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SOLAR ENERGY FLOW CHANNELS IN AN LSC

P. I. : A. H. Zewail, Amos Noyes Laboratory of
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Pasadena, California 91125

J. S. Batchelder speaking.

NOTE:

Some of the results presented herein are in the process of publication or patenting. Earlier reference to the concept and practice of utilizing molecular energy transfer in a solar concentrator can be found in B. A. Swartz, T. Cole, and A. H. Zewail, "Photon Trapping and Energy Transfer in Plastic Matrices: an Efficient Solar-Energy Concentrator", Optics Letters, V. 1, no. 2, pp73-75, 1977.

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For the past several years we have been studying the luminescent solar concentrator, (LSC), particularly from the standpoint of what effect the various energy transfer mechanisms will have in a multi-dye LSC. The result is an enumeration of the various channels of energy flow, as well as dividends in the forms of techniques for improving the device performance. These results are now in the process of being published or patented, so here we will give only a brief sketch of the pertinent points.

The first figure show the quintessential LSC, an infinite flat ribbon geometry known as a planar solar concentrator, or PSC. For typical materials such as glass or plastic, total internal reflection of luminescence results in the trapping of about 75% of the incident flux within the absorption bands of the dyes or ions used. This can be raised through the utilization of non-planar or ripple geometries, an example of which is shown in the second figure. This corrugated LSC is a series of adjacent cylindrical sections, the ratio of the back surface and front surface radii being the measure of their curvature. The following figure shows the effect of this curvature on the area of the critical cone, which is the probability that a luminescent photon will escape out the face rather than being trapped by total internal reflection.

The next figure shows a very simplified flow diagram of the channels for energy exchange in an LSC. An interesting effect is the self-absorption feed-back loop, seen in the center of the figure. As shown in the next figure, there is an overlap between the absorption spectrum of a typical absorber and the emission spectrum, which is the far left curve in the lower sequence. Emission from the dye can therefore be re-absorbed by another dye molecule, or self-absorbed, with the subsequent emission spectra shifted into the red as shown. Quantifying this effect lets us compute the magnitude of this self-absorption effect as a function of the characteristic dimension of the device and the dye concentration. As a computational tool one can ignore the self-absorption channel and use an effective quantum efficiency for the dye which is smaller than the true quantum efficiency, and which depends on the surface geometry as well and the device size and dye concentration. Such an effective quantum efficiency has been experimentally measured here, and is shown in the following figure.

Surprisingly enough, reflections at the interface between the LSC and the photovoltaic cell (PVC) can have a substantial effect due to the high angular divergence of the output light from an LSC. The next figure shows the light intensity seen from a point on the PVC as a function of polar angle for the PSC geometry. The results for three different optical densities across the PSC are shown. We conclude that a textured or roughened surface PVC will be necessary along with an anti-reflection coating to achieve good optical coupling between the LSC and the PVC.

The primary effect of including more types of absorbers in an LSC is that the initial absorbed solar flux is increased. In the next figure is shown the fraction of the solar flux absorbed by five different LSCs, each containing one more dye species than the last. For typical dye concentrations, it can be seen that a five dye system will absorb about 60% of the flux with an energy above the band-gap of a gallium arsenide cell. As shown in the following figure, we have demonstrated this additive effect in a two dye system: the top curve is the combined absorption spectrum of the two dyes used, while the lower curve is the current response of a silicon cell attached to the edge of the device.

The final figure shows the theoretical gain of a PSC. The geometric gain of any concentrator is the area exposed to sunlight divided by the active area of the absorber. The thermodynamic gain is the energy density gain computed from the black body photon temperature at the absorber. For concentrators using geometric optics such as lenses or mirrors, these two gains are always equal, and will be on the straight diagonal line on the graph. As long as the device dimensions are moderate, a PSC (or in general an LSC) will have a higher energy density gain than the equivalent concentrator using geometric optics.

A prototype design consists of a two layer LSC in series, with one layer connected to silicon cells and the following layer connected to gallium arsenide cells. For geometric gains of several hundred and concentrator costs of thirty dollars per square meter, we anticipate a performance of 15% total efficiency at fourty cents per peak watt.

THE PLANAR SOLAR CONCENTRATOR (PSC).

