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COST EFFECTIVE FLAT PLATE PHOTOVOLTAIC MODULES USING LIGHT TRAPPING

FINAL REPORT, JPL CONTRACT #955787

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EXECUTIVE SUMMARY

This report and Appendix A give the results of the study. The Final Report details the analyses and calculations performed to arrive at the design guidelines, and Appendix A is an Optical Design Guide which contains rules and guidelines for the practicing photovoltaic design engineer.

Through Contract #955787 from the Jet Propulsion Laboratory, Low Cost Solar Array Project, Science Applications, Inc. is extending prior in-house work in optical trapping in "thick films" to form a design guide for photovoltaic engineers. A thick optical film can trap light by diffusive reflection and total internal reflection. Light can be propagated reasonably long distances compared with layer thicknesses by this technique. This makes it possible to conduct light from inter-cell and intra-cell areas now not used in photovoltaic modules onto active cell areas.

The Design Guide shows the reader how to construct photovoltaic modules to use and even to exploit this concept. By SAI calculations up to 20% improvements in standard module performance can be expected. Even larger improvements can be received in special modules constructed to exploit these thick film effects as discussed in the Final Report.

Acknowledgements

Science Applications, Inc. wishes to thank the Jet Propulsion Laboratory for support and encouragement. In particular, Mr. Don Bickler and Mr. Paul Alexander of the Low Cost Solar Array Project (LSA), Production Processes and Equipment area, and Mr. Ed Cuddihy of the LSA Encapsulation area provided data and guidance in the performance of this work.

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1.0 INTRODUCTION

This study has been conducted for the NASA Jet Propulsion Laboratory (JPL) low cost solar array project (LSA). LSA is the lead center for photovoltaic (PV) flat plate technology. JPL works with industry to develop cost-effective PV systems that will meet or exceed DOE goals. Science Applications, Inc. (SAI) has developed a proprietary means of increasing the solar radiation impinging on the individual cells in a PV panel. The technique uses light trapping in the encapsulant layer above and to the side of each cell.

On the basis of an unsolicited proposal from SAI to JPL, it was agreed that SAI expertise could be of value to the industry in two ways, and the following study goals were determined:

(1) Development of an Optical Design Guide--Summarization of detailed computer simulation and tests into rules-of-thumb, graphs, etc., that exhibit the performance gains possible by various design options.

(2) Cost/Benefit Analysis--Development of costs of manufacturing, both of panels and balance of systems, and operation and maintenance (O&M) costs to compare with the performance benefits predicted from item (1).

The contract established a statement of work and a schedule for the completion of this work and the delivery of results. [The Statement of Work and Schedule, as extracted from the contract, are presented as Appendix B.]

1.1 BACKGROUND AND LIGHT TRAPPING PHYSICS

The basic work behind the current study effort derived from a discovery by Knasel and Hougton at SAI that the addition of white paint to the underside of a conventional photovoltaic panel caused increased output. The reason was due to the trapping of light after undergoing diffuse reflection from the white paint involved in light trapping.

Figure 1-1 illustrates the physical principles involved in light trapping. A light ray may enter from any angle and is refracted in the cover material. If the ray does not strike a cell directly, it is diffusely reflected at the bottom of the panel by a white paint layer. Diffuse scattering follows a cosine distribution of intensity (Lambert's Law). Light rays between the zenith and the critical angle escape, those of large angles are trapped by total internal reflection and are directed downward. They may strike a cell, or rediffuse by scattering.

SAI Independent Research and Development projects have demonstrated practical gains with transparent encapsulant and diffuse layers between photovoltic cells and a better theoretical understanding was obtained. Improved theoretical basis for this effect was reported in the patent applications, and was also published in the technical literature.[1,2] The conclusions reached showed maximum increase in intensity is limited to the value n^2, where n is the index of the cover sheet. For glass $n=1.5$ and an increase, or gain of 2.25 is the maximum available, while about 1.8 was measured. The use of higher index layers in conjunction with the superstrate material hold promise of a significant increase in gain.

Other work in this area included JPL sponsored work at GE (reference 4), work at JPL by Mach and Volk (reference 5) and studies at ARCO Solar (reference 6).

1.2 DEFINITIONS

In order to appreciate the optical effects to be discussed, the following definitions should be helpful.

- Thin Film Optical Systems--Two dimensional structures that reflect, refract or transmit light dependent on the wavelength and the optical properties of the materials--optical radiation goes forward or backward only.

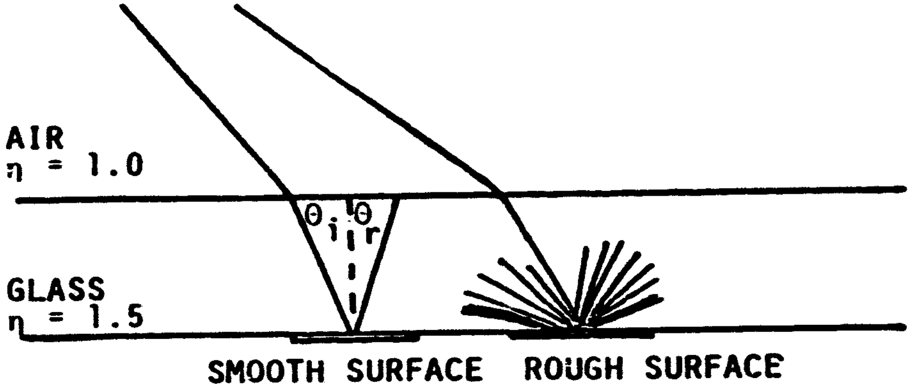


Figure 1-1. Refraction, Reflection In Thick Films

- Thick Film Optical Systems--Three dimensional structure that reflect and transmit optical radiation forward or backward, with propagation possible transverse to layer structure.

- Light Trapping refers to propagation in thick films where light is trapped in high index materials by total internal reflection. Light is not normally trapped unless it is scattered in a diffuse (i.e., non-specular) manner.

- Refraction and reflection are the principal optical interactions in thick films (refer to Figure 1-1):

  - -- Refraction: bending of oblique rays as they pass from one medium to another having a different refractive index.

  - -- Reflection: the return of radiation by a surface without change in wavelength.

    - Specular--from a smooth surface; angle of incidence (Θ_i) equal angle of reflection (Θ_r).

    - Diffuse--from a rough surface; into many (sometimes all) directions of a hemisphere.

    - Most surfaces contribute specular and diffuse components.

- Diffuse light trapping is accomplished when an incident ray enters a higher index transparent layer and is scattered.

- An example related to photovoltaic modules is shown below in Figure 1-2.

1.3 STRUCTURE OF REPORT

In the following parts of this report, Section 2.0 discusses the methodology including assumptions used sources of data, optical and cost modeling

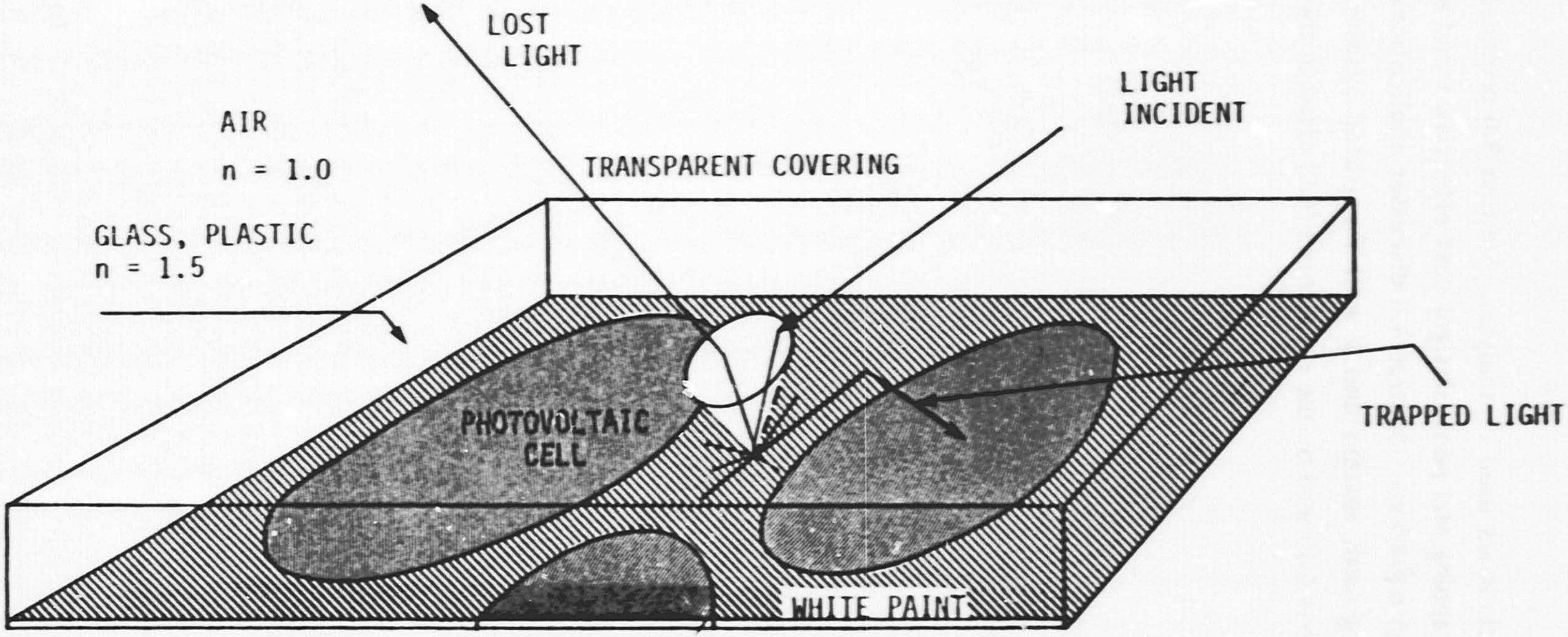


Figure 1-2. Light Trapping By Diffuse Reflection In Thick Film

methods and the techniques used in analysis. Section 3.0 provides study results dealing with light trapping and panel design, cost effective trend in panel design and simplified design equations. Section 4.0 discusses applications including the minimum design, a growth system and a wall integrated system. Section 5.0 gives study conclusions followed by the references (6.0) cited in the report.

2.0 METHODOLOGY

The following paragraphs provide details of the methods, techniques, and considerations that are used in the definition and analysis of light trapping photovoltaic panels.

2.1 SOURCES OF DATA AND ASSUMPTIONS USED IN THE STUDY

The data and assumptions used in the study have come from many sources. Data is required on photovoltaic cell efficiency, size, cost; module and array construction materials, their physical properties, costs, etc. SAI has taken steps to assure that a consistent set of data was obtained, that agreed with DOE/JPL's best estimates both of current and projected (future) values.

For example, the figures for efficiencies, and costs of PV cells and figures for projected change with time can vary widely from manufacturer to manufacturer. SAI has used JPL and DOE values for cell and materials parameters where these have been available. In other cases, known values, average values or a best guess have been used. In cases where parameters may vary over a wide range or are subject to change, performance/cost sensitivities were investigated parametrically.

2.2 DISCUSSION OF DATA BASE

The kinds of data that are required for the evaluation of light trapping in PV panels and specific sources for this data are discussed briefly in the following paragraphs.

2.2.1 Cell Encapsulation and Attachment

Data was obtained defining generic cell incapsulation and attachment schemes. SAI determined physical properties and optical and mechanical properties from JPL sources, the literature, and contracts reports. Specific topics covered included:

1. Identified basic materials used
2. Determine basic layer configurations:
   - anti-reflection coating
   - cover (glass)
   - highly refractive materials
   - adhesives
   - pottants
   - cells
   - substrates
   - heat dissipation materials
3. Optical properties of transparent materials
   - transmission
   - reflection
   - fresnel losses
   - diffusion characteristics
   - UV absorption
   - property changes over time
   - surface shapes
   - geometry and cross-section
4. Mechanical properties, all materials
   - layer thicknesses
   - stiffness
   - hardness
   - resistance to impact (hailstones, etc.)
   - abrasion
   - chemical attack (e.g., SO_2)
   - temperature stress
   - mechanical stress
   - humidity

The purpose of these data is to allow choice of the best combination of materials to produce the best array configurations to be modeled by cost benefit computer simulation.

Reports reviewed indicated that cells are interconnected and encapsulated to form modules in three generic ways.

- Substrate bonded-cells bonded to the top of rigid substrate with transparent encapsulant top cover.
- Superstrate bonded-cells bonded to the underside of a transparent rigid superstrate with back side pottant.
- Laminated- in an integral transparent laminate and encapsulant without a rigid member.

Module cross sections for the substrate design are shown in Figure 2-1, and for the superstrate in 2-2.

There is much information on bonding and encapsulants and many tests have already been performed, such as weathering, transmission, u.v. absorption, mechanical strength, etc. A list of various encapsulants and physical optical and thermal properties were assembled.

