DESIGN REQUIREMENTS FOR HIGH-EFFICIENCY HIGH CONCENTRATION RATIO SPACE SOLAR CELLS

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SUMMARY

A miniaturized Cassegrainian concentrator system concept has been developed for low cost, multi-kilowatt space solar arrays. The system imposes some requirements on solar cells which are new and different from those imposed for conventional applications. The solar cells require a circular active area of approximately 4 mm in diameter. High reliability contacts are required on both front and back surfaces. The back area must be metallurgically bonded to a heat sink. The cell should be designed to achieve the highest practical efficiency at 100 AMO suns and at 80°C. The cell design must minimize losses due to non-uniform illumination intensity and non-normal light incidence. The primary radiation concern is the omnidirectional proton environment.

INTRODUCTION

Recently, a practical, low cost sunlight concentrator system concept for space applications has been developed (reference 1). Multi-kilowatt solar arrays can be assembled using miniaturized Cassegrainian type optical concentrator elements that are assembled into matrices of parallel and series connected solar cells, modules, panels, and array blankets. Predicted solar cell operating temperature in earth orbit in the order of 80°C for solar illumination levels of 100 air mass-zero suns makes silicon an acceptable solar cell material; however, significant system efficiency improvements and cost reductions are projected for use of higher efficiency cells such as gallium arsenide and multiple-bandgap cells. This concentrator system imposes some requirements on the cells whether silicon or gallium arsenide, that are new and different from those that are typically imposed on non-concentrator solar cells for space arrays.

This paper defines those solar cell parameters that play important roles in the over-all array system efficiency and reliability which cannot be optimized by the array manufacturer, but rather must be addressed by solar cell designers and manufacturers.

CONCENTRATOR SYSTEM DESCRIPTION

The miniaturized Cassegrainian concentrator concept is illustrated in figure 1. The primary parabolic reflector concentrates the incident sunlight onto a secondary hyperbolic reflector which in turn directs the sunlight to the solar cell. Under off-pointing conditions, the concentrated sunlight also reflects from the surfaces of a tertiary, conical reflector.

The solar cell back side is metallurgically bonded to a heat sink similar to the bonding of a power transistor to its heat sink. Analysis indicates that for this type of bonding the cell to heat sink temperature gradient is negligibly small for concentration ratios up to and beyond 1000. The heat sink which serves as part of the electrical circuit, is mechanically stiffer and stronger than the solar cell and will transmit during orbital thermal cycling thermomechanical stresses into the cell.

The interconnector/solar cell joints are made by parallel-gap welding or ultrasonic joining, depending upon the cell's sensitivity to welding. The cell front contact interconnector attachment pad will be larger in area than the solar cell, resulting in an overall size of about 6 by 6 mm. The concentrated sunlight will reach the solar cell through a 4 mm diameter hole in the pad.

A multiplicity of the elements depicted in figure 1 are assembled into modules, several modules into panels, and several panels into array "blankets". A panel would typically be 2 x 4 m in size and approximately 12 mm (0.5 inch) thick. On each panel, a number of solar cells are electrically connected in parallel and series in conventional fashion. The selected theoretical geometric concentration ratio of 150 is reduced by reflection losses, light spillage, and light blockage to a net ratio of approximately 100. The concentrator element packing factor at the panel level is 0.90.

SOLAR CELL ARRAY SYSTEM LEVEL REQUIREMENTS

From a system point of view, the key solar array design driver for solar cell arrays of multi-hundred kilowatt ratings in near-earth orbits is cost. The total cost of electrical power (kW) at any given time in orbit, as well as the cost of energy (kWh) throughout the useful mission life span, is composed of several cost elements that relate to various aspects of the array design as shown in table 1. The overall life cycle cost scenario for a space solar array system parallels that of a typical terrestrial system (not restricted to a photovoltaic power system): over a long period of service life, the accumulated maintenance and repair costs become substantial relative to the initial acquisition cost, and as the wear-out life is approached, periodic maintenance and repair costs increase to a level where it becomes more cost effective to replace the system.