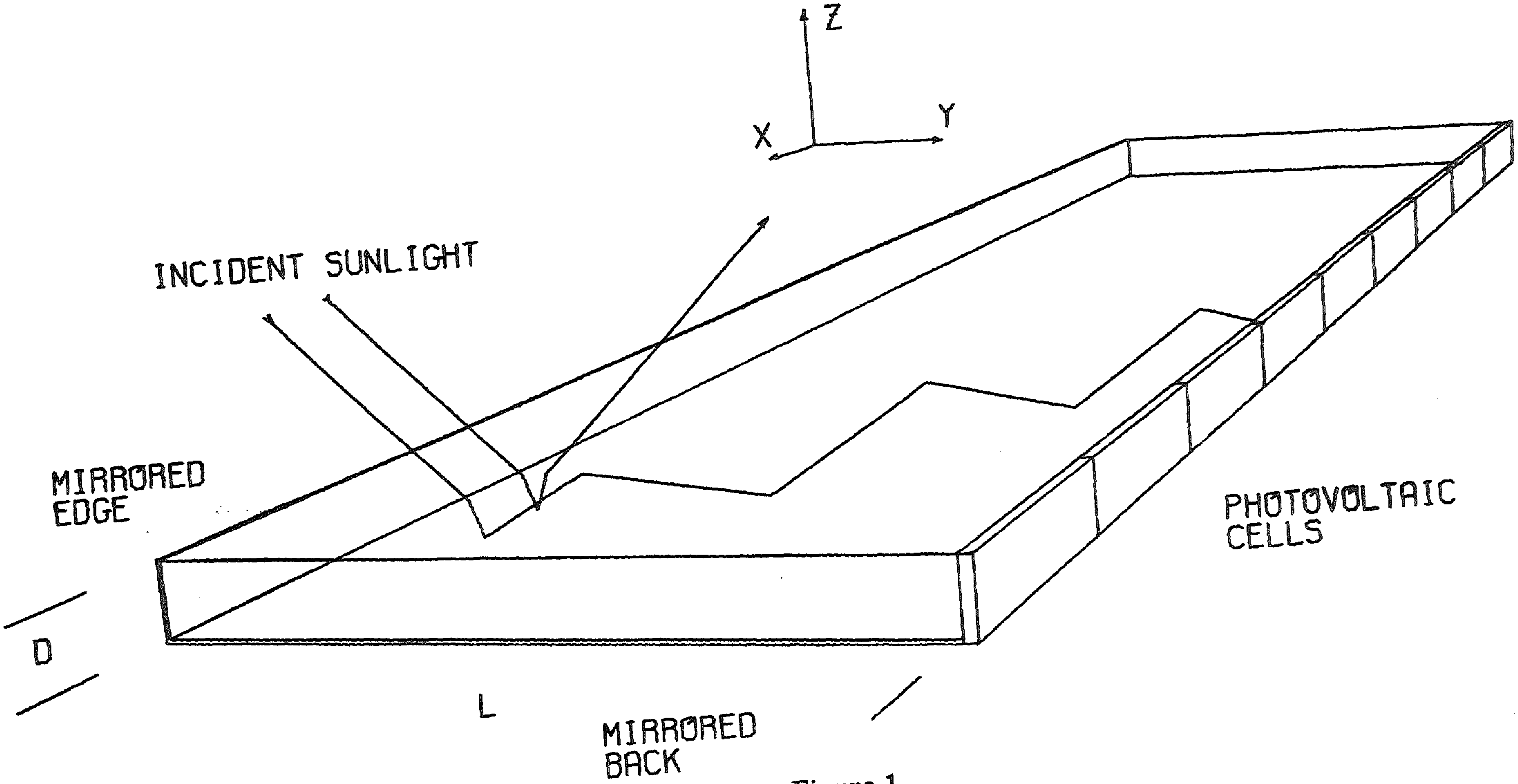


Figure 1.

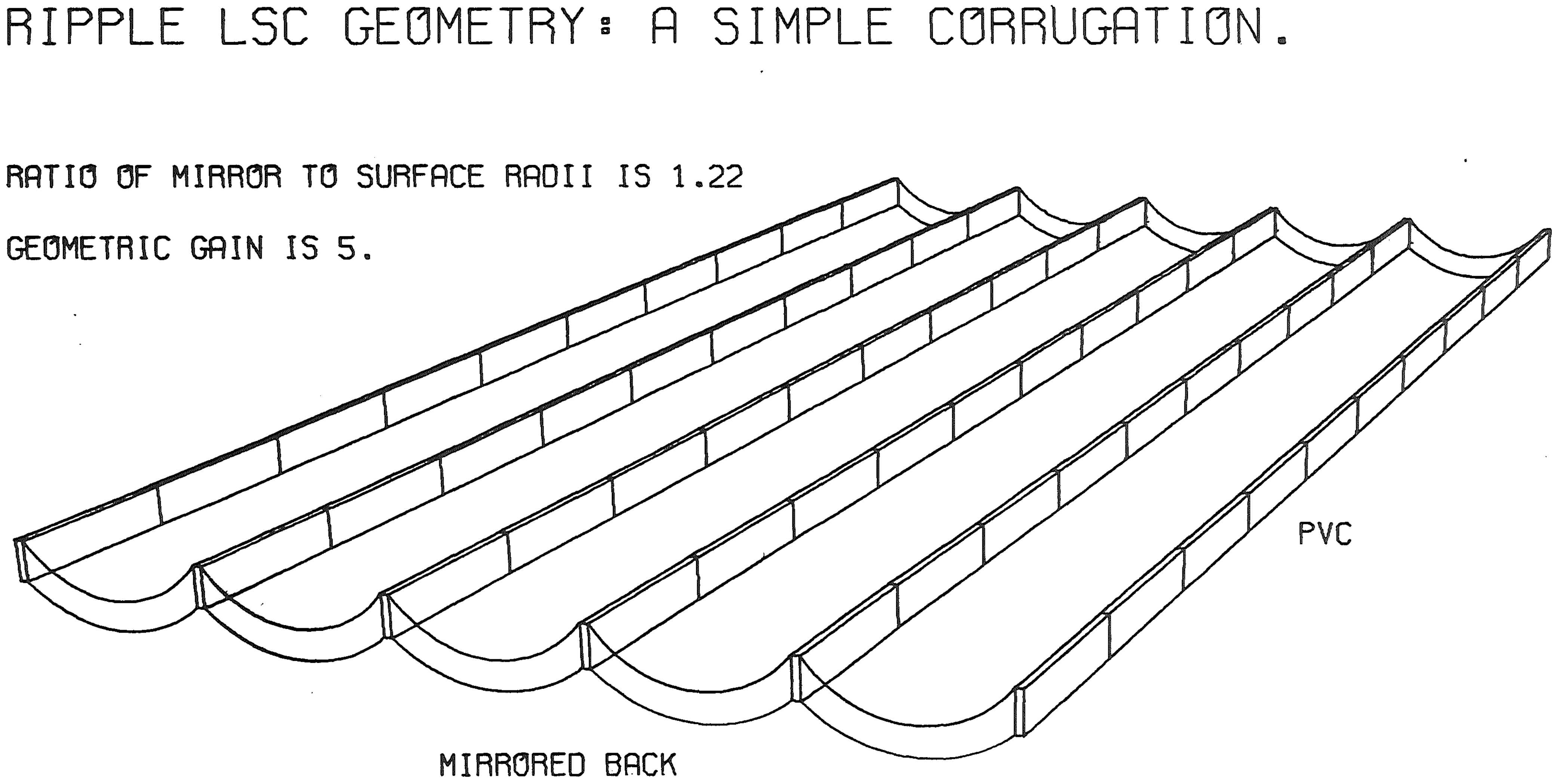

RIPPLE LSC GEOMETRY: A SIMPLE CORRUGATION.
RATIO OF MIRROR TO SURFACE RADII IS 1.22
GEOMETRIC GAIN IS 5.
PVC
MIRRORED BACK

Figure 2.