The general incapsulation scheme consists of:

1. outer covers
2. pottants
3. substrates
4. back covers
5. adhesives

Typical materials choices for each are:

- superstrates - sode-lime glass
- substrates - fiberboard, flakeboard, mild steel, glass reinforced concrete

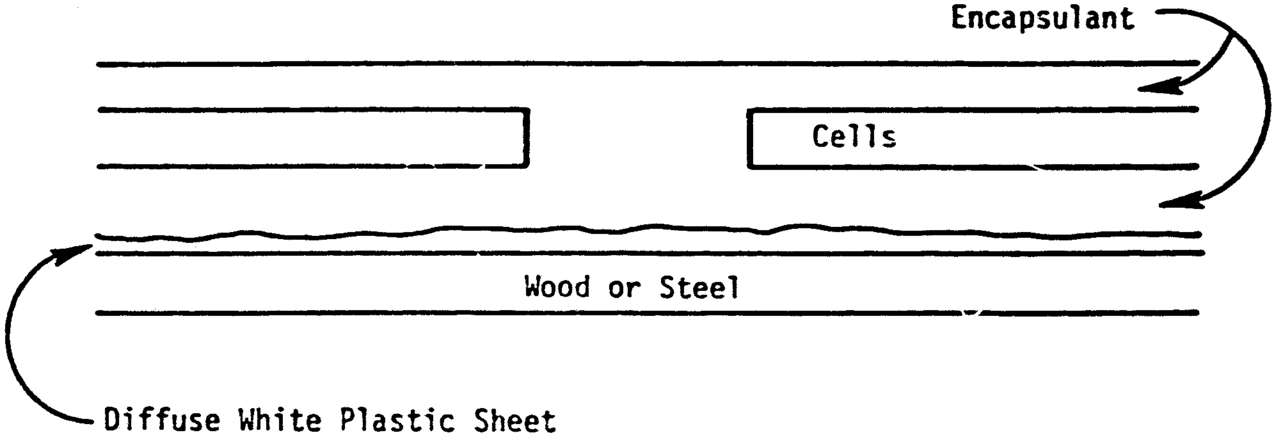


Figure 2-1. A Photovoltaic Module with Substrate Design

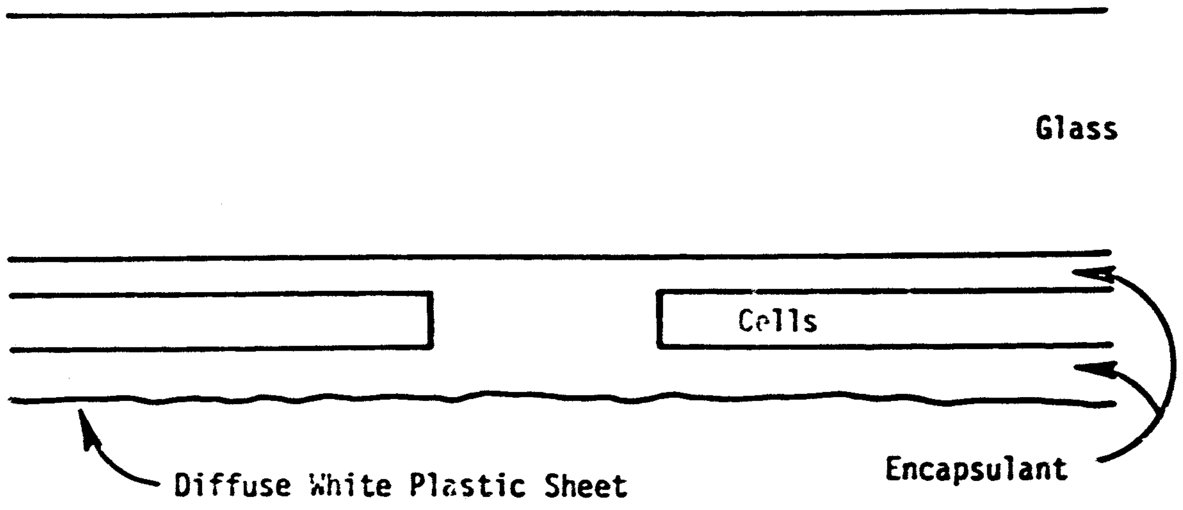


Figure 2-2. A Photovoltaic Module with Superstrate Design

- elastomeric pottants - ethylene/vinyl acetate (EVA); ethylene/propylene diene; polyvinyl chloride platisol; poly-n-Butyl acrylate; silicone/acrylate blends; aliphatic polyurethanes
- covers - mylar, tedlar, aluminum foil (w/superstrates); korad 201-R, tedlar 100-BG-30-UT (w/substrates)

JPL contractor studies have determined that EVA is one of the most useful pottants, and is used in two forms[1]

- EVA - clear form to cover cell top
- EVA-W - pigment white for reflectance behind cell

A vaccum-bag process has been developed and found to be an excellent encapsulation method. While silane is used for bonding (20-30 lbs/in) to glass, using silane for bonding to hardboard is not good because bonds are severely weakened by water. Isolation from water is needed before hardboard can be used as a substrate.

Flourocarbon polymers (especially FEP) had best mechanical properties in JPL contractor studies.

Plexiglass acrylic compounds performed almost as well and maintained high optical transmission value.

PVC, polycarbonate, cellulose acetate butyrate all degraded badly losing all mechanical properties.

Tedlar 100BG30UT, Korad 201-R uv absorbers and Korad (acrylic) films are more weatherable but loses uv absorbing capabilities after several years. They cost \$.05 ft^2 and are available in 3 mil thick.

Aliphatic urethane, ethylene/propylene-diene rubber polyvinyl chloride plastisol also investigated as encapsulants but little additional data is available.

A substrate bonded scheme has been developed by Spire Corp.[2] It uses an integral glass encapsulation for solar cell arrays electrostatic bonding in terrestrial solar cells (ESB). ESB forms permanent bonds between Si and glass without adhesives. Stronger than either material being joined and very durable encapsulation method-good for a minimum of 20 years; economics show that ESB can meet 1 36 LSA goals.

In summary then, within the module bonding is two methods.

- Electrostatic bonding (ESB) for superstrate designs only.
- Pottant bonding-for either of the two module schemes. There are two manufacturing process for potting:
  - -- lamination
  - -- casting

Typical elastometric pottants include[1]

- ethylene/vinyl acetate (EVA)
- ethylene/propylene plastisol
- polyvinyl chloride plastisol
- poly-n-Butyl acrylate
- silicone/acrylate blends
- aliphatic polyuretranes

Of these, EVA appears to be one of the superior pottants. SAI located data on the properties of a series of EVA copolymers. Average density ranges about 0.95 g/cm^3, tensile strength at yield point between 600 and 2800 psi, elongation at yield up to 1000%, cost about $0.65/lb, 66% to 78% UV transmission and 92% to 91% visible transmissions and an index of refrction of 1.48 to 1.49. Data on other pottants as well as on the remaining transparent members (glass, craneglass) is of similar values.

According to JPL sources the most acceptable bonding "sandwich" is one that is made up of a set of layers

- o glass
- o pottant made of Craneglas, a clear glass fibre non-woven mat and EVA intermixed

- cell
- pottant
- back foil

Craneglas is used to prevent air bubbles in the EVA encapsulation. This trend toward thicker and more complex encapsulation could be exploited by optical trapping.

2.2.2 Cell Sizes and Shapes

Data was obtained to define cell sizes and shapes.

The basic wafer shapes are circular and square. From these circular, part circular, square rectangular and hexagonal cells can be made. Of these, only circular cells cannot be packed to 100%, their packing fraction being $\pi/4$ at maximum. For light trapping some space is desired between cells. Therefore partial cell wafers are to be considered. The information that was collected included:

1. size of cells
2. shapes of cells
3. efficiency of individual cells
4. efficiency of cut up cells
5. cost of cells
6. how cost rises as cells are cut up and how this compares to increased efficiency
7. ease of interconnecting whole wafers and partial wafers
8. percent of metalization for the different cell sizes and shapes

The purpose of these data are to make studies of light trapping cost effectiveness. Light that is incident on the areas between cells can be diffused and reflected back down to solar cell areas. Therefore the size and shapes of the cells are important because it determines the minimum size and shapes of the diffusing areas between cells. This must be studied in order to determine how effective these areas are in enhancing the performance of the solar cells.

SAI found typical size and shapes in the Solar Cell Array Design Handbook.[3]

In summary then, cell sizes and shapes vary widely, there being no standards for these measures. Basic cell wafers are predominantly round, while some square wafers are beginning to be produced. In the round wafer, normal 2, 3, and 4 inch diameters exist with 3 being the most common. Manufacturers may trim the round sizes down to reduce defects.

Round cells are frequently trimmed to be partially or fully square to improve packing. As a compromise, half, quarter, and even smaller part circle cells are offered, again for the improved packing in large modules, or to produce modules with one dimension smaller than a typical wafer size.

Square or rectangular cells are found in a variety of sizes 1, 4 and recently larger sizes have become possible. Polysilicon twelve inch wafers would be generally cut into 4 inch squares because of the lack of familiarity in design or manufacture with anything as large as a 12 inch wafer. Cells are frequently cut further.

Ribbon cells are typically 1 inch by 4 inches in rectangular form, and can be longer. There appears to be no comprehensive study of the cost and performance trade off to cell cutting, or wafer size or shape. More data is needed in this area.

2.2.3 Cell Grid Structure and Geometry

Data was obtained to define grid geometrics, blockage, and layout, in order to determine this:

1. metalization patterns on the cells
2. the cross-sectional structure of the grids
3. width of grids
4. total area covered by metalization
5. efficiency of current collection by various grid patterns and areas

6. how much light is blocked by the metalization
7. how these patterns must change for different cell sizes and shapes to maintain best efficiency
8. different types of metals used in the grids and compare them

These data were collected due to the fact that the metalization on the front of the cells block the incident light from that portion of the cell. The greater the metalization, the better the current collection but this lowers the power available from the PV effect by reducing the total light. The area covered by the grid may also be employed in light trapping if a diffusing reflective coating can be applied. This means that an accurate means of registration will also have to be examined for cost/power effectiveness.

Very little information on grid geometries, blockage and layout was found in an initial look at JPL literature on hand and additional information was ordered. About the only characteristics found have been simply "shadowing" or total percent area covered by metalization. The IEEE Photovoltaic Specialists Conference (1976, 1978) books contain some information on metalization.

SAI determined that the front surface grid causes between 5 and 10% light blockage in a normal cell design. This figure appears to be about constant for any flat plate cell technology, but may be somewhat higher for concentrating cells. Very little work has been done on measuring grid blockage accurately. Additional study will be made of the grid cross-sectional geometries and grid materials to determine if light trapping can be utilized. Since no better data can be obtained, optical properties of grid material (silver, tin, nickel, copper and 60/40 solder) was obtained from textbooks.

2.2.4 Cell Interconnections and Module End Effects

Data was obtained to define cell interconnection schemes, cell spacing, requirments for inner-cell area. Data included:

1. Series connected cells

2. parallel connected cells

3. series-parallel connected cells

4. amount of wire, posts, connectors needed for interconnection

5. electrical losses due to interconnectors

6. amount of intercell area needed for these items

7. how cell spacing varies with interconnection schemes

8. what other mechanical considerations and encapsulant considerations are needed for interconnection materials.

The purpose of the data is to exploit the intercell area.

The spacing between the cells can be used for the highly reflective diffuse material for light trapping. If this area must also be used for interconnection materials, this will reduce the available inter-cell area. Knowing the requirements for inter-cell area help to determine the light trapping ability of the inter-cell area. Potentially the interconnection wires and terminal posts and other materials between the cells can also be coated with a white diffusely reflective pigment, making a dual use of the area.

SAI found that interconnection schemes can either be parallel or series. Diodes are sometimes used to bypass a dead cell. Modules are usually made of cells which are all connected in series. These modules can be interconnected in series, parallel, or in combination. Space between cell is used for terminal posts.

Even in square cell modules certain intercell area is reserved for interconnections--about 8%. In round cell modules the cells do not touch-lowering the theoretical packing factor of $\pi/4$ (.785) to values as low as 0.5. More widely spaced cells are possible but certain wiring loses and costs need to be accounted for in these designs. In the JPL Block IV module procurement, the packing factors of modules ranged from 0.62 to 0.85 for example (normal and rectangular cells). At the end of the module, "dead" areas exist due to imperfect packing schemes, edge gaskets and the like.

2.2.5 Cell Efficiency as a Function of Illumination and Temperature

Data were collected to define cell temperature and efficiency parameters as a function of cell illumination. Data were reviewed in order to:

1. determine cell temperature as a function of cell illumination for various types of cells and configurations
2. determine cell efficiency as a function of cell illumination
3. since efficiency will also depend on temperature, examine passive (or active) cooling methods for different cell configurations
4. obtain IV curves for various cells such as the family of IV curves for different cell illuminations and temperatures.

The purpose of these data is to modify the cell output due to increased cell illumination.

Light trapping will increase the amount of light hitting the cell. The amount of power capable of being produced by the cell is not directly proportional to the amount of incident light. As more light strikes the cell, the efficiency is also increased. Therefore even more power can be realized. But, there is a problem with increased illumination and that is temperature. The hotter the cell, the lower its efficiency. Since light trapping will increase cell illumination and temperature, these effects will need to be considered along with effective cooling methods.

One review report was located concerning JPL tests. An approximate rate of power decrease of 0.5%/C° is reported for a series of modules tested.[4] For these modules, an average temperature rise above ambient of 25°C per 100 mW/CM^2 is indicated, although these values depend strongly on the module design. The net effect of an insolation of 100 mW/CM^2 (light trapping with a gain of 2 is thus a 12.5% decline in the approximate factor of two power increases that would have been calculated without consideration of thermal effects.