For the space solar array discussed in this paper, a recurring cost goal of $30/W in 1979 dollars has been established. This cost includes all materials and labor up to the array blanket level, but excludes bench quality assurance, integration and test, and main structural support, orientation, power transfer, and other components. The $30/W goal is expected to be achievable by the mid 1980s with a Cassegrainian type concentrator concept and, if achieved, would reduce the equivalent cost for present planar space arrays by approximately one order of magnitude. The projected cost breakdown for the Cassegrainian concentrator array is shown in table 2. The solar cell unit cost will be approximately proportional to the amount of semiconductor material used as shown in figure 2 and, hence, will decrease by approximately the same factor as the sunlight concentration ratio increases. The amount of material used for concentrator optical elements is, to a first order approximation, nearly independent of the concentration ratio. However, increasing manufacturing complexity and precision required at higher concentration ratios is expected to drive the cost for the optical elements upward. Summing the theoretical solar cell and optical element cost curves results in a cost minimum near concentration ratios between 50 and 200. For this reason, a concentration ratio of 100 to 150 was chosen for more detailed study.

CONCENTRATOR SOLAR CELL DESIGN REQUIREMENTS

The key requirements according to which a concentrator solar cell for the miniaturized Cassegrainian concentrator concept for space applications should be designed and optimized are summarized in figure 3. These requirements are discussed below in detail.

Solar Cell Size

The required solar cells are relatively small in size, approximately 5 x 5 mm over-all with a 4 mm diameter active area. The exact over-all size must be determined based on a trade-off between heat transfer from the cell to the heat sink, cell cost variation with size, thermomechanical stress considerations, required contact area and ease of assembly. The cells could be round; however, square or rectangular cells of this small size may be easier to manufacture.

Solar Cell Contacts

The contact metallization system must be chosen to assure high mechanical strength, long thermal cycling fatigue capability, metallurgical stability throughout the terrestrial as well as the space operational periods of the total life span.

The current densities in the contacts of concentrator cells will be high. As an example, at 20% in-orbit conversion efficiency and 100-sun input, a typical solar cell output would be about 0.7A at 0.5V. If all of this current were to be extracted from the 4 mm circular opening in the front contact through a 2.5 μm (0.1 mil) thick metal layer, the current density would be about $2000 A/cm^2$. While such current density is not expected to cause ion migration, it certainly could cause excessive series resistance losses.

The most convenient cell contact configuration is the conventional front/back contact. This configuration permits the entire back contact area to be metallurgically bonded to the heat sink, assuring the lowest possible electrical and thermal impendances between the solar cell and the heat sink. As an alternate to a back surface reflector, the back contact may have a circular opening of about 4.5 mm diameter to permit photovoltically unusuable infrared radiation to exit from the cells and reach space through a corresponding opening in the heat sink.

The front contact preferably covers the entire semiconductor front area, except for a central, circular, 4 mm diameter opening that permits the concentrated sunlight to reach the cell's active area. Even though the front contact covers the entire cell area to obtain high mechanical load carrying capability and low electrical resistance, it is desirable to minimize the shadowing of active cell area by the front contact.

The light catcher cone should preferably be metallurgically joined to the solar cell front side to maximize heat transfer from the cone to the heat sink and to eliminate light losses that would occur in the gap between the cell surface and the lower truncated cone edge of a light catcher cone not mounted to the cell front surface. If the cone could not be joined directly to the front cell contact, it would have to be joined to a flat interconnector which in turn would be joined to the front cell contact.

Electrical Requirements

The concentrator solar cell should be designed for the highest practically achievable cell efficiency at 100 AMO suns and at 80°C cell temperature. A minimum cell efficiency of 20% for silicon cells and 30% for GaAs and tandem-junction cells is required at 28°C and 100 AMO suns. The AMO (airmass zero) solar spectrum is somewhat modified by degraded mirror spectral reflectance and coverglass spectral transmittance. Optical degradation due to the space environment is expected primarily in the short-wavelength range of the spectrum below 0.4 μm.