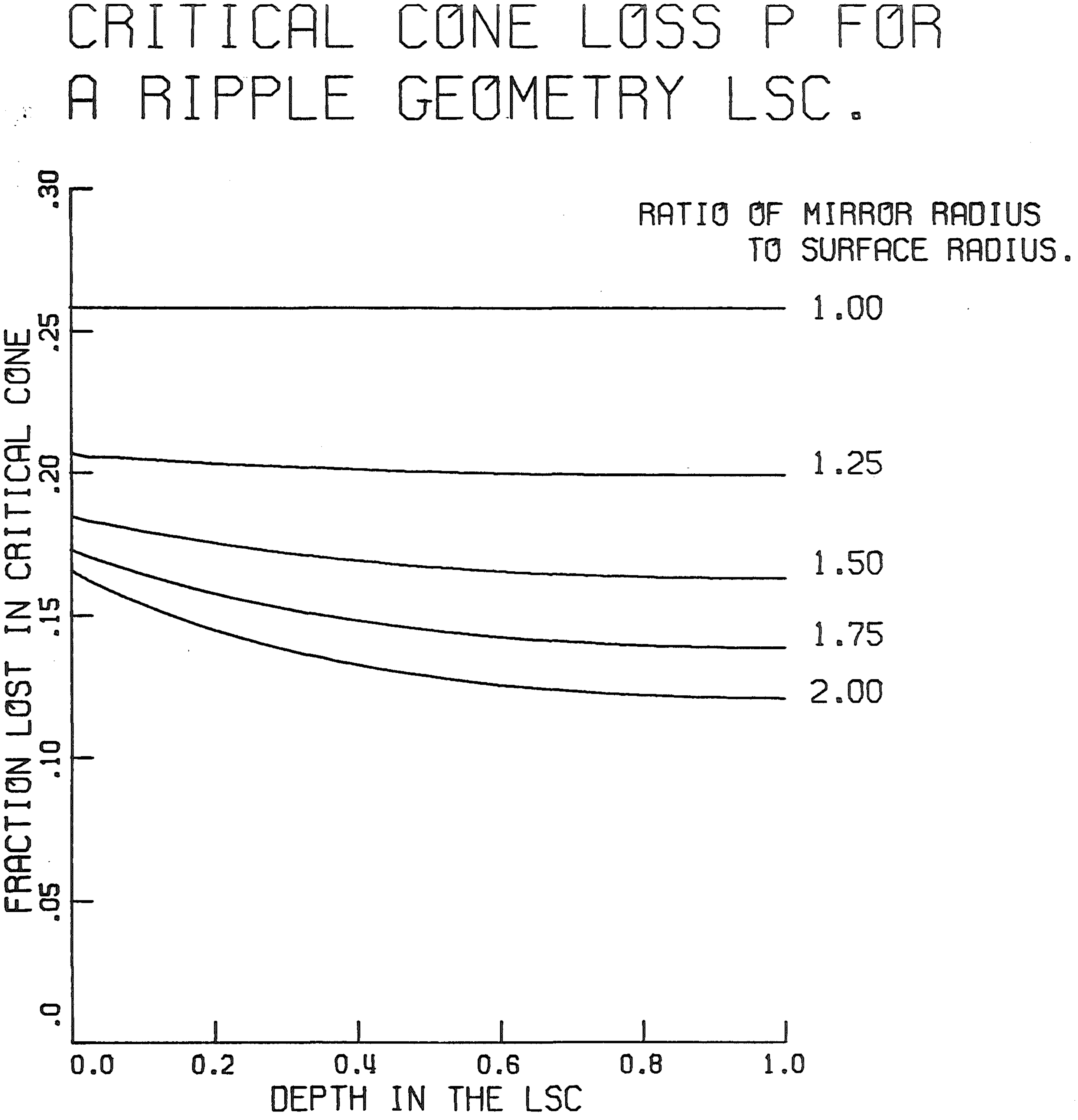

CRITICAL CONE LOSS P FOR A RIPPLE GEOMETRY LSC.
RATIO OF MIRROR RADIUS TO SURFACE RADIUS.
1.00
1.25
1.50
1.75
2.00
FRACTION LOST IN CRITICAL CONE
.0
.05
.10
.15
.20
.25
.30
0.0
0.2
0.4
0.6
0.8
1.0
DEPTH IN THE LSC

Figure 3.