In conclusion, as cell light levels increase, cell efficiency increases (in theory), assuming a maximum power match is maintained. However increased light requires increased cell cooling to maintain a normal operating temperature. If this is not provided, cell temperature will rise and cell efficiency will decline.

During the contract period a JPL review reference was located giving a comprehensive set of data on module efficiency effects at elevated light levels and temperatures. These data were adequate for Task 1 modeling. Background reports were requested, provided by JPL, and used to validate the equations to ajdust efficiency.

2.2.6 Modules with Trapping and Diffusing Layers

In discussing the trapping and diffusing layers, it is helpful to consider four major groupings of layers.

- The anti-reflection layers--these couple light efficiently to the bulk optical material.
- The transmission layers--these correspond to the bulk of the cross-section. Their purpose is to transmit the light to the cells.
- The high index layers--these provide additional ray bending and enhance trapping.
- The diffuse layer--this diffuses the light and provides the basic mechanism for later trapping.

The optical variables to be considered at each location are detailed depending on the layer purpose. Figure 2-3 illustrates the basic panel cross-section required for light trapping to be effective. Figure 2-4 is shown to define the various layers in detail and to indicate additional layers that are important in Figure 2-5. In addition, lateral dimensions are required of the 3D structure and these are also included in Figure 2-5.

The method employed utilizes exact analytic solutions of physical optics equations for refraction, and specular reflection. Diffuse reflection is treated in two ways:

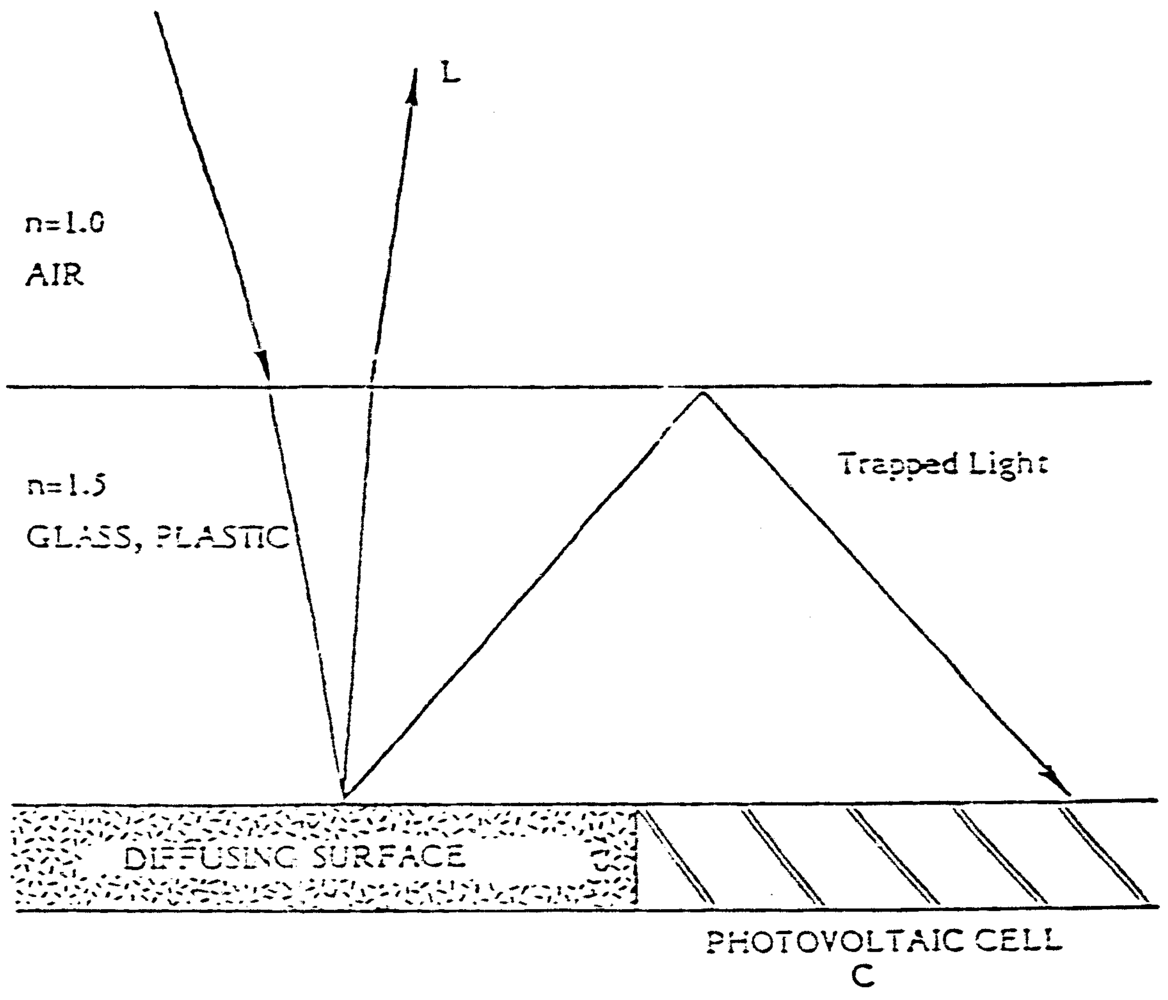


Figure 2-3. Basic Cell Geometry

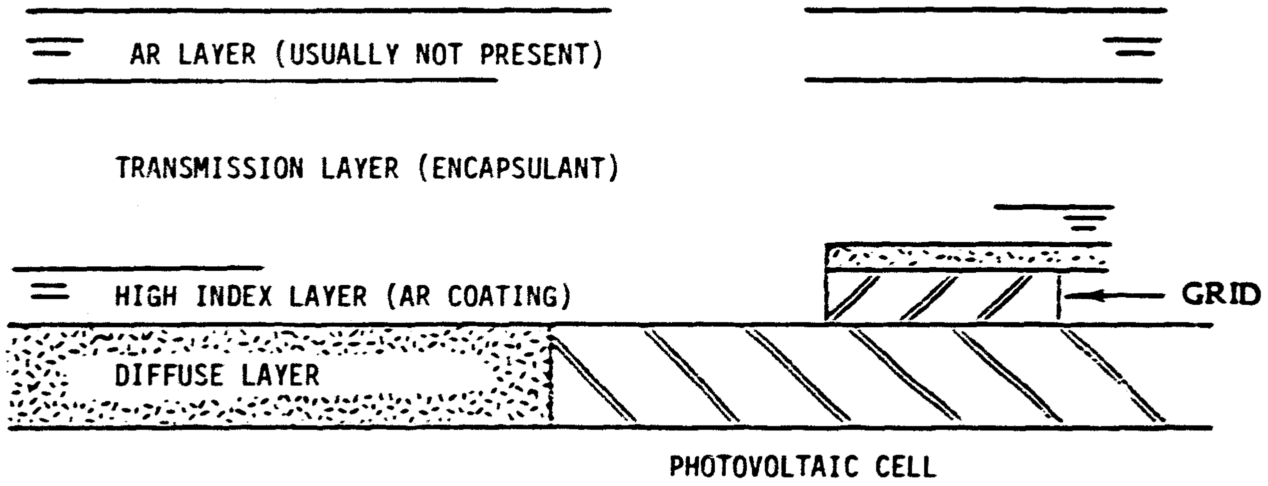


Figure 2-4. Detailed Definition of Cell Encapsulant Layering

Location	Variable Name	Variable Range	Comments
Anti-reflection Section	Thickness	Zero	
Layer A1	Index of Refraction		
.	Real	Discrete values from 1.23 to 1.50	Determined by material constraints
.			
.			
AN	Imaginery	Zero	
Transmission Section			
Layer T1	Thickness	0.50mm to 2cm	
.	Index of Refraction		
.	Real	Discrete values 1.5 to 2.0	Determined by material constraints
.			
TN	Imaginary	Absorption length 4m^{-1} to 0	
High Index Section			
Layer H1	Thickness	0.1mm to 1mm	
.	Index of Refraction		
.	Real	2.0 to 2.8	
.	Imaginary	Zero	
HN			
Diffusing Section	Reflectivity	0.75 to 1.00	
	Reflection pattern	empirical determined	Lambertian approximation used if no data available
Cell spacing	Packing fraction	0.90 to 0.10	
Cell grid	Grid coverage fraction		
	grid spacing	5 to 15%	grid width

Figure 2-5. Optical Variables to be Studied

(1) As a Lambertian distribution with empirical normalization

(2) As a fully empirical function of azimuth and elevation angles.

Method (1) is used for most of the work because it is simpler and of adequate accuracy for the highly diffuse reflecting surfaces of interest. Method (2) is employed to check test data. The SAI proprietary computer program causes results of gain versus one independent parameter to be printed out in graphical form. This will be explained in detail later in this section.

In summary, illustrations of photovoltaic module designs for a variety of packing factors is shown in Figure 2-6. The summary of the module thought to represent the industry 1980-82 baseline design is given in Figure 2-7.

2.2.7 Materials for Higher Index Layers

The index of refraction of the more common superstrates, glass and clear plastics is around 1.5. The maximum theoretical trapping gain has been determined to be $(N)^2$ hence glass can be expected to provide a maximum gain of 2.25. Tests, as stated earlier, have recorded gains of 1.8 and higher. If higher index materials are used for the diffusing layer of the panel gains should be increased. Figure 2-8 shows the maximum gain values for several candidate materials that range in values for N from 1.5 to 2.9 provided other material parameters, for example, transmission do not degrade this performance.

2.3 OPTICAL MODELING METHODS EMPLOYED

2.3.1 Introduction

Photovoltaic cells will be more effective if light can be easily concentrated to their active area. Two problems emerge when designing an optical concentrator, the cost for good optical systems and the loss of acceptance angle when concentrating. What is required is a very low cost optical system with a wide angular acceptance obviating the need for tracking.

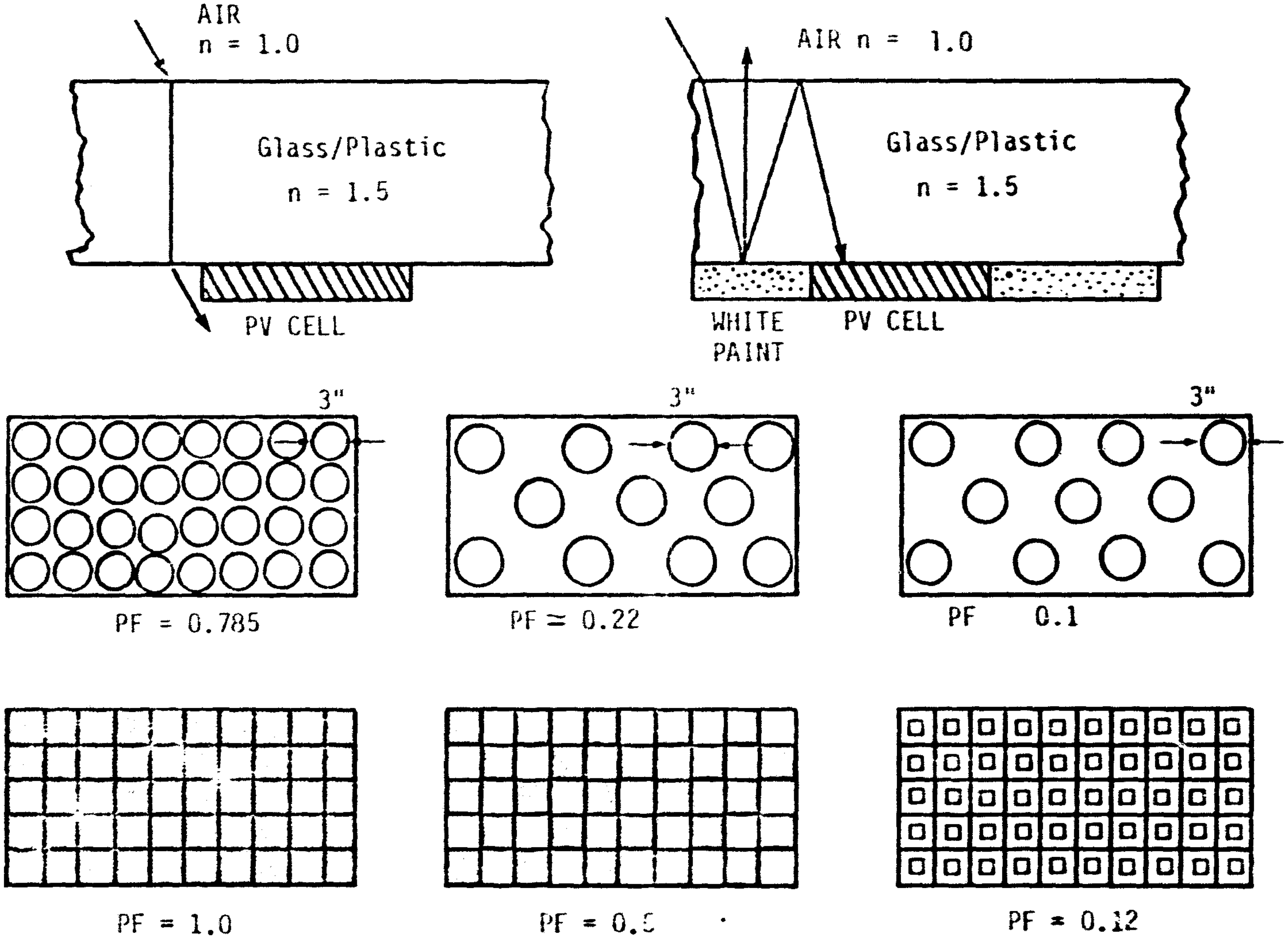


Figure 2-6. Module Layout, Cell Spacing Geometry

OPTICALLY IMPORTANT MODULE LAYERS FROM SUN SIDE DOWN	PREFERRED MATERIAL CHOICES AND NOMINAL THICKNESS	
	LAMINATION	CASTING
SUPERSTRATE DESIGN:		
TOP COVER	LOW IRON, TEMPERED SODA-LIME GLASS, 125 MIL MINIMUM	SAME
POTTANT	ETHYLENE VINYL ACETATE (EVA) OR ETHYLENE METHLYACRYLATE (EMA), 5 MIL MINIMUM	POLY-N-BUTYL ACRYLATE, OR ALIPHATIC POLYETHER URETHANE, OR GE SILICONE 534-044, 5 MIL MINIMUM
SPACER	NON-WOVEN GLASS MAT TO ACHIEVE MINIMUM POTTANT THICKNESS - CRANEGLAS	MAY NOT BE REQUIRED
SUBSTRATE DESIGN:		
TOP COVER	BIAXIALLY ORIENTED POLYMETHYLMETH - ACRYLATE (PMMA) OR TEDLAR, 3 MIL	SAME
POTTANT	NONE REQUIRED ON SUN SIDE	SAME
FOR EITHER MODULE:		
CELLS	FOUR INCH ROUND OR FOUR BY ONE INCH RECTANGULAR, PACKING FACTOR 0.6 TO 0.85	SAME

---

*SOURCE: JPL LETTER TO SAI OCTOBER 1, 1980.