An important aspect of efficiency optimization has to address (i) shadowing of the active cell area by contacts and grid lines, (ii) non-uniformity of the incident, concentrated solar illumination, and (iii) the angle of incidence of the concentrated sunlight on the solar cell active area.

The non-uniformity of illumination arises primarily from imperfections in the optical elements, alignment errors between the various optical elements, and from system sun pointing errors. Figure 4 illustrates the case of a perfectly aligned optical system oriented at 0° off-point angle and at a 1° off-point angle. (The actual intensity contours are smooth; the depicted contours were computer-generated by a ray-tracing program using a relatively small number of rays.)

The angle of incidence of the concentrated sunlight varies over a relatively large range of angles due to the wide entrance aperture geometry of the Cassegrainian system. Figure 5 shows the relative energy that is incident at various angles. Most energy reaches the cell at angles in the range between about 10 and 23 degrees. To maximize the solar energy input to the cell at such angles, surface texturing may be required.

Radiation Resistance

The concentrator solar cells are shielded from radiation by approximately 0.15 mm (0.006 inch) thick fused silica equivalent from the front and by a much greater thickness from the back side. Radiation damage in the cell is caused primarily by protons in the lower and intermediate earth orbits. At geosynchronous altitude, the damage is roughly one-half due to electrons and one-half due to protons. The proton energy spectrum of interest to the solar cells ranges from near-zero energy to over 10 MeV after emerging from the shields. The low energy protons (in the order of 10 to 100 keV) are especially worrisome in that they tend to come to rest on surfaces and near the junction where they do much more damage than the higher energy protons (MeV-level) that penetrate the cell. It may become necessary to increase the solar cell shield thickness to protect the ultrahigh efficiency solar cell structures from excessive damage; however, all one can do is to reduce the number of protons of a given energy that enter into a cell throughout the total mission duration.

Thermophysical Properties

Analyses have shown that the solar cell orbital operating temperature of concentrator arrays, and hence the orbital operating efficiency capability, is as strongly dependent on solar cell absorptance values as it is for planar arrays. Achievement of a low value of solar absorptance is therefore mandatory. With polished front surface, back surface reflector cells, values of 0.75 are in production today. However, front surface texturing, which may be required to reduce reflectance, raises the absorptance. Another approach is to let the incident excess infrared radiation pass through the cell and through an opening in the cell back side contact and heat sink. Another, more costly approach would utilize spectrally selective filters on the coverglass and/or the solar cell. Solar absorptance values near 0.6 would certainly be desirable.

The value of the cell's emittance is not critical because the small cell area contributes only negligibly to cooling of the system by radiation heat exchange.

Coverglass Interface

Four options for installing a coverglass in front of the concentrator solar cells are illustrated in table 3 together with the corresponding trade-off criteria. Each configuration has technical and economic considerations that need be examined.

Reliability Issues

High contact reliability and electrical stability of concentrator solar cells are of paramount importance. Table 4 illustrates some of the more important reliability issues.

CONCLUSIONS

The possibility of solar cell efficiency improvement by sunlight concentration opens a new avenue of potentially reducing space array system size, weight, and cost, especially in conjunction with the use of more advanced very high efficiency solar cell structures.

An order of magnitude reduction in space array recurring costs and an array area reduction by 5% relative to equal-output planar arrays (14% efficient cells at 28°C) has been projected in reference 1 for a 100-sun concentrator concept using 20% efficient silicon solar cells at 28°C. An area reduction of 30% could be achieved with 30% efficient (at 28°C) gallium arsenide or multiple bandgap solar cells at a negligible recurring cost penalty, allowing for as much as a \$2 per cell (\$8/cm^2) part cost.