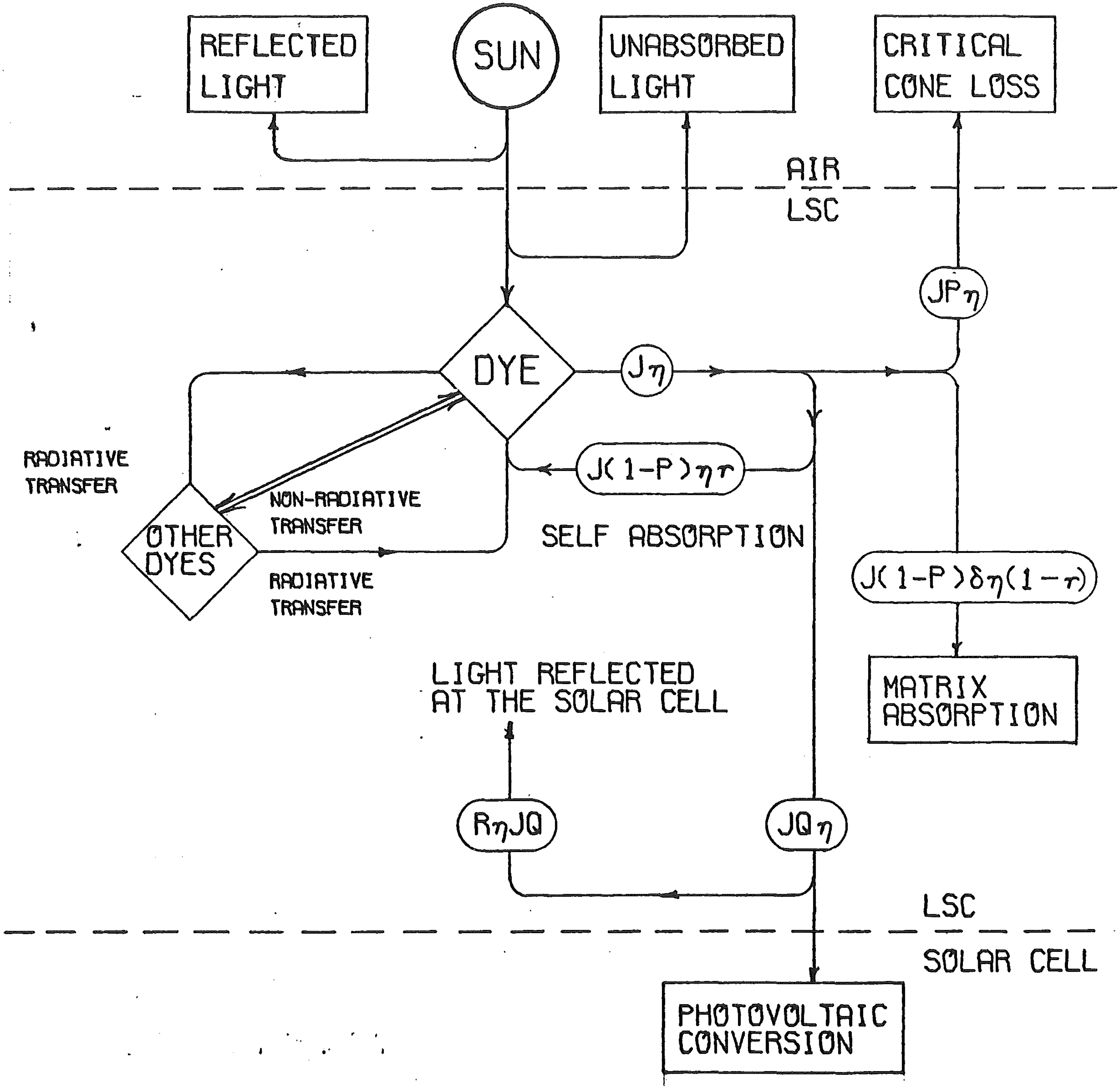

REFLECTED LIGHT
SUN
UNABSORBED LIGHT
CRITICAL CONE LOSS
AIR
LSC
JPη
DYE
Jη
RADIATIVE TRANSFER
J(1-P)ηr
NON-RADIATIVE TRANSFER
OTHER DYES
SELF ABSORPTION
RADIATIVE TRANSFER
J(1-P)δη(1-r)
MATRIX ABSORPTION
LIGHT REFLECTED AT THE SOLAR CELL
RηJQ
JQη
LSC
SOLAR CELL
PHOTOVOLTAIC CONVERSION

Figure 4.

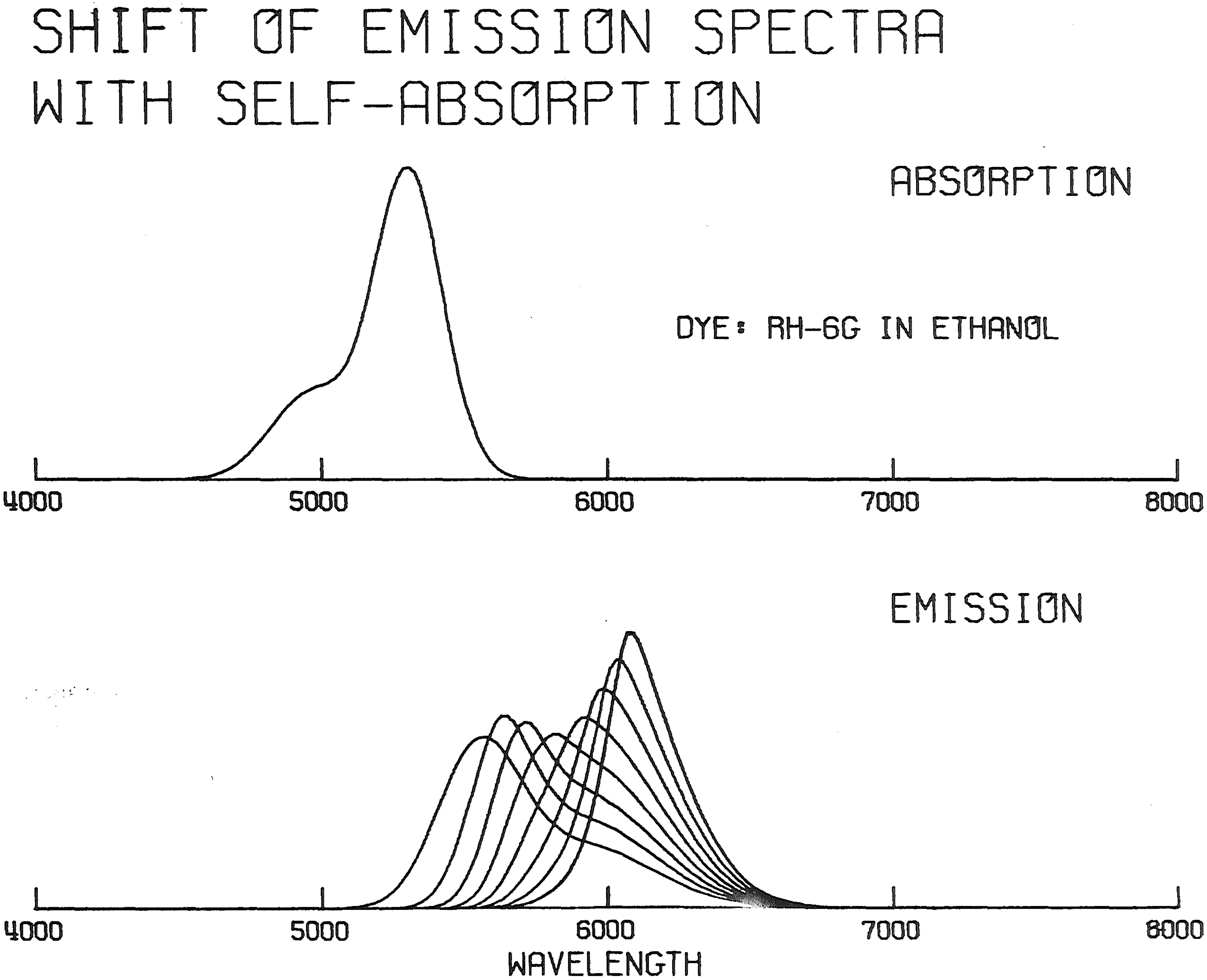

SHIFT OF EMISSION SPECTRA
WITH SELF-ABSORPTION
ABSORPTION
DYE: RH-6G IN ETHANOL
4000
5000
6000
7000
8000
EMISSION
4000
5000
6000
7000
8000
WAVELENGTH

Figure 5.