Figure 2-7. Definition of Layers in Baseline Module Section*

MATERIAL	N	MAX GAIN
Glass	1.5	2.25
B_aSO_4	1.6	2.56
$MgCO_3$	1.7	2.89
Anatase	2.5	6.25
Rutile T_1O_2	2.6	6.76
Diamond	2.9	8.41

Figure 2-8. Index of Refraction and Maximum Trapping Gain for Several Candidate Differsing Layer Materials

Flat plate photovoltaic cell arrays utilize transparent encapsulation for environmental isolation, and generally have both intercell areas and intracell areas that are inactive. The technical innovations described here allow use of these inactive areas to trap light and thus to increase the optical radiation on the photovoltaic cells without loss of angular acceptance.

Optical concentrators normally imply loss of angular acceptance. It is generally required that a given optical concentrating system with concentration ratio C and angular acceptance θ satisfies the Abbe inequality[5] (in three dimensions) $C \leq (1/\sin\theta)^2$. This inequality is a straightforward result of the conservation of the area of phase space defined by the system. If the system is immersed in a medium of index n, the inequality becomes $C \leq (n/\sin\theta)^2$. When all angles are accepted the concentration (or gain) is less than or equal to n^2. To SAI's knowledge, no one has yet demonstrated a practical way to utilize the index effect with a system of full acceptance, for example, a flat plate solar energy system. This section describes SAI's concepts to exploit the higher index cover sheets that are required for environmental isolation on flat plate solar collectors to provide optical concentration in addition. The system described is a flat plat photovoltaic (PV) array, but similar use of these ideas in flat plate thermal systems or with electro-optical sensors are also possible.

The technique involves the trapping of light in the transparent covering of flat plate solar energy converters, see Figure 2-9. Light that reaches the photovoltaic cell active area is converted to electricity. That light which strikes intercell areas or cell grid (intracell areas) is diffused. Via this diffusion some percentage (typically 50 percent) is trapped in the encapsulant layer, the remainder is lost. The trapped light propagates in the layer and is either absorbed or rediffused. This basic process can increase the radiation on a cell by a considerable amount, (up to a 70% increase).

What the conclusions of this effort includes is that optical layers which are thick films are an important new optical design concept. The ability of thick films to propagate optical radiation in a transverse direction raises the

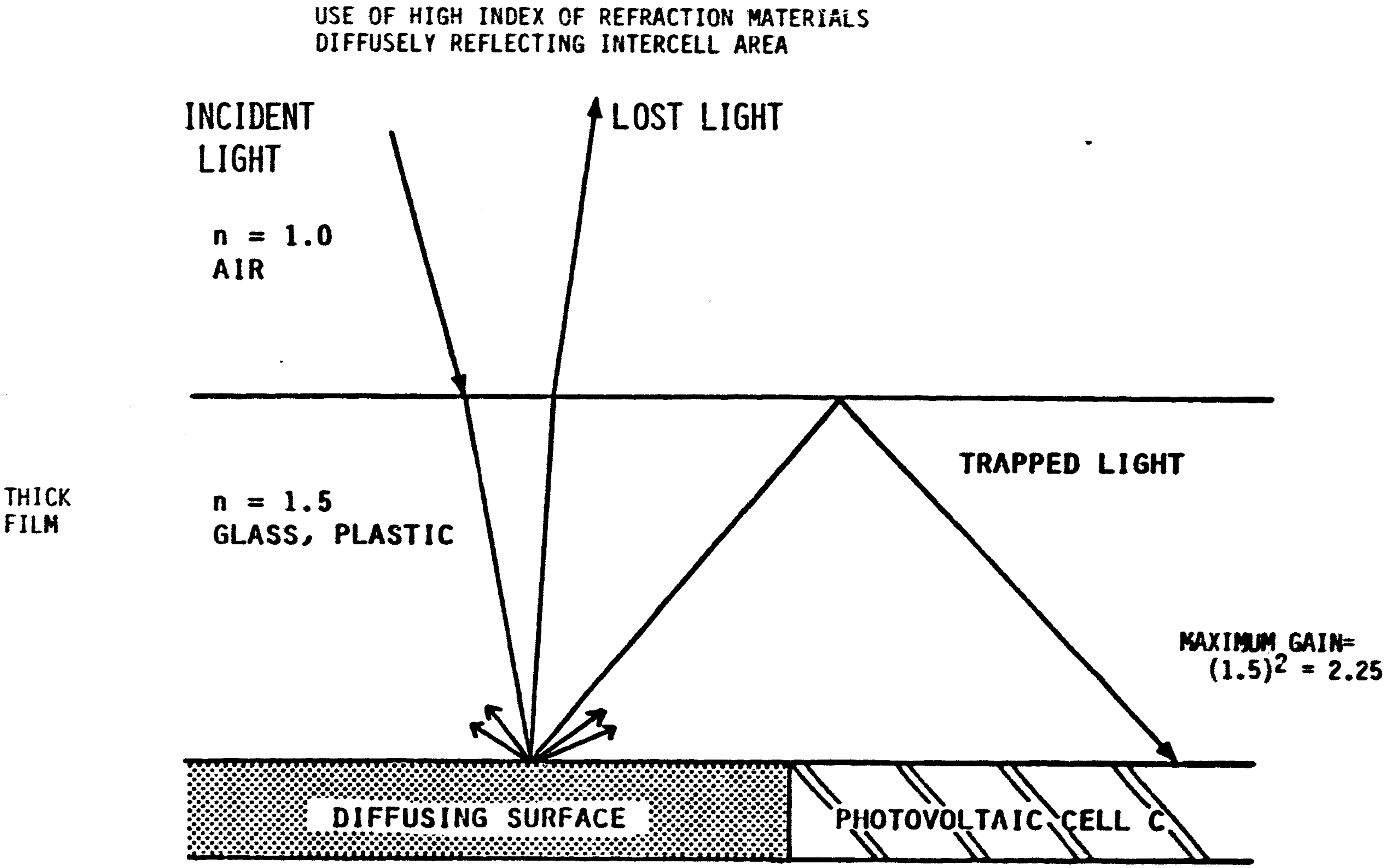


Figure 2-9. Light Trapping Concept

possibility that optical concentration (called gain) can be achieved. Such systems would have the following properties:

- Maximum theoretical gain for any receiving element would be limited to the square of the ratio of indices, $(\eta_{high}/\eta_{low})^2$
- Maximum gain for an array of elements that trap would be limited to the ratio of the total area to area of receiver, A_{total}/A_{rcvr}
- The gain wil be limited also by the absorption of the thick film.

As was discussed in Section 1, a thick film is inherently different from and useful in addition to an optical thin film. However little or no design information or equations exist in their use.

Thus SAI has modeled light trapping using closed form solutions, and Monte-Carlo simulation, and has conducted experiments to validate this modeling. These efforts are described briefly below.

2.3.2 Closed Form Solutions

The application described is a flat plate non-tracking sysem photovoltaic array in which photovoltaic cells are coupled to the back of a transparent sheet, with the intercell areas being coated with a highly reflective diffusing layer. Incident light strikes either PV cells or the diffusing surface: the diffused light which leaves the surface at an angle less than the critical angle ($\theta_c = \sin^{-1}(1/n)$ is lost, but the rest undergoes total internal reflection at the air-sheet surface and is directed back to the surface. The concentration arises from the fact that the cells receive both direct and diffused/reflected light. The amount lost in diffusion depends on the index of refraction of the trapping layer (n) and the diffusing pattern of the reflective surface. A procedure for calculating the gain of a light trapping panel is necessary for system design. In a limiting case of very many small PV cells distributed on the diffusing surface, the gain is easily calculated analytically. If the PV packing fraction is C and the fraction of diffused light lost out the critical angle is L, then for unit incident intensity, C is collected by cells directly with no diffusion, L(1-C) is lost, and T = 1-C-L+LC is rediffused, of which Ct is collected by cells, etc. Iteration of this argument yields a gain of $1/(1-t)$. This will be explained in more detail.

A simplified equation that will treat gain as a function of cell packing fraction and relative index of trapping layer can be derived in a straight forward way, assuming an infinte medium. Refer to Figure 2-10. By drawing out all the possible ray paths, and starting with one unit of intensity and applying the loss and reflection factors at each step, the series solution for gain is as given. Luckily this infinite series has a closed form sum, which is indicated in the figure. This case included no Fresnel loss. To include the Fresnel loss the calculation is similar. In detail, from Figure 2-10 we see that without the inclusion of a front Fresnel loss one would obtain on the cell:

$$C + (1-C)(1-L)C + (1-C)^2(1-L)^2C + \ldots$$

whereas, with no diffusion a cell would receive C units of energy. The gain is defined as:

$$\text{Gain} = G = \frac{\text{energy with trapping}}{\text{energy without trapping}}$$

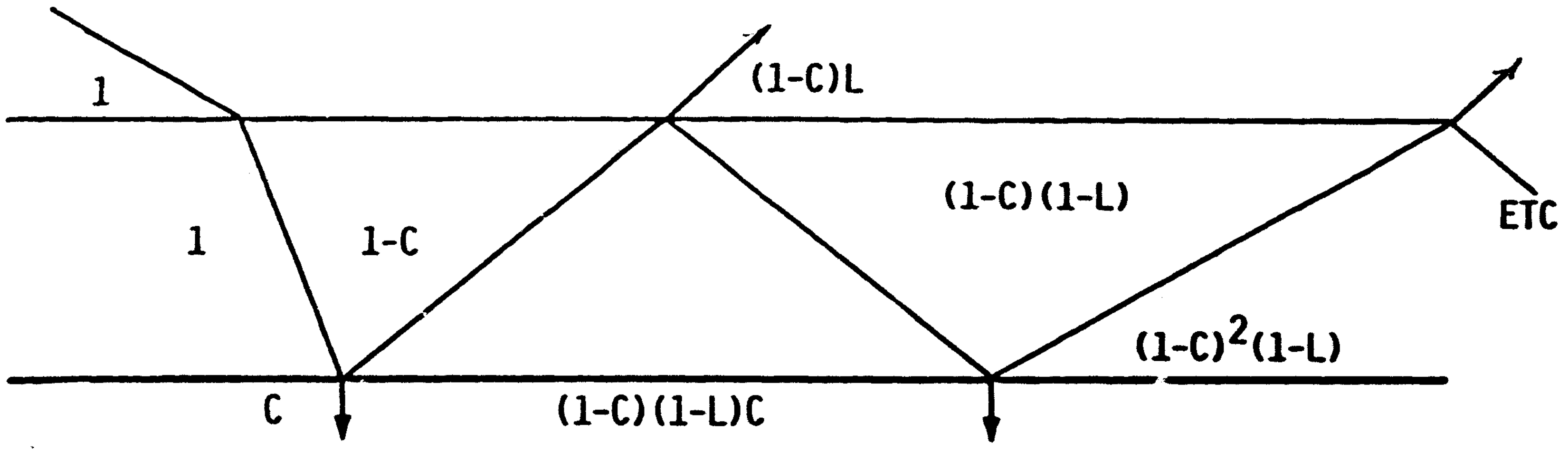
For the case of Figure 10, the gain is indicated in the figure.