* A portion of this work was performed under contract NAS8-32986 for NASA MSFC.

REFERENCE

1. Study of Multi-kilowatt Solar Arrays for Earth Orbit Applications. TRW Final Technical Report No. 33295-6001-UT-00 on Contract NAS8-32986 with NASA MSFC dated 19 Sept. 1980.

Table 1. Cost Elements Related to Array Design

Array Design Parameter	Life Cycle Cost Relationship
Smaller Area	• Lower assembly cost • Lower cost for lesser amount of orbit maintenance fuel required • Higher solar cell unit cost
Lower Mass	• Lower recurring materials cost • Potentially lower launch cost (Volume-related)
Smaller Stowed Volume	• Potentially lower launch cost (Mass-related)
Longer In-orbit Life	• Potentially higher recurring cost • Lower cost for fewer replacement units (recurring and transportation) • Lower cost for less in-orbit repair/maintenance work

Table 2. Projected Concentrator Array System Recurring Specific Costs (in 1979 Dollars)

	Specific Recurring Costs ($/W) (1987 Technology)
Element	Concentrator Array
Solar Cells	5.7
Covers	-
Optical Elements	2.5
Substrates	-
Heat Sinks	0.7
Harnesses	4.3
Materials	1.9
Blanket Labor	5.5
Structures	4.6
Structure Labor	4.7
Total	30.0

Table 3. Coverglass Mounting Options

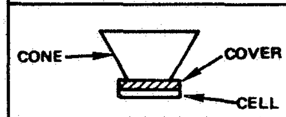
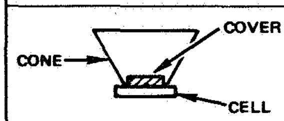
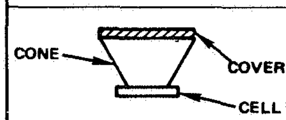
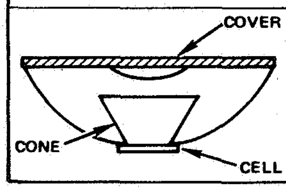
OPTION	TYPE	MASS	INTENSITY (SUNS)	DARKENING		COMMENTS
				COVER	ADHESIVE	
	ELECTROSTATIC BOND OR INTEGRAL	LOW	100	POSSIBLY SEVERE	NONE	• REQUIRES DEVELOPMENT AND TEST EVALUATION
	ADHESIVE MOUNTED	LOW	100	POSSIBLY SEVERE	SEVERE	• NOT PRACTICAL
	SEPARATELY MOUNTED	MEDIUM	20	MEDIUM	NONE	• BASELINE DESIGN
	SEPARATELY MOUNTED	HIGH	1	LOW	NONE	• IMPEDES CELL COOLING • POOR MECHANICAL STRENGTH (VIBRATION FAILURES)

Table 4. Solar Cell Related Reliability Issues

Potential Failure Modes	Failure Cause	Design Action
Cell contact separation from semiconductor material	• Failure rate increase with increasing temperature • Hot spot phenomena	• Lowest possible solar absorptance • Connection of many cells in parallel
Interconnector-to-cell contact and cell contact-to-heat sink joint fatigue cracking	• Thermal cycling in orbit	• Matching of coefficients of linear thermal expansion • Selection of best joining process (ultrasonic, welding, brazing, etc.) • Selection of long-fatigue life metals (durability, etc.) • Reduction of temperature range
Anomalous electrical degradation (fill factor, efficiency, etc.)	• Thermal cycling in orbit • Radiation	• Solar cells must be able to tolerate various environmental stresses