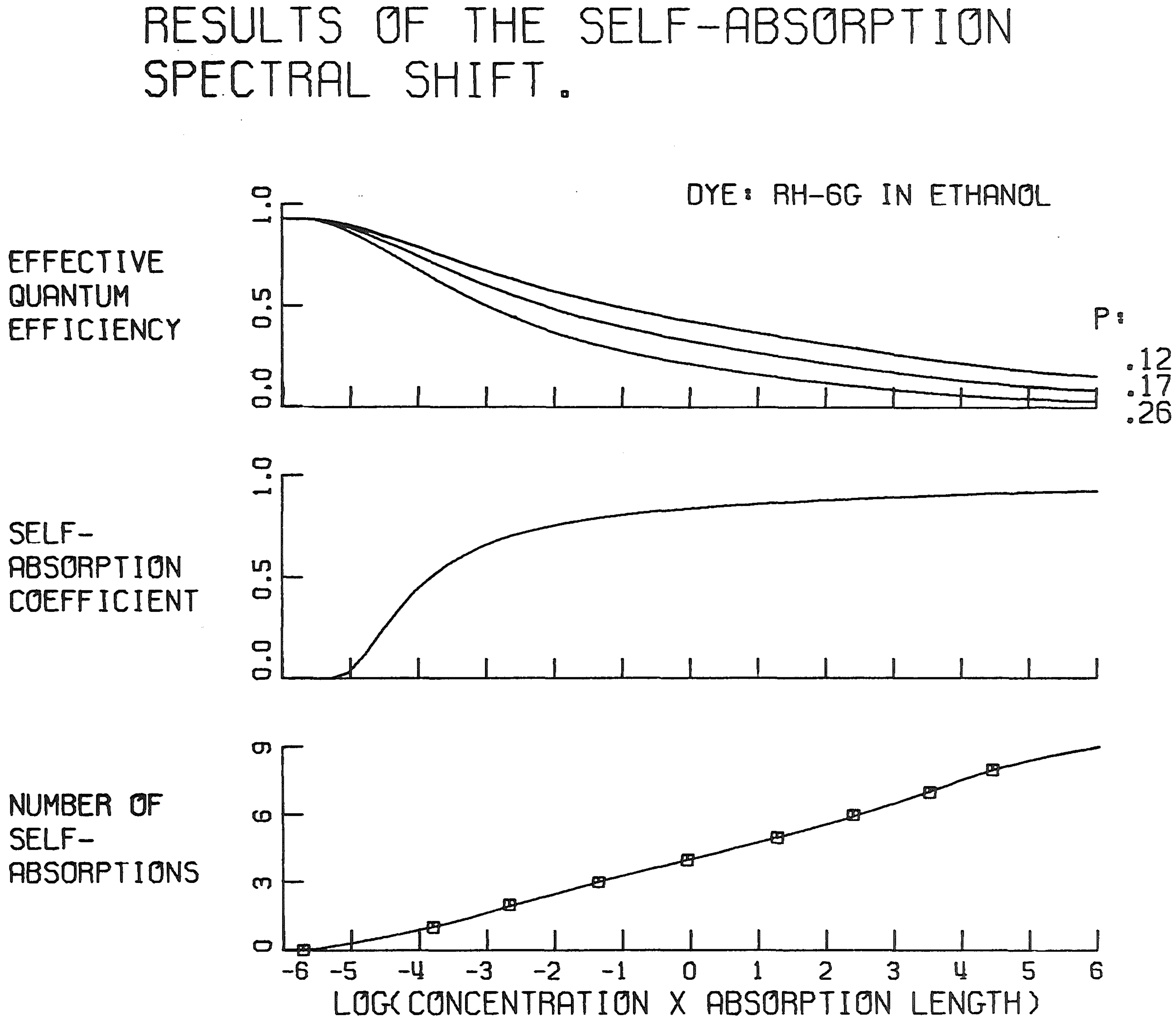

RESULTS OF THE SELF-ABSORPTION SPECTRAL SHIFT.
DYE: RH-6G IN ETHANOL
EFFECTIVE QUANTUM EFFICIENCY
1.0
0.5
0.0
P:
.12
.17
.26
SELF-ABSORPTION COEFFICIENT
1.0
0.5
0.0
NUMBER OF SELF-ABSORPTIONS
9
6
3
0
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
LOG(CONCENTRATION X ABSORPTION LENGTH)

Figure 6.