When a front Fresnel loss coefficient F is added to the derivation of Figure 2-10, the series solution for the amount of energy received by the cell is given by:

$$(1-F)C + (1-F)C\,(1-C)\,(1-L) + (1-F)C(1-C)^2(1-L)^2 + \text{etc.}$$

whereas a cell with no diffusion would receive (1-F)C only. The gain is then

$$\sum_{n=0}^{\infty}((1-C)(1-L))^n = \sum_{n=0}^{\infty}(1-C-L+LC)^n = \sum_{n=0}^{\infty}(1+\alpha)^n = \frac{1}{\alpha}\,;\ \alpha = C+L-LC$$



$$G = \left[1 + \underbrace{(1-C)(1-L)}_{1-C-L+LC} + (1-C)^2(1-L)^2 \cdot \cdot \cdot\right]$$

$$G = \sum_{n=0}^{\infty} (1-C-L+LC)^n = \sum_{n=0}^{\infty} X^n = \frac{1}{1-X} = \frac{1}{C+L-LC}$$

Figure 2-10. Derivation of Closed Form Solution
Case of no Fresnel Loss

or

$$G = \frac{1}{C+L-LC},$$

which is the gain for an encapsulated cell with diffusion trapping, this gain is given by:

$$G' = \frac{1-F}{C+L-LC}$$

for a cell compared to a bare cell (no encapsulant)

The terms in the series are all easily estimated

N = ratio of inner to outer index = n_2/n_1

C = packing fraction, set by initial conditions

F = Fresnel loss at front face

$$\left(\frac{n_2-n_1}{n_2+n_1}\right)^2 = \left[\frac{(n_2/n_1)-1}{(n_2/n_1)+1}\right]^2 = \left(\frac{N-1}{N+1}\right)^2$$

L = loss due to no-total internal reflection

$$L = 1-\cos^2\theta_c = \sin^2\theta_c$$

By Snell's Law

$$\sin^2\theta_c = \left(\frac{n_1}{n_2}\right)^2 = \left(\frac{1}{N}\right)^2$$

Therefore

$$\lim_{C\to o} G = \frac{1}{C+L-LC} = \frac{1}{L} \text{ as } C \to 0$$

$$= \left(\frac{n_2}{n_1}\right)^2 \cong (N)^2 \text{ as } C \to 0$$

Thus the gain approaches the theoretical limit when the cell packing fraction goes to zero.

Likewise when the packing fraction approaches one an important limit is reached

$$\lim_{C \to 1-E} G = \frac{1}{(1-E)+L-L(1-E)}$$

$$= \frac{1}{1-E+LE}$$

$$= \frac{1}{1-E(1-L)}$$

$$1+E(1-L)$$

Thus the gain of the small diffusing area, E, is (1-L) indicating only a one "bounce" approximation gives a reasonable result.

In a similar way we derived simplified expressions for the case where a Fresnel reflection F at the n_1 to n_2 interface is included. A second set of of rays were were generated and an equation developed as shown previously. The result is

$$G = \frac{1}{C+L-LC-LF+LCF}$$

The case of a finite reflectivity R at the lower, diffusing boundary was also considered. When every ray leaving the diffusing surface is reduced by R, the gain expression becomes

$$G = \frac{1}{1-R(1-C-L+LC+LF-LCF)}$$

Finally when less than the optimum thickness is used the gain is reduced. Empirically the optimum thickness is $t/\ell \approx 0.3$, when t is the thickness and ℓ the size of the active cells. By analysis of exact calculation (to be explained in section 2.3.2) it was determined that

$$G(T) = 1 + G(o)-1 \quad (1- 1- \frac{3.33t}{\ell}{}^{3})$$

In later entries G(0) is called G_o for simplicity.

These equations can also be applied to the cases where two or more layers are used. A simple equation for employment in two layers of n_2, t_2 and n_3, t_3 is given by

$$N = n_3 + t_3 (n_3 - n_2)/t$$

where $t = t_2 + t_3$

This rule (discussed in more detail in Section 4) can be applied in any of the prior equations. It is obvious that a similar equation for three or more layers could be developed.

These equations have been programmed on a HP9845 microcomputer and used to estimate the performance of the systems designed in the remainder of the report.

In conclusion, the simplest form of the closed form approximate solution (Figure 2-11) uses these assumptions:

- Single trapping layer, index n_2; placed in air, index n_1
- No absorption in layer
- No Fresnel reflections
- Homogeneous mixture of diffusing layer and cells
- Perfect diffuse (Lambertian) reflection between cells.

1) GAIN WITH NO FRESNEL REFLECTIONS

$$G_o \; 1/(C+L-LC)$$

2) GAIN WITH FRESNEL REFLECTION AT TOP LAYER

$$G_o = 1/C+L-LC-LF+LCF)$$

3) GAIN WITH FINITE REFLECTIVITY $R \leq 1.0$

$$G(R) = 1/ \left[1-R(1-C-L+LC+LF-LCF) \right]$$

4) GAIN FOR LESS THAN OPTIMUM THICKNESS $t/\ell \leq 0.3$

$$G(T) = 1 + \left[G_o - 1 \right] \; (1 - (1-3.33t/\ell)^3$$

5) THE EFFECT OF R AND t CAN ALSO BE INCLUDED

$$G = f(\ell, R, N, t, C)$$

6) EFFECTS OF ADDITIONAL LAYERS CAN BE ADDED BY MODIFYING THE SINGLE LAYER EQUATION VALUES FOR N AND t

$$G = f(\ell, R, fN(n_2, n_3, \ldots), ft(t_2, t_3, \ldots), C)$$

Figure 2-11. Simplified Design Equations

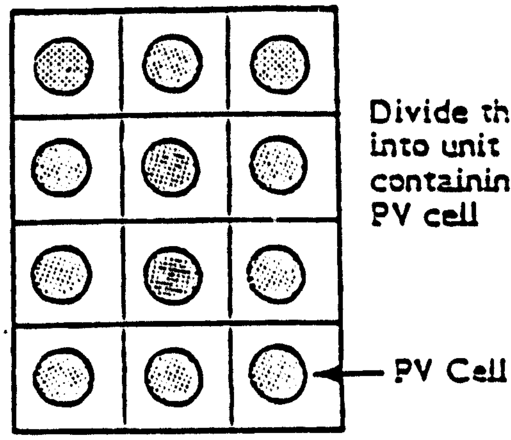
All the closed form calculations assume that the light propagated through the trapping layer travels a distance large compared to the cell size and intercell spacing, so that the packing fraction seen by diffused rays is the same as that for the system as a whole. This assumption breaks down for panels where the cells of finite size are either very widely or very closely spaced, and for trapping layers which are quite thin. A more general approach using Monte Carlo techniques takes account of these and other effects are discussed next.

2.3.3 Monte Carlo Simulation

A computer model was developed which treated the problem of light diffusion and propagation by Monte Carlo methods. Here, each diffused unit of light is broken up into 100 individual rays, each of which is individually propagated through the optical system. These rays are given angles and energies which effectively sample the real distribution of diffused light; the distribution is integrated by randomly choosing the rays' angles so that the distribution of rays is flat in solid angle; each ray is then weighted (given the appropriate fraction of the total light energy to be diffused) by the diffusion intensity distribution of the surface being modeled. Propagation of the rays includes the effects of Fresnel reflection at boundary layers, (for the case of two transparent layers of different refractive index) attenuation losses in the transparent medium, and non-unity total reflectance of the diffusing surface.

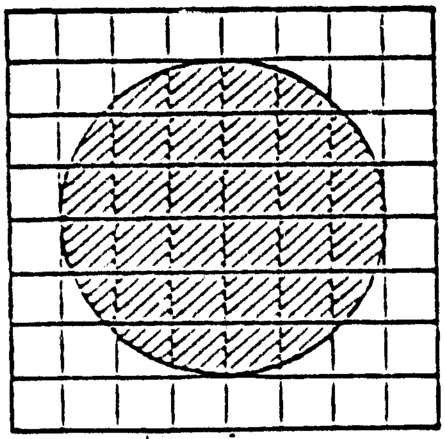
For the calculations reported here, we have modeled the diffuse reflector as a pure Lambertian surface. The white paint surface was found to be Lambertian except that deviations from the Lambertian distribution at large incident angles were measured. These did not affect the calculated gain to any great extent when modeled and compared to the pure Lambertian case.

The surface and diffusing model described above is applied to a light trapping PV panel by dividing the panel into square subdivisions each containing a single PV cell (Figure 2-12). This square is the basic unit modeled, and it is assumed that a panel is an infinite plane of such squares, to avoid any edge effects in the calculation. The square if further divided into a large number of "cells", each of which is designated as a diffusing cell or an active (PV area) cell. One unit of light is assumed incident on each cell: light on active cell is absorbed and accumulated; light on diffusing cells is broken up and propagated as described above. Rays leaving the unit square are assumed by reciprocity to represent rays leaving another such square in the panel, from the same cell and in the same direction; the ray "comes down" on the appropriate cell in the modeled square. Alternatively, the model can regard the exterior of the unit square as totally black; all light leaving is lost and no light enters from outside. The propagation procedure is followed for each of the diffusing cells, the light energy deposited in each cell from diffusion is accumulated, and the process is repeated until less than 1% of the original light remains to be rediffused. The gain is then the total quantity of light accumulated by the active areas divided by the quantity which they would have received without trapping.



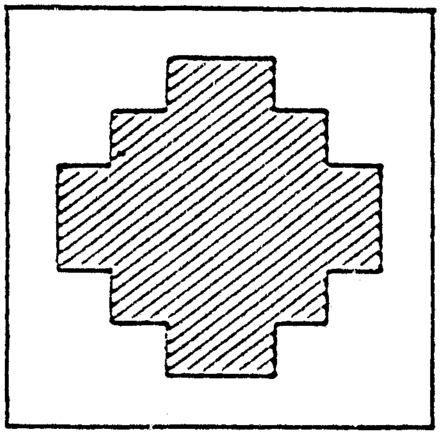
Divide the panel into unit squares containing a single PV cell

Solar Panel



Divide the unit square into cells

Unit Square



Designate each cell as active (PV) or diffusing area

Unit Square

Figure 2-12. Model Preparation

2.3.4 Validation of Optical Model

SAI has measured the gain in a small light trapping system consisting of a single 2 cm square cell coupled to the center of a large square of ½" thick plastic; the diffusing surface is white paint on the bottom. The packing fraction was varied by masking off areas of the top surface and measuring the total power arriving at the cell. This procedure is simple and relatively free from systematic biases, but it does undermeasure the gain since there are no contributions to the single cell from light incident beyond the square. However, some of the light diffused beyond the square will be diffused back in, and the mask on the top surface of the plastic did not create sharp edges on the diffusing surface. The results of the model calculation for the "black exterior" and the "infinite panel" cases are shown in Figure 2-13 as the bottom and top solid lines, along with the measured gains. The dashed line is an average of the two calculations, representing an estimate of the effects of back diffusion and fuzzy edges mentioned above. The agreement is quite satisfactory, considering the uncertainties.

The model has been used to calculate numerous cases in which the packing fraction, the refractive indices and thicknesses of one and two trapping layers, and the cell size have been varied. These studies indicate that the gain is strongly driven by both packing fraction and trapping layer thickness. The refractive indices are also important but in practice are less amenable to independent choice on purely optical grounds.

The gain is dependent on good optical coupling of both diffuser and PV cells to the trapping layer, and is strongly dependent on the layer thickness and the packing fraction. These facts suggest that optimization of the design of production line panels making use of the trapping effect is very important, and that presently available white-backed PV panels may not be utilizing optical trapping fully.