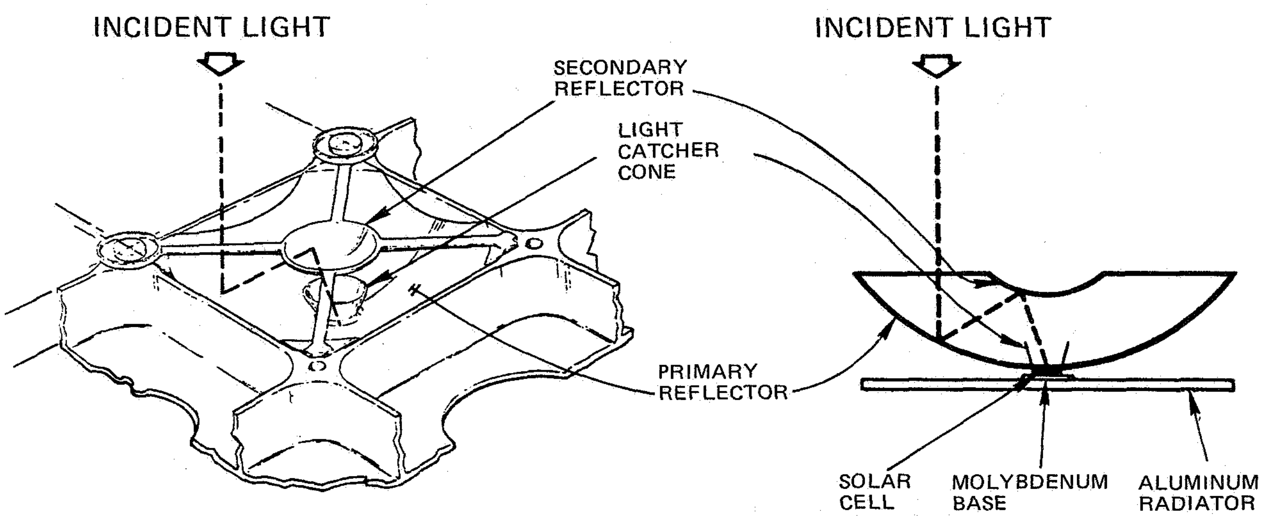


Figure 1. Cassegrainian Concentrator Element Concept

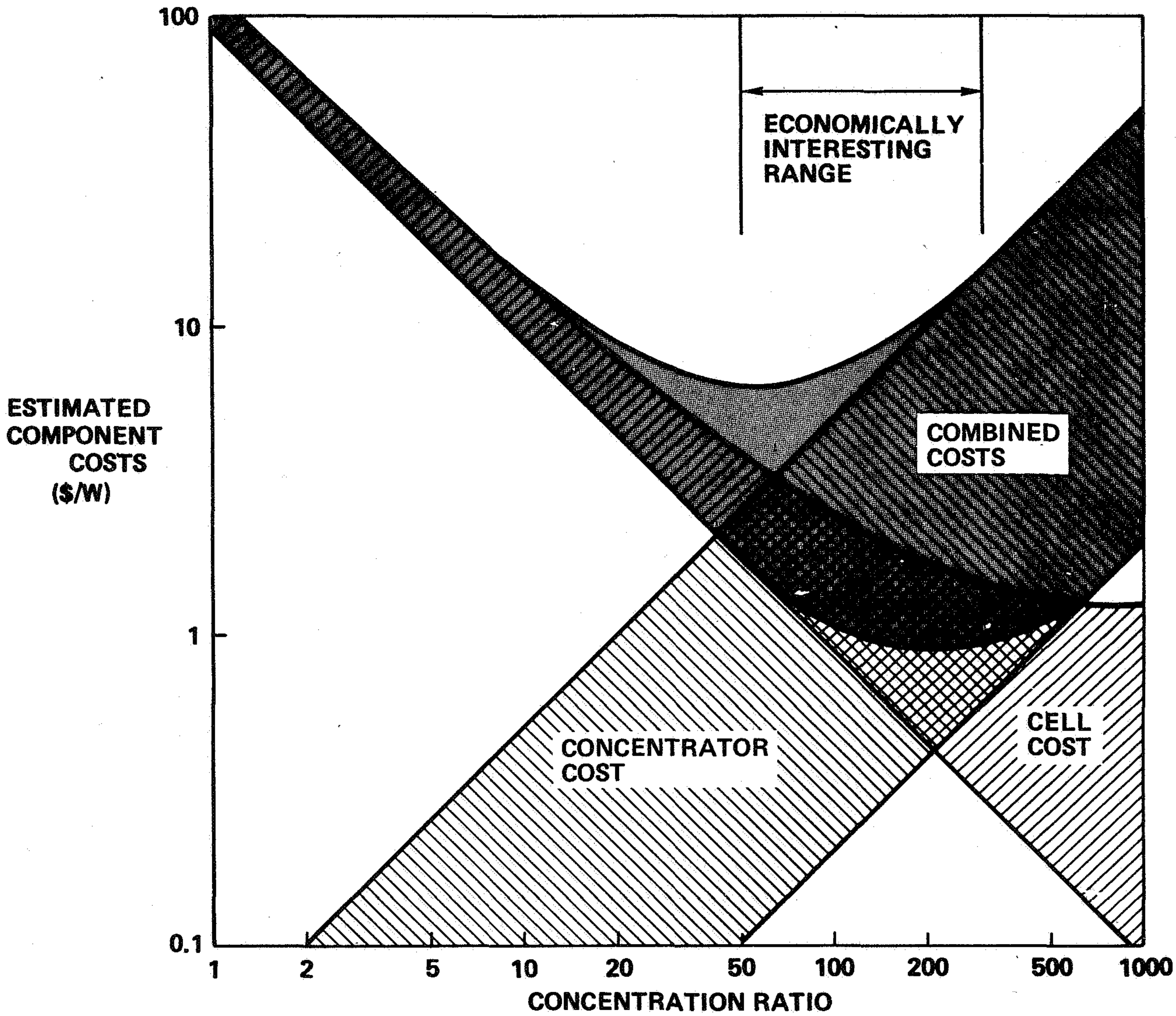
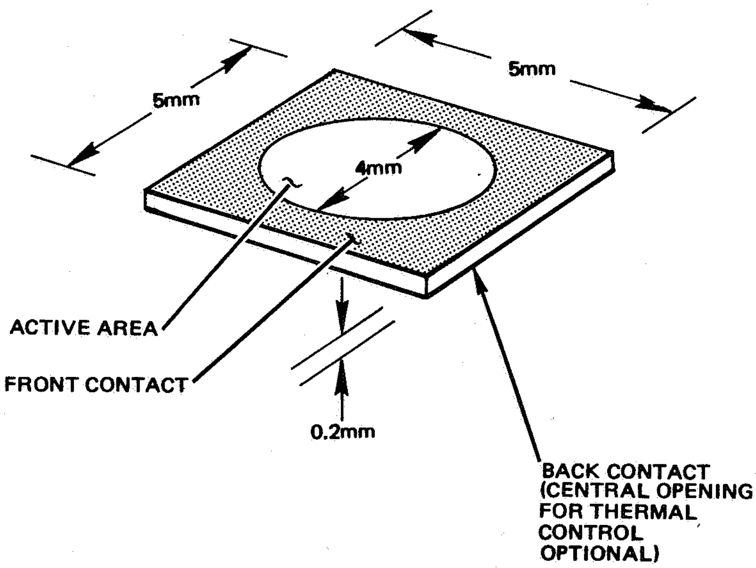


Figure 2. Selection of Minimum-Cost Concentration Ratios



PARAMETER	REQUIREMENT
EFFICIENCY AT 28°C, 100 SUNS	20%, Si 30%, Ga As
NORMAL OPERATING TEMPERATURE	80°C
TEMPERATURE CYCLING RANGE	-100°C TO +100°C
TEMPERATURE CYCLES	60,000 CYCLES
SOLAR ABSORPTANCE	≤ 0.75
ANGLE OF INCIDENCE	0 TO 30°, 20° NOMINAL
RADIATION TOLERANCE	PROTONS 1 TO 10 MeV

