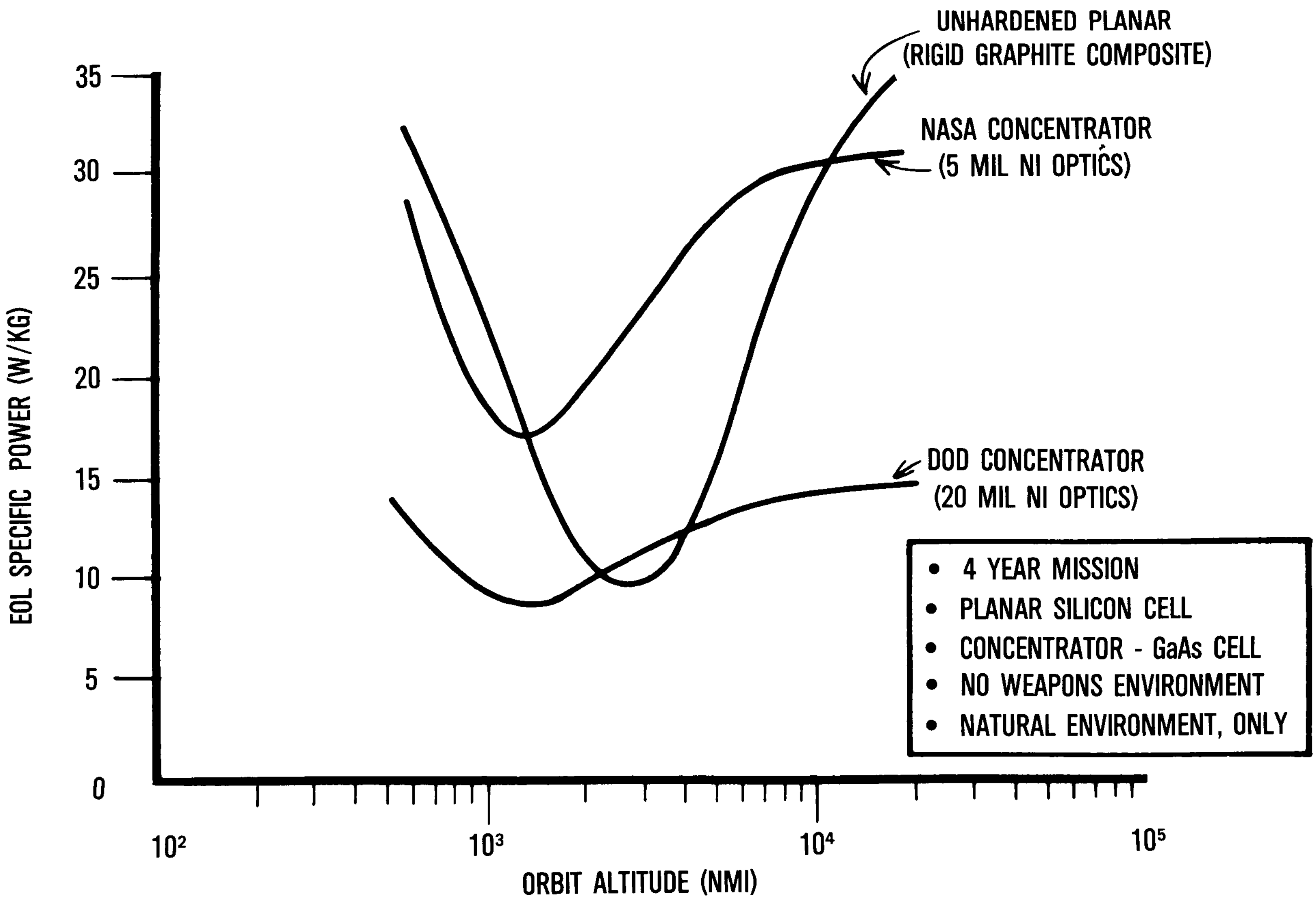

FIGURE 2. EOL PLANAR AND CONCENTRATOR PERFORMANCE