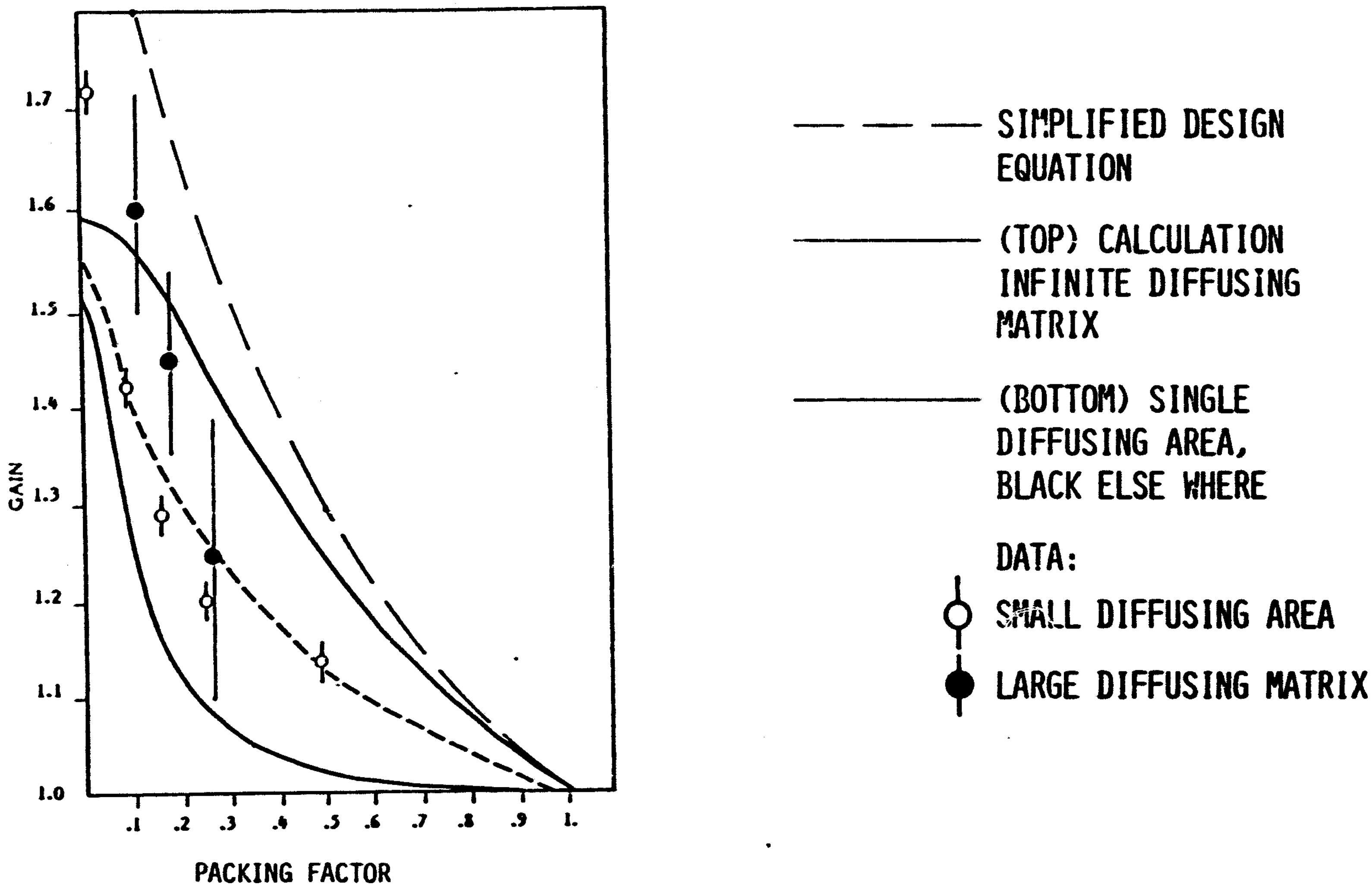


Figure 2-13. Experimental Confirmation

The achievable gains offer a real possibility for reducing the cost/watt of photovoltaic power in the near and medium term. The effect should be used in production design studies to determine the feasibility of its application to production panels; a design handbook incorporating both physical and costing model results should be developed for designers and manufacturers; the use of the effect in other than flat plate PV systems (e.g., concentrating PV or solar thermal systems) should be investigated.

2.4 DESIGN EQUATIONS

2.4.1 Closed Form Results

Using the closed form equations derived in section 2.3.1, a series of design graphs have been developed to cover the following ranges of parameters:

- single encapsulant layer index of refraction n=1.5, 2, 2.5, 2.8
- backing fraction 0 to 1.0
- normalized encapsulant layer thickness t/l 1, 1/2, 1/6, 1/8, 1/12, 1/16, and 1/24

Gain versus packing factor is plotted in Figures 2-14 through 2-17 for 4 inch diameter cells reflectivity R=0.85.

2.4.2 Comparison of Closed Form With Monte Carlo Results

The next step is to compare the closed form solutions with the Monte Carlo results and to make whatever empirical modification to the closed form to bring them into better agreement with the Monte Carlo results. Based on that comparison SAI has reparameterized the closed form equation to match the array of Monte Carlo modeling results, in a simple set of equations to aid the designer in estimating the gain to be expected from a light trapping configuration. It should be emphasized at this point that the Monte Carlo results and the simplified equation are expected to be valid only for modules using substantially round or square cells, especially for low t/ℓ. One can expect higher gains than those reported here for the case of long thin cells, and the improvement will increase as t/ℓ decreases.

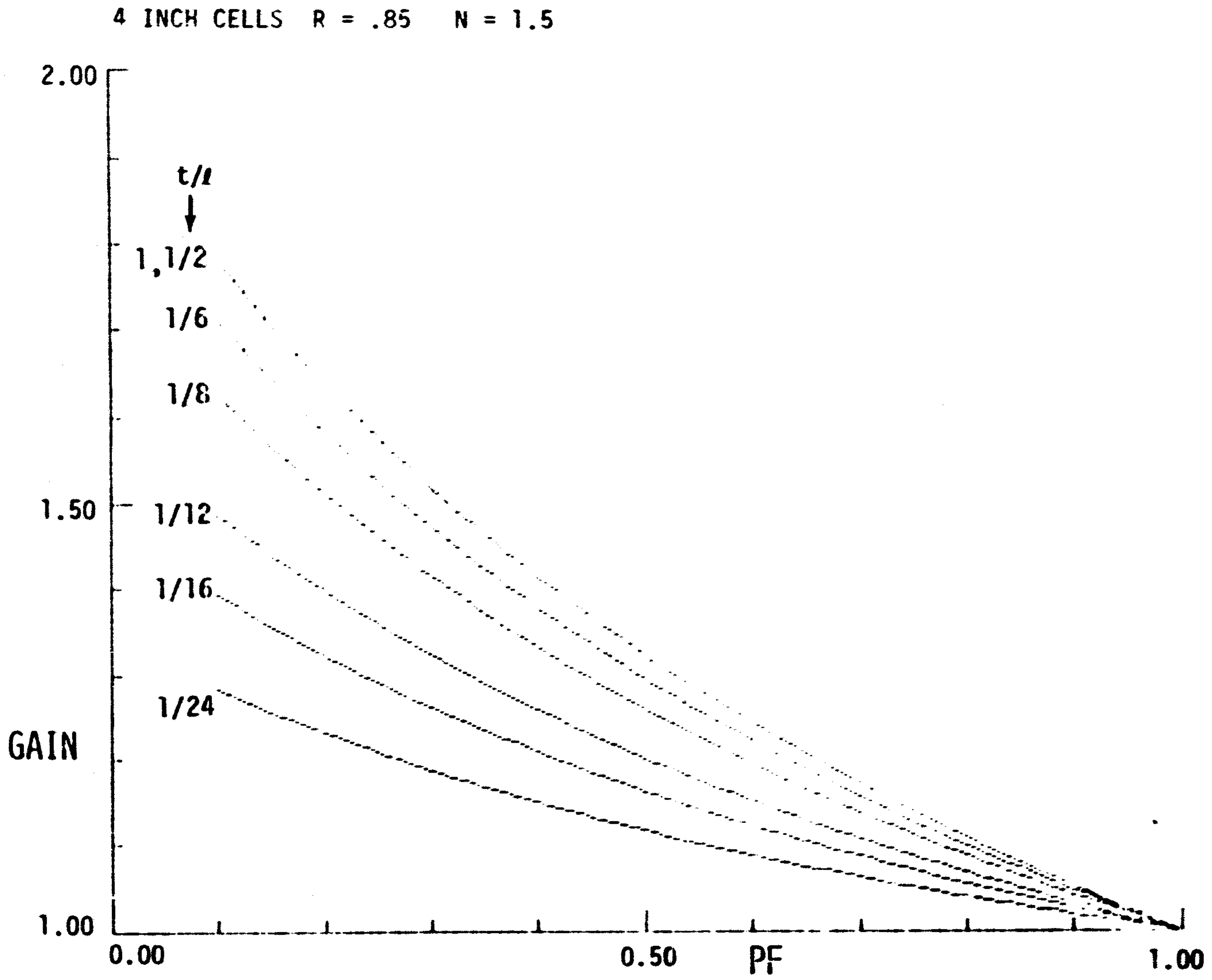


Figure 2-14. Design Equations for Various Index of Encapsulant, Thickness and Packing Factor

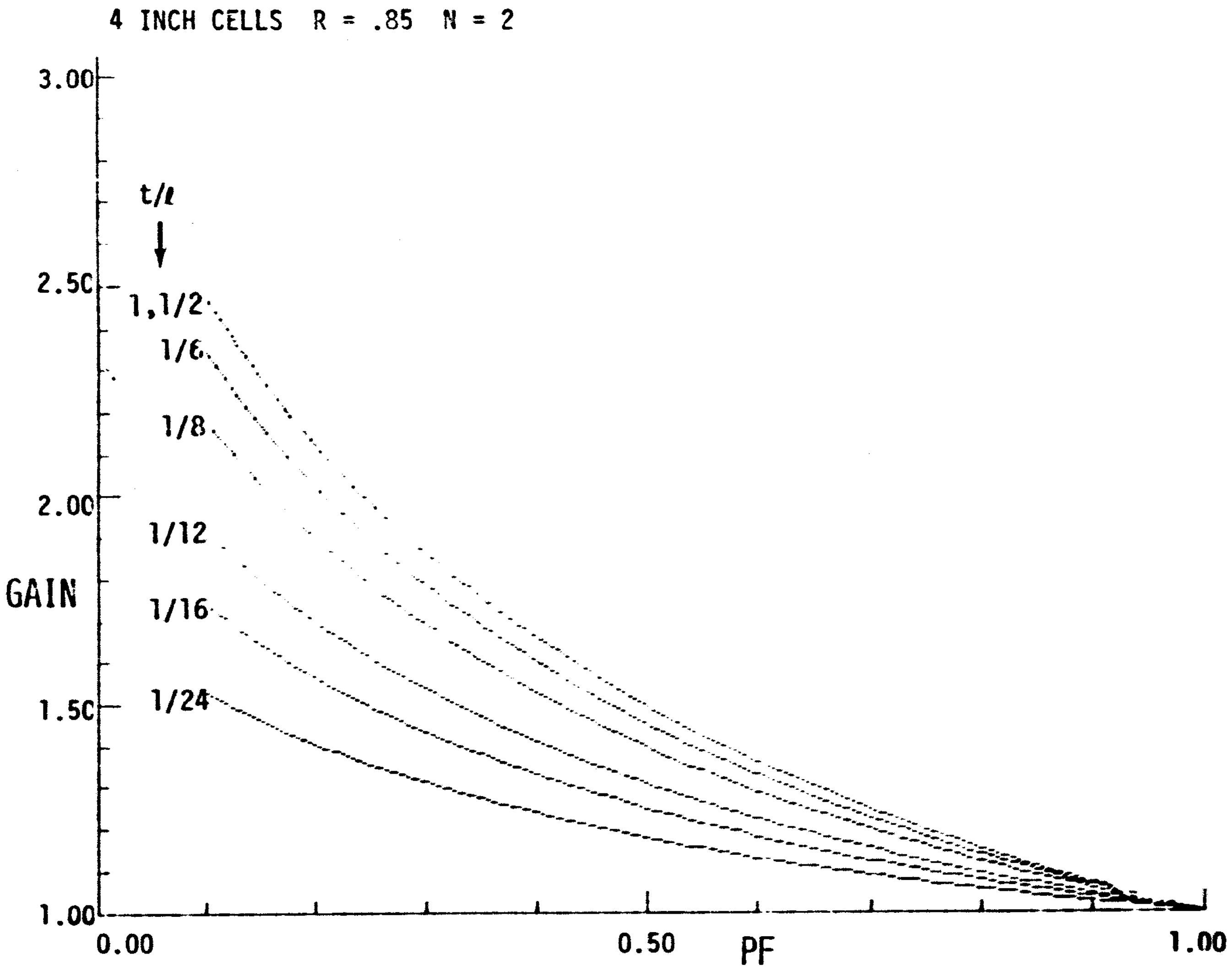


Figure 2-15. Design Equations for Various Index of Encapsulant, Thickness and Packing Factor

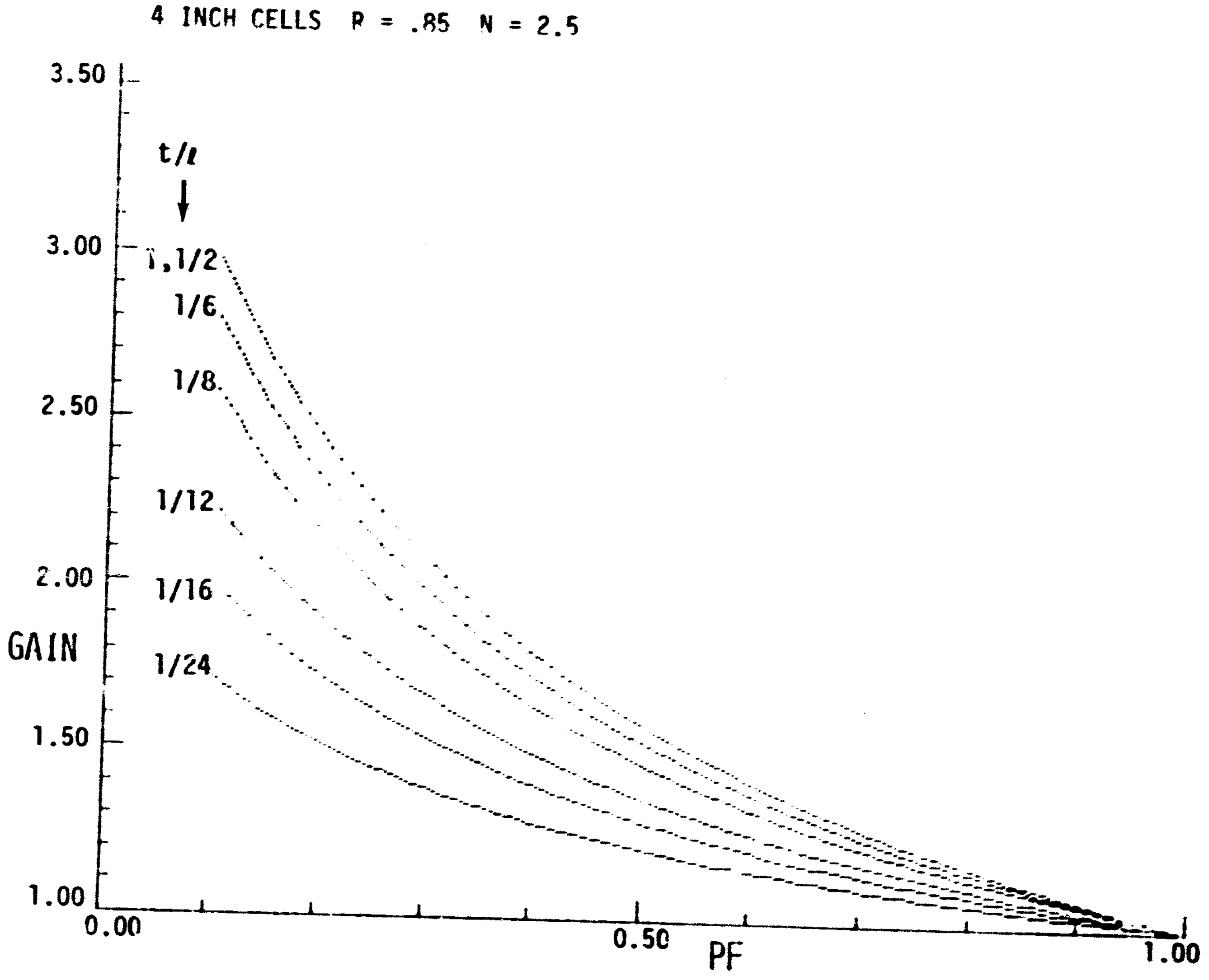


Figure 2-16. Design Equations for Various Index of Encapsulant, Thickness and Packing Factor