Figure 3. Concentrator Solar Cell Reference Design and Requirements

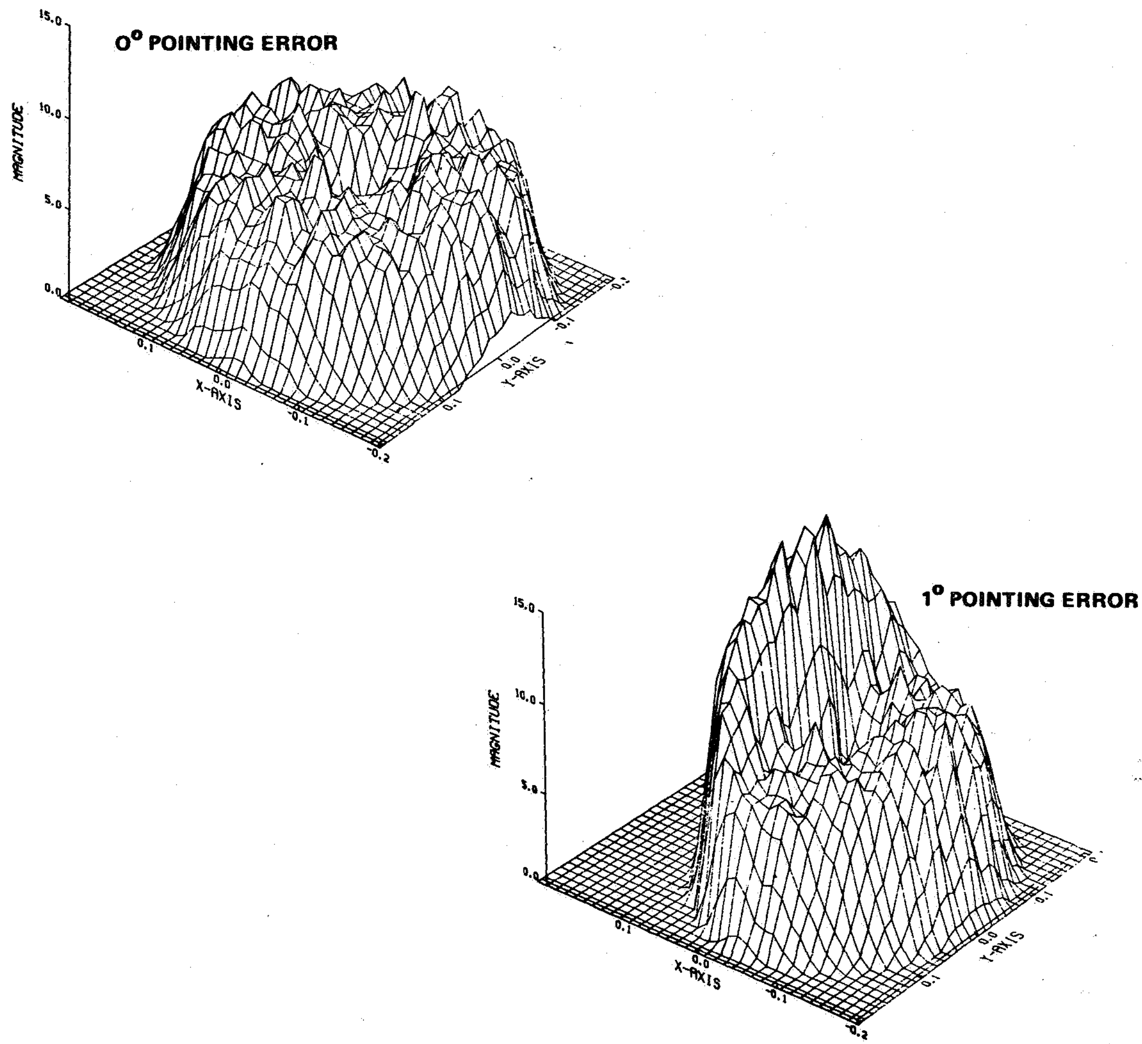


Figure 4. Cassegrainian Concentrator Intensity Uniformity