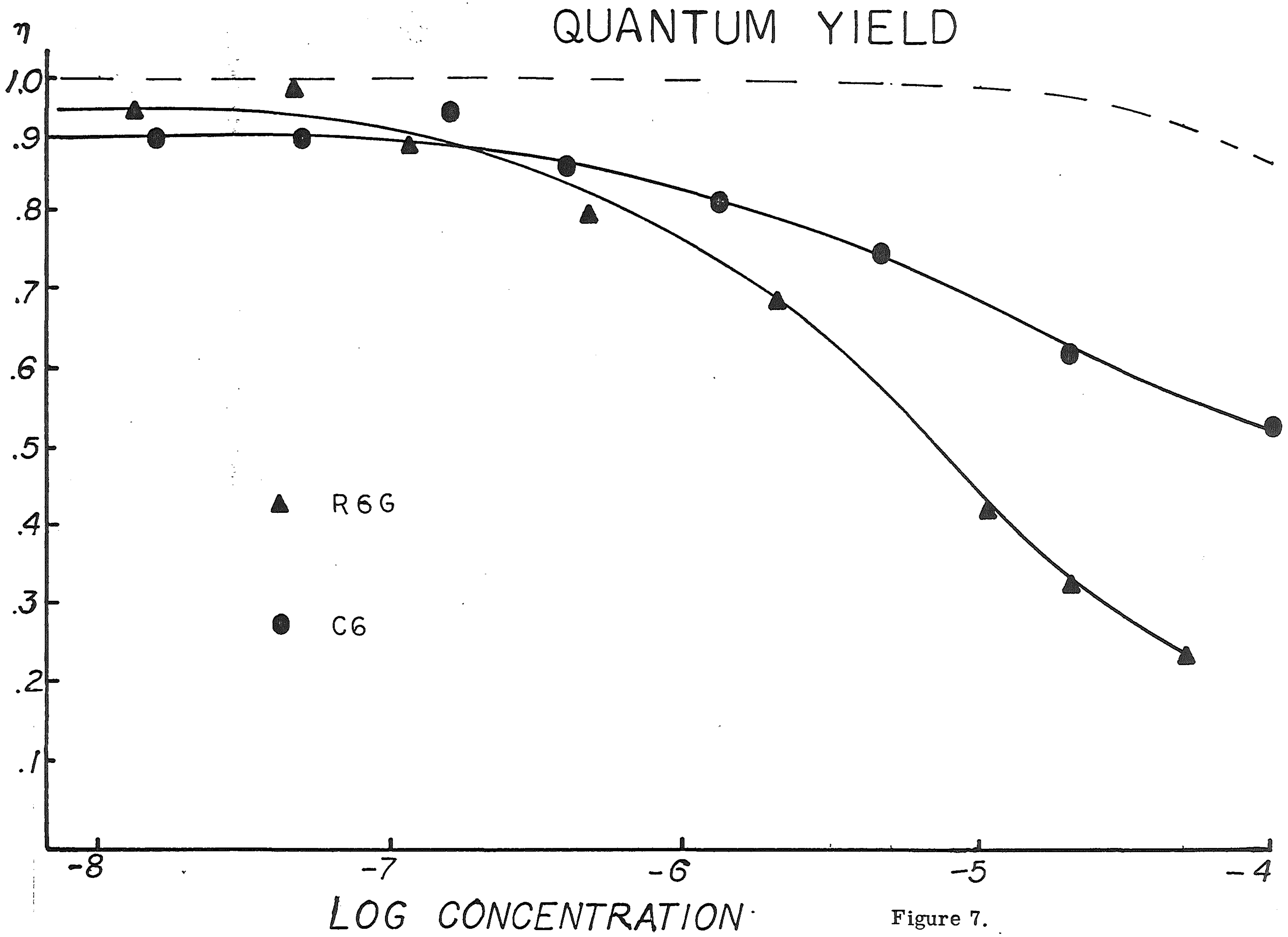

QUANTUM YIELD
η
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
R6G
C6
-8
-7
-6
-5
-4
LOG CONCENTRATION

Figure 7.

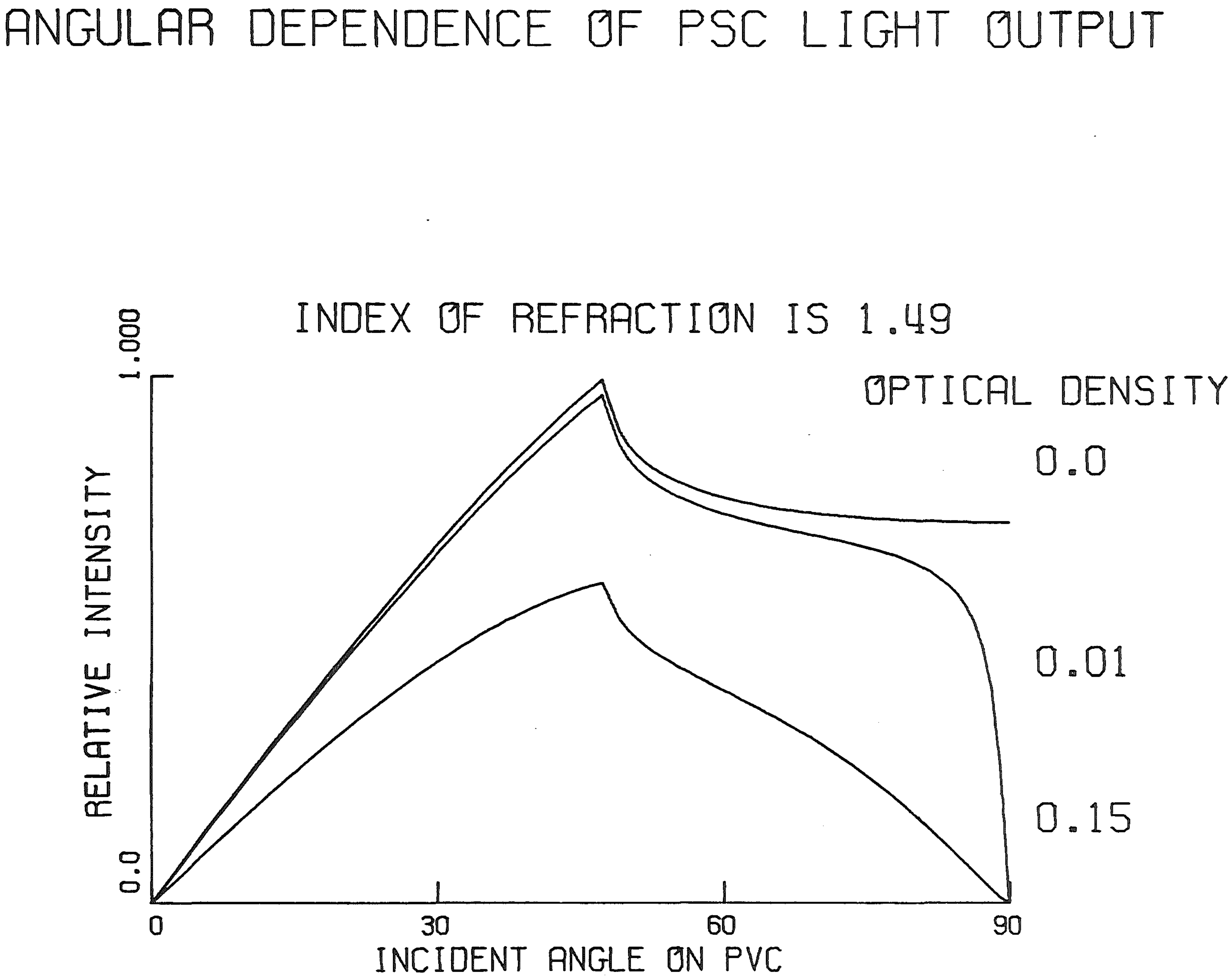

ANGULAR DEPENDENCE OF PSC LIGHT OUTPUT
INDEX OF REFRACTION IS 1.49
OPTICAL DENSITY
0.0
0.01
0.15
1.000
0.0
RELATIVE INTENSITY
0
30
60
90
INCIDENT ANGLE ON PVC

Figure 8.