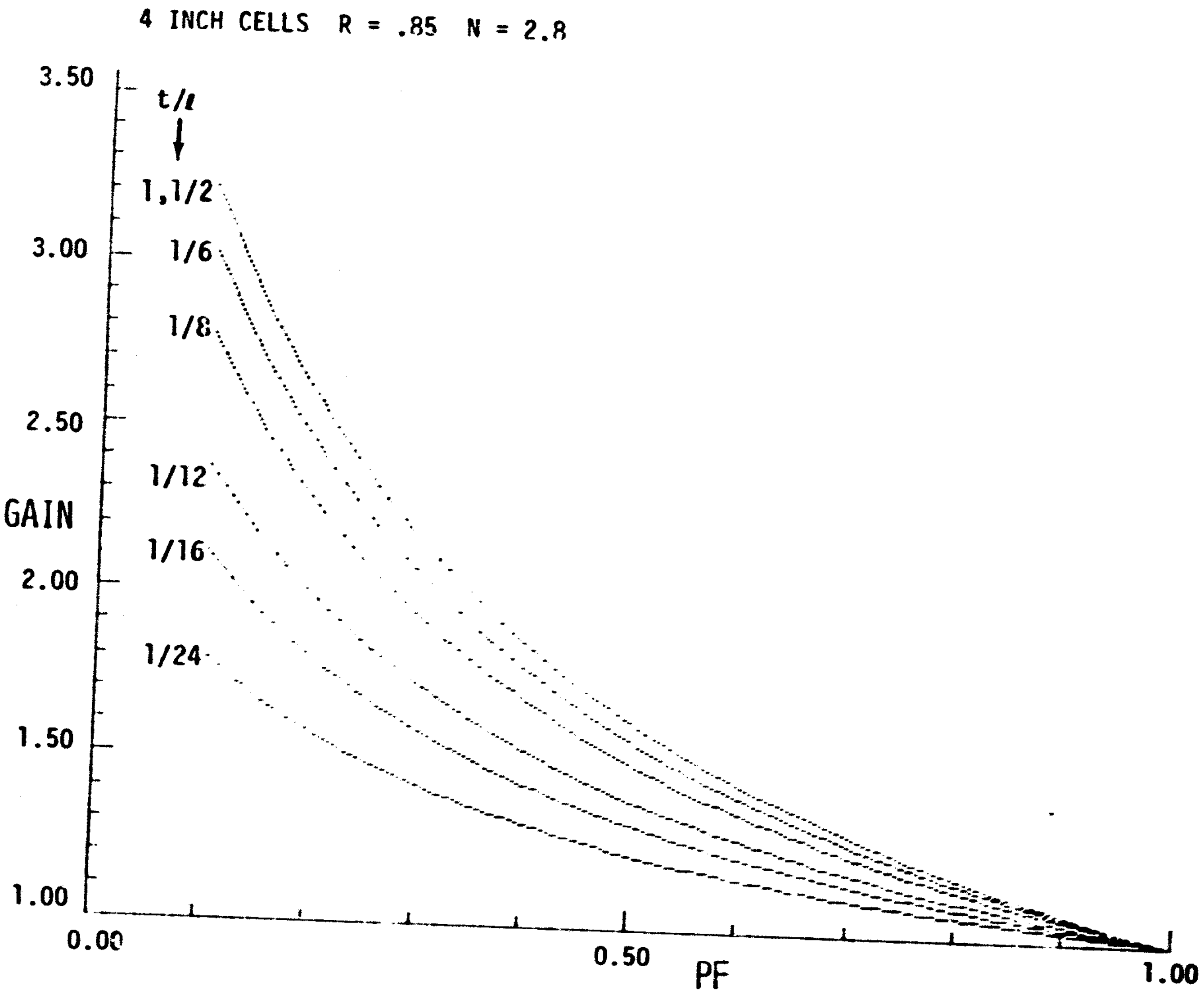


Figure 2-17. Design Equations for Various Index of Encapsulant, Thickness and Packing Factor

Figure 2-18 shows the Simplified Design Equations, and Figures 2-19 to 2-33 show the equations plotted against the Monte Carlo results (points). The closed form equation versus computer calculation comparison form is as follows:

- Labels
    - Cell diameter (inches) or side if square
    - Reflectivity of white diffusing layer, R
    - Total thickness above cell, t
    - Index of refraction above cell, N
- Axes
    - Y axis, gain on cell, G
    - X axis, packing factor, PF
- Line
    - Closed form equation
    - Points, Monte-Carlo mean (X) and error (BAR)

The case of 4" diameter cels with 1/8" trapping is of special interest as those dimensions are representative of currently produced modules. We have fit the data for this case, using two values for the reflectivity, to a two-straight-line model. The results are shown in Figures 2-34 and 2-35. The fits are displayed in Figure 2-36.

2.5 COST BENEFIT METHODS EMPLOYED

This section discusses how costing information is used to compare cost to performance. A simple sketch of the solar cell, and its surrounding diffusing area is shown in Figure 2-37. In this analysis it is assumed that the performance characteristics of this sector is identical to those characteristics of the entire collector which may be composed of many of these square sectors, the number depending on desired peak power output.

Simplified Design Equations

n = index of refraction of trapping layer

ℓ= diameter of solar cell

t = thickness of trapping layer

R = total reflectance of diffuser

C = packing fraction of module

L = diffused lost through critical core = $(1/n)^2$

F = Fresnel reflectivity of air-layer interface = $(n-1)^2/(n+1)^2$

$$G_o(C) = \left[1 - R(1-C-L + LC + LF - LCF)\right]^{-1}$$

P_o = Packing Fraction turn-over point

$$= 0.8 - 2(t/\ell)$$

G = gain

$$= \begin{cases} 1 + \left[G_o(c)-1\right] \left[1-(1-3.33\ t/\ell)^3\right] & C > P_o \\ 1 + \left[G_o P_o)-1\right] \left[1-(1-3.33\ t/\ell)^3\right] & C \leq P_o \end{cases}$$