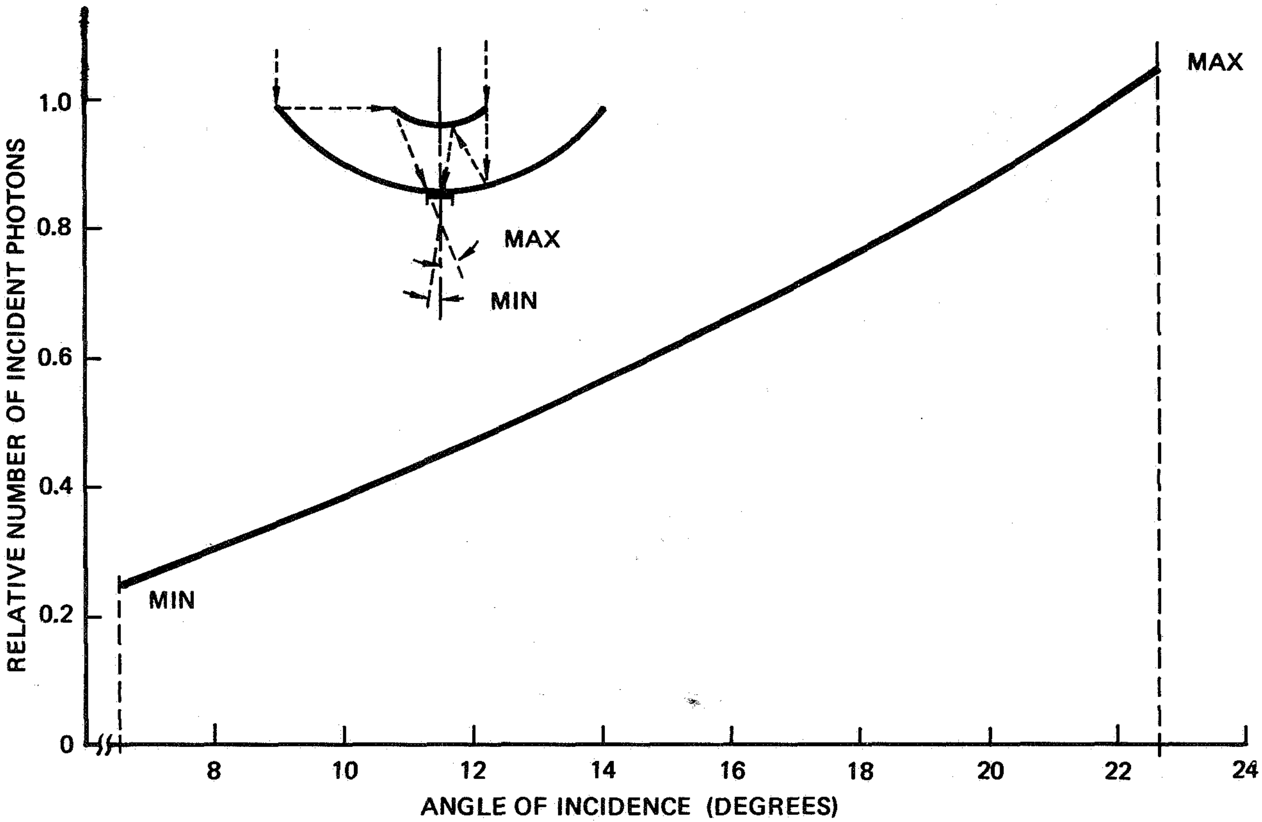


Figure 5. Relative Angular Distribution of Solar Energy Incident On a Concentrator Solar Cell