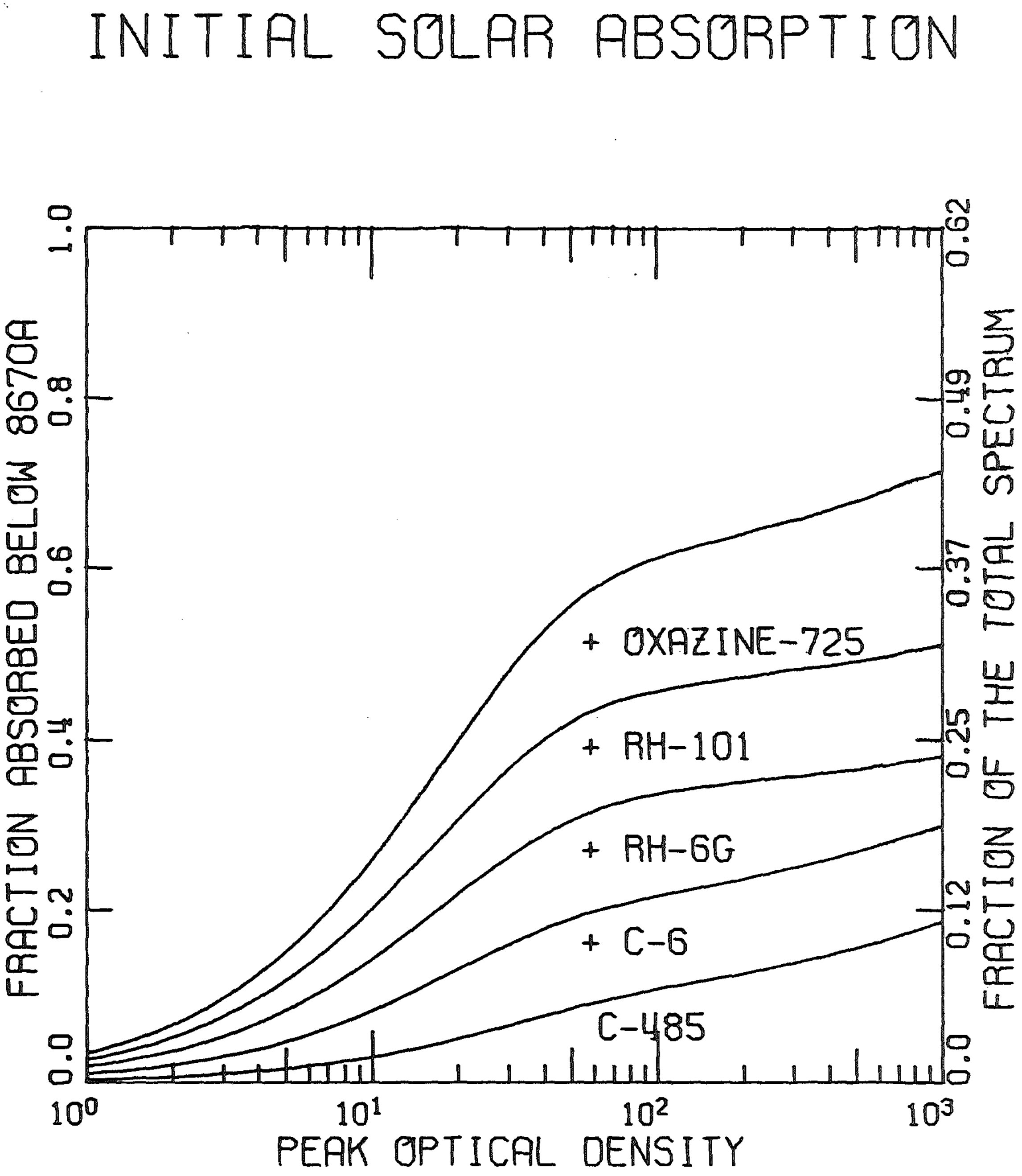

INITIAL SOLAR ABSORPTION
FRACTION ABSORBED BELOW 8670A
0.0
0.2
0.4
0.6
0.8
1.0
FRACTION OF THE TOTAL SPECTRUM
0.0
0.12
0.25
0.37
0.49
0.62
+ OXAZINE-725
+ RH-101
+ RH-6G
+ C-6
C-485
10^0
10^1
10^2
10^3
PEAK OPTICAL DENSITY

Figure 9.

FIG. 4 Optical Excitation Spectra of
Mixed-Dye Planar Solar Concentrators
PSC (C-6/Rh-6G)

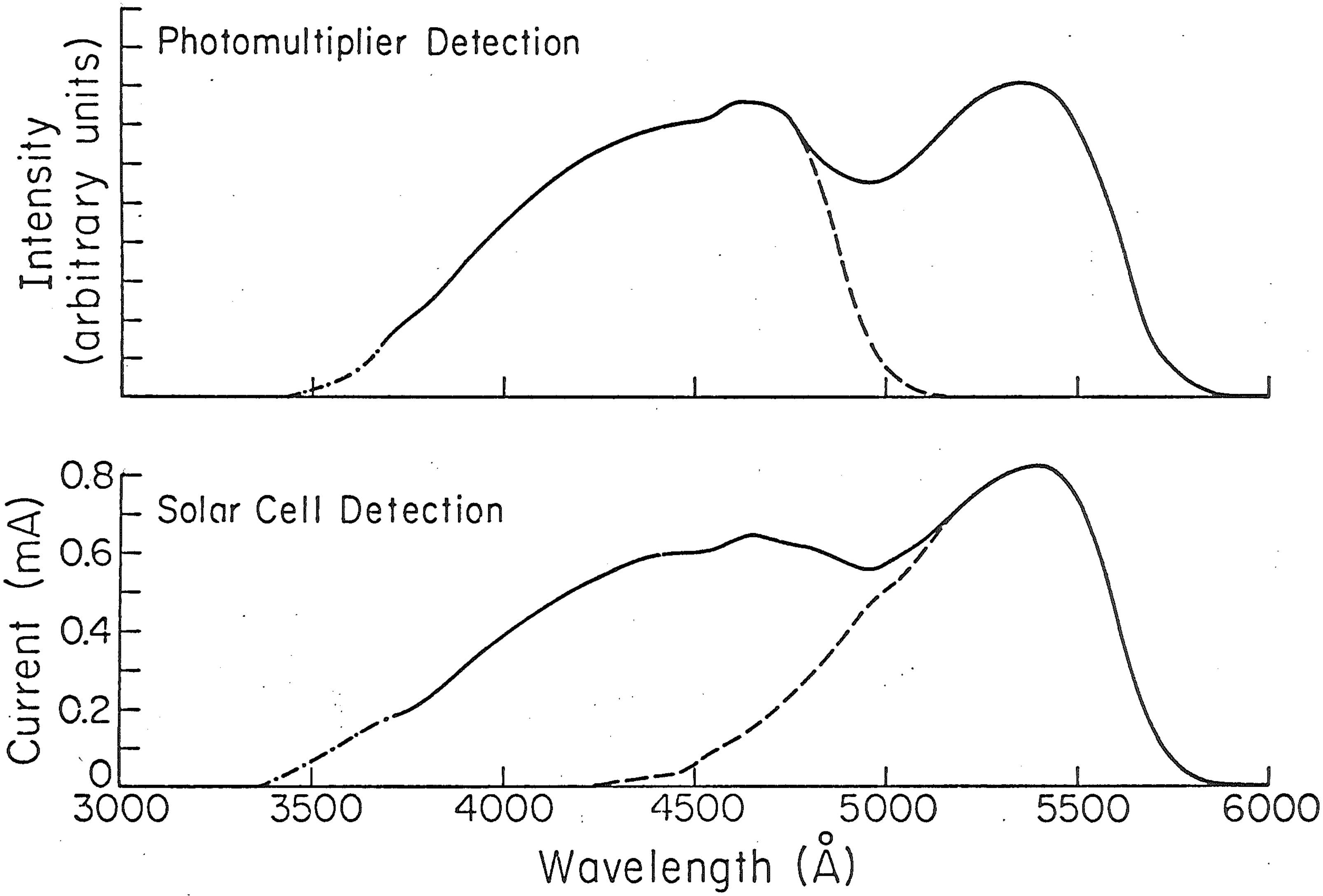
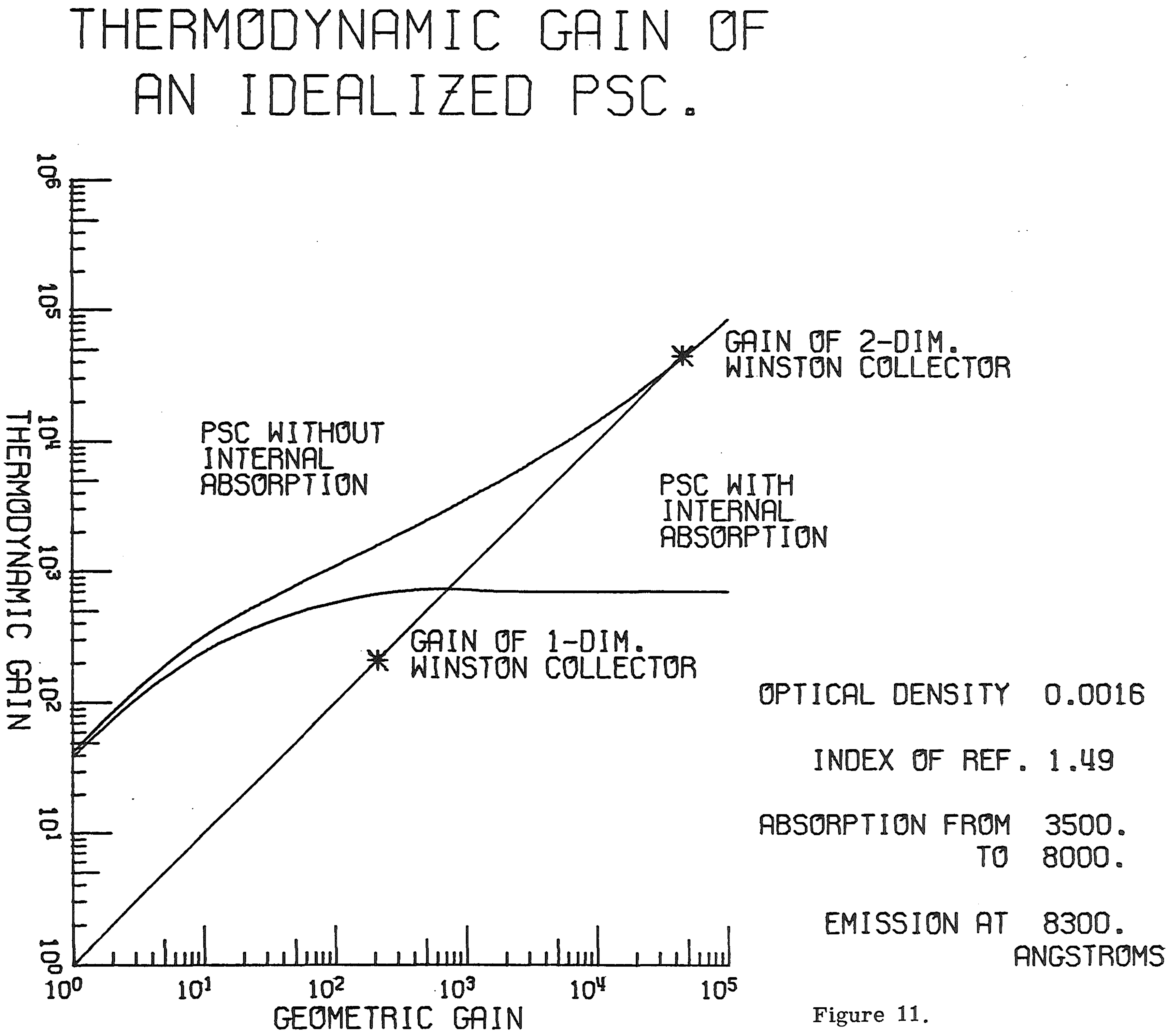


Figure 10.



THERMODYNAMIC GAIN OF AN IDEALIZED PSC.
THERMODYNAMIC GAIN
10^0
10^1
10^2
10^3
10^4
10^5
10^6
GEOMETRIC GAIN
10^0
10^1
10^2
10^3
10^4
10^5
GAIN OF 2-DIM. WINSTON COLLECTOR
PSC WITHOUT INTERNAL ABSORPTION
PSC WITH INTERNAL ABSORPTION
GAIN OF 1-DIM. WINSTON COLLECTOR
OPTICAL DENSITY 0.0016
INDEX OF REF. 1.49
ABSORPTION FROM 3500. TO 8000.
EMISSION AT 8300. ANGSTROMS

Figure 11.