Figure 2-18. Simplified Design Equations

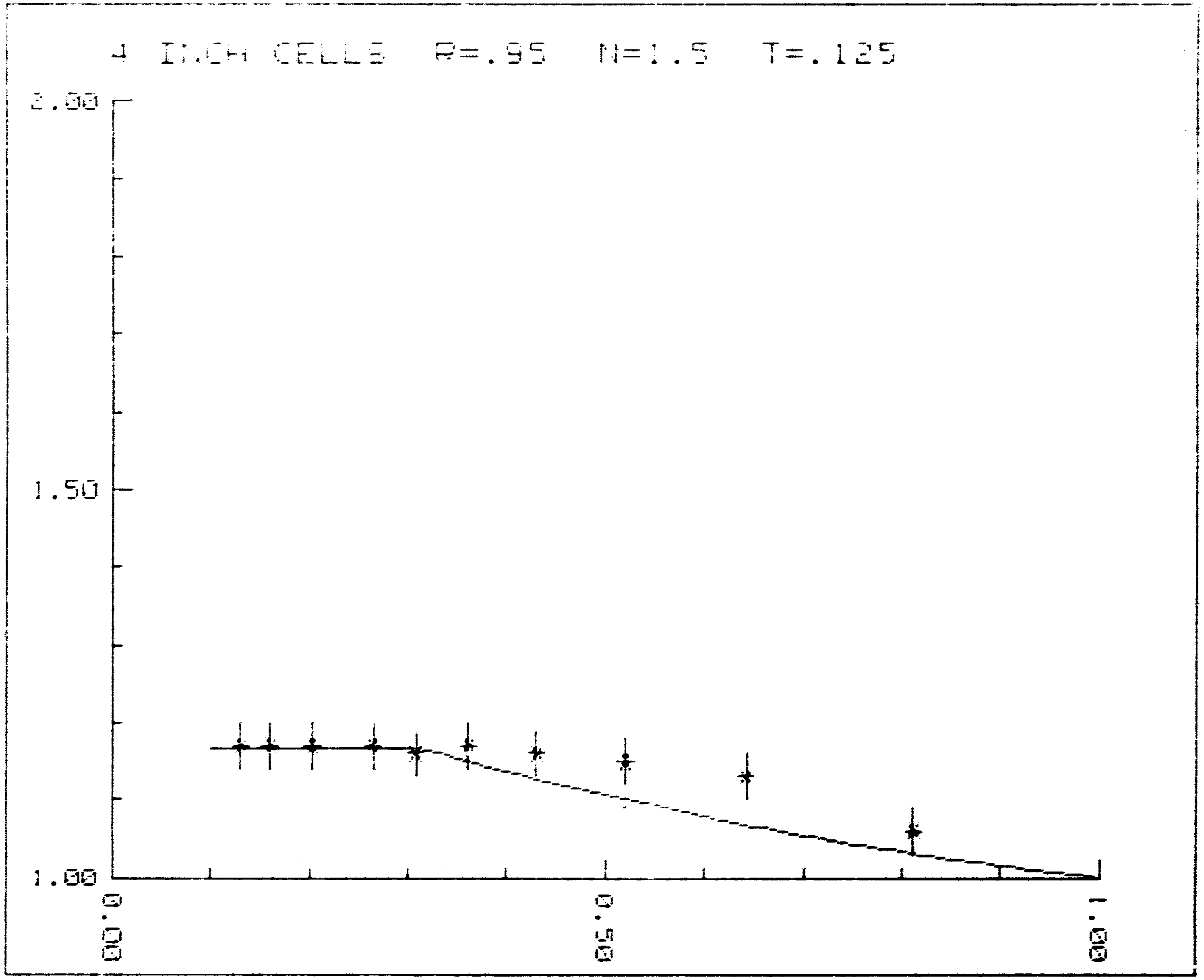


Figure 2-19 Results From Equations Plotted Against Monte Carlo Results

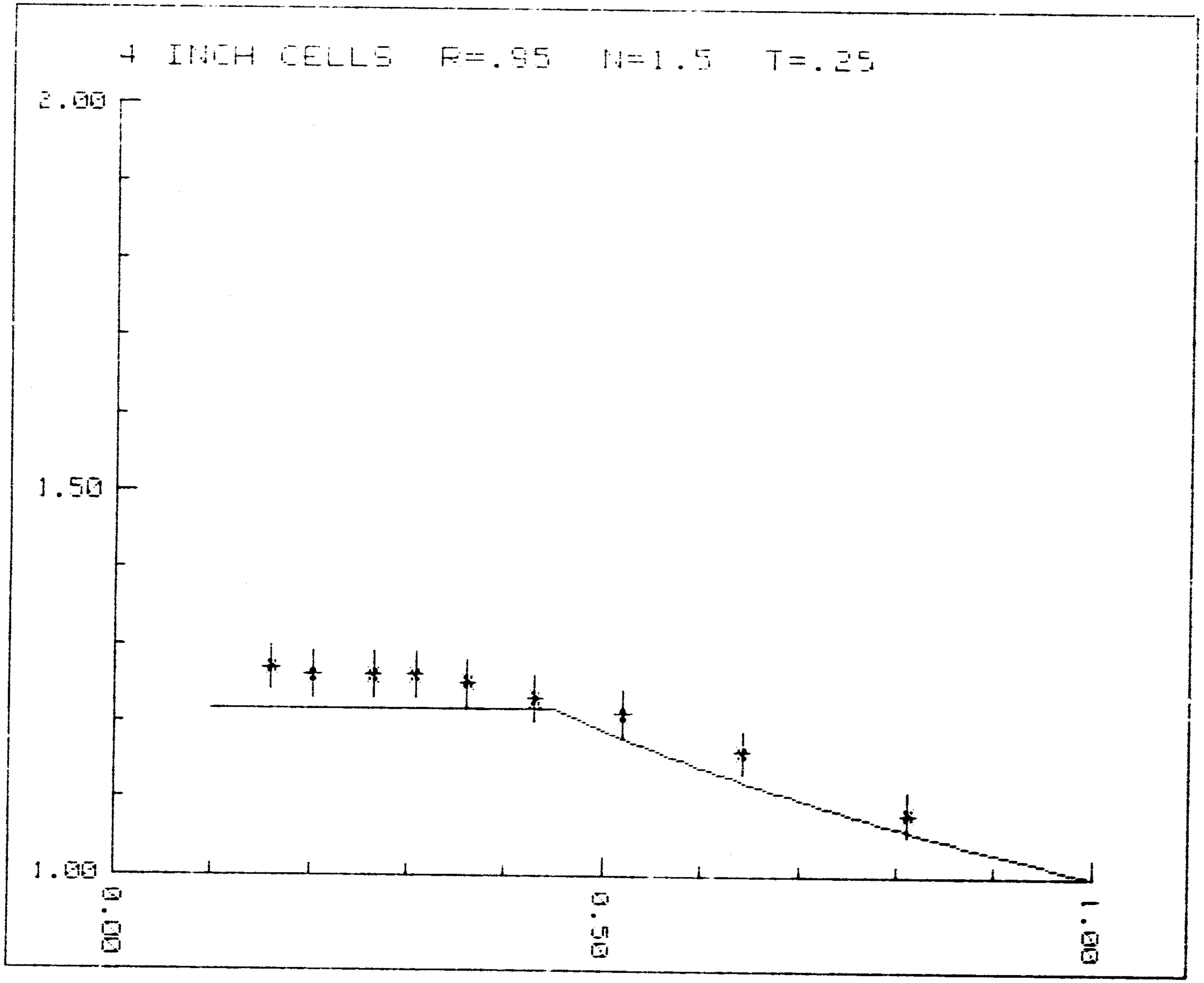


Figure 2-20 Results From Equations Plotted Against Monte Carlo Results

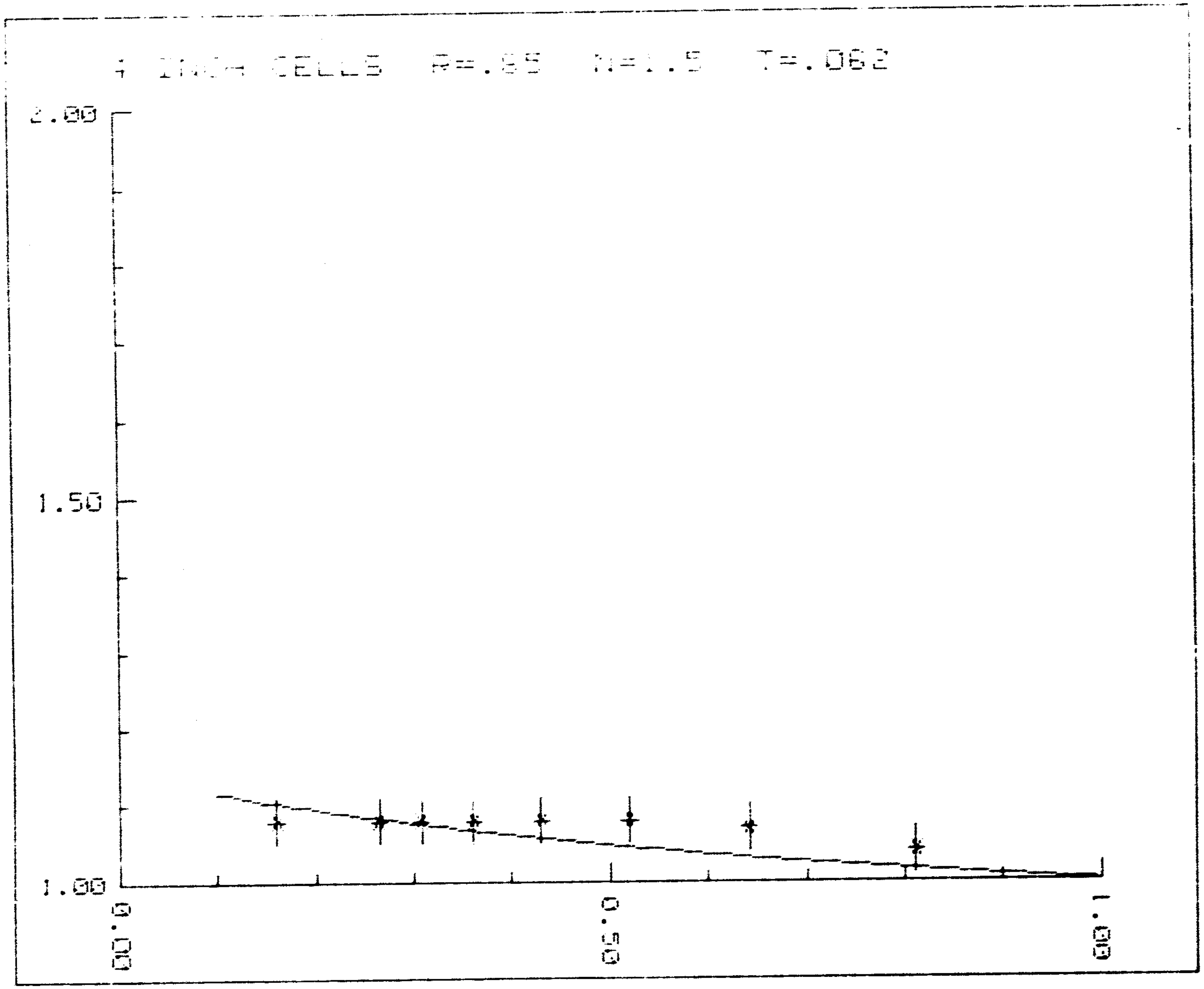


Figure 2-21 Results From Equations Plotted Against Monte Carlo Results

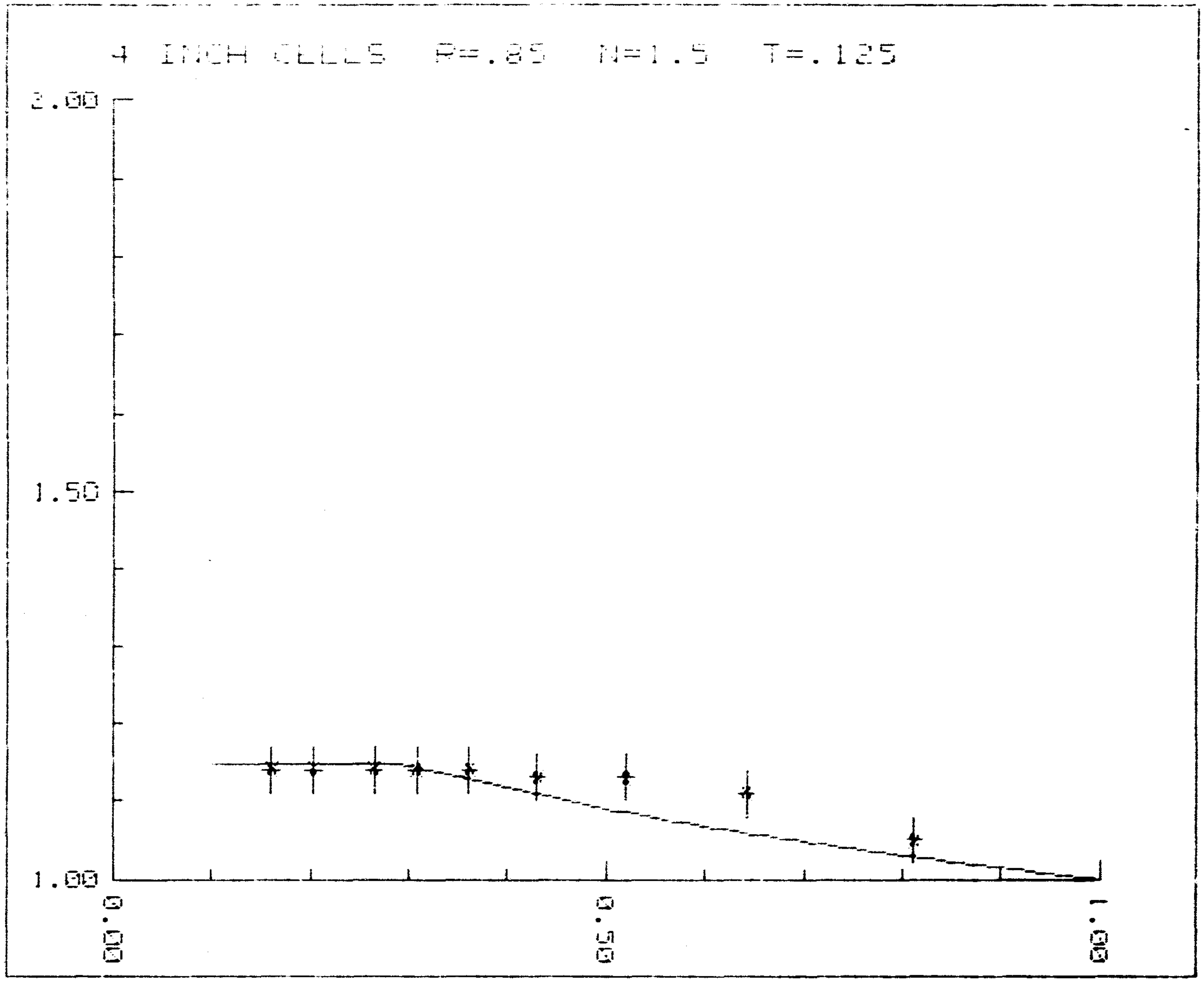


Figure 2-22 Results From Equations Plotted Against Monte Carlo Results

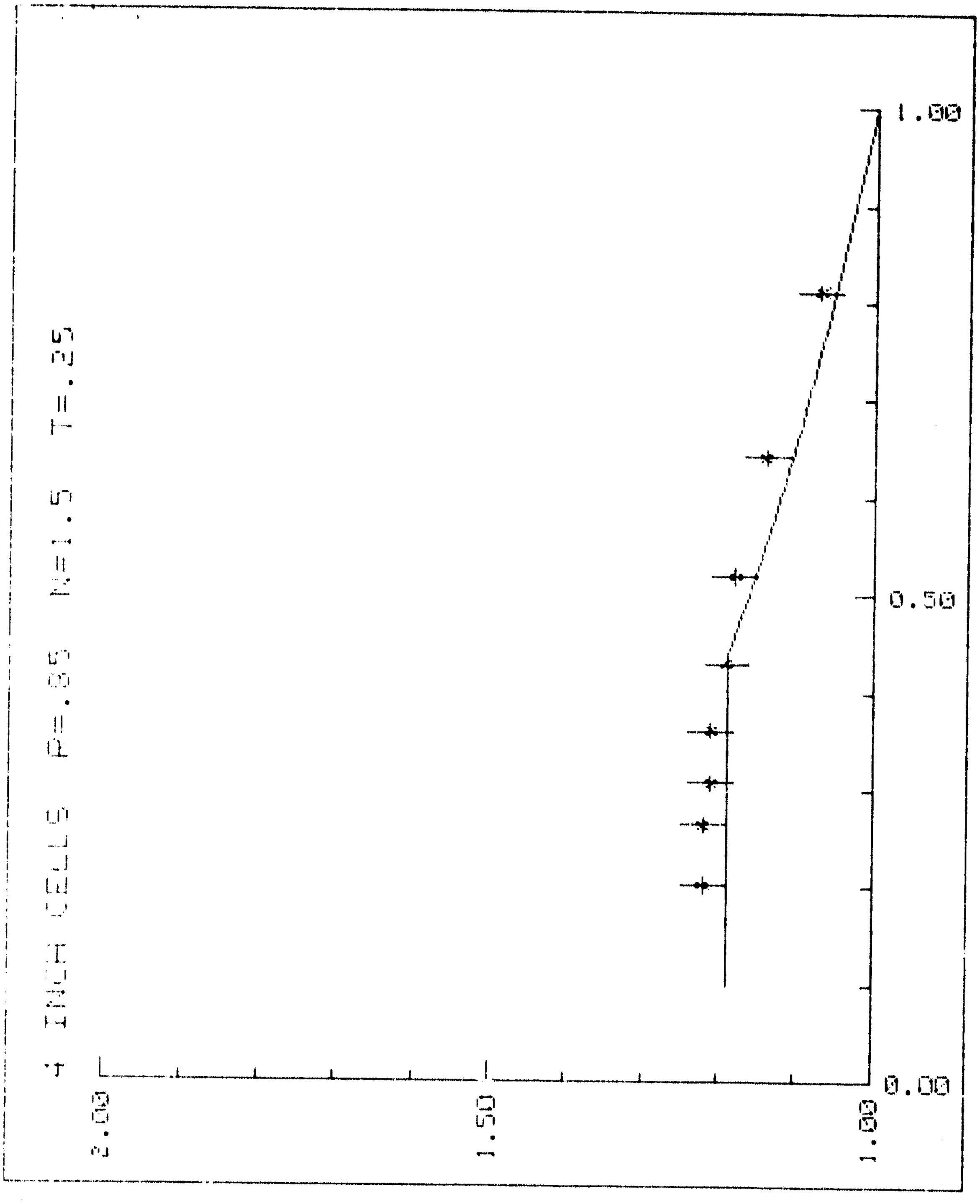


Figure 2-23 Results From Equations Plotted Against Monte Carlo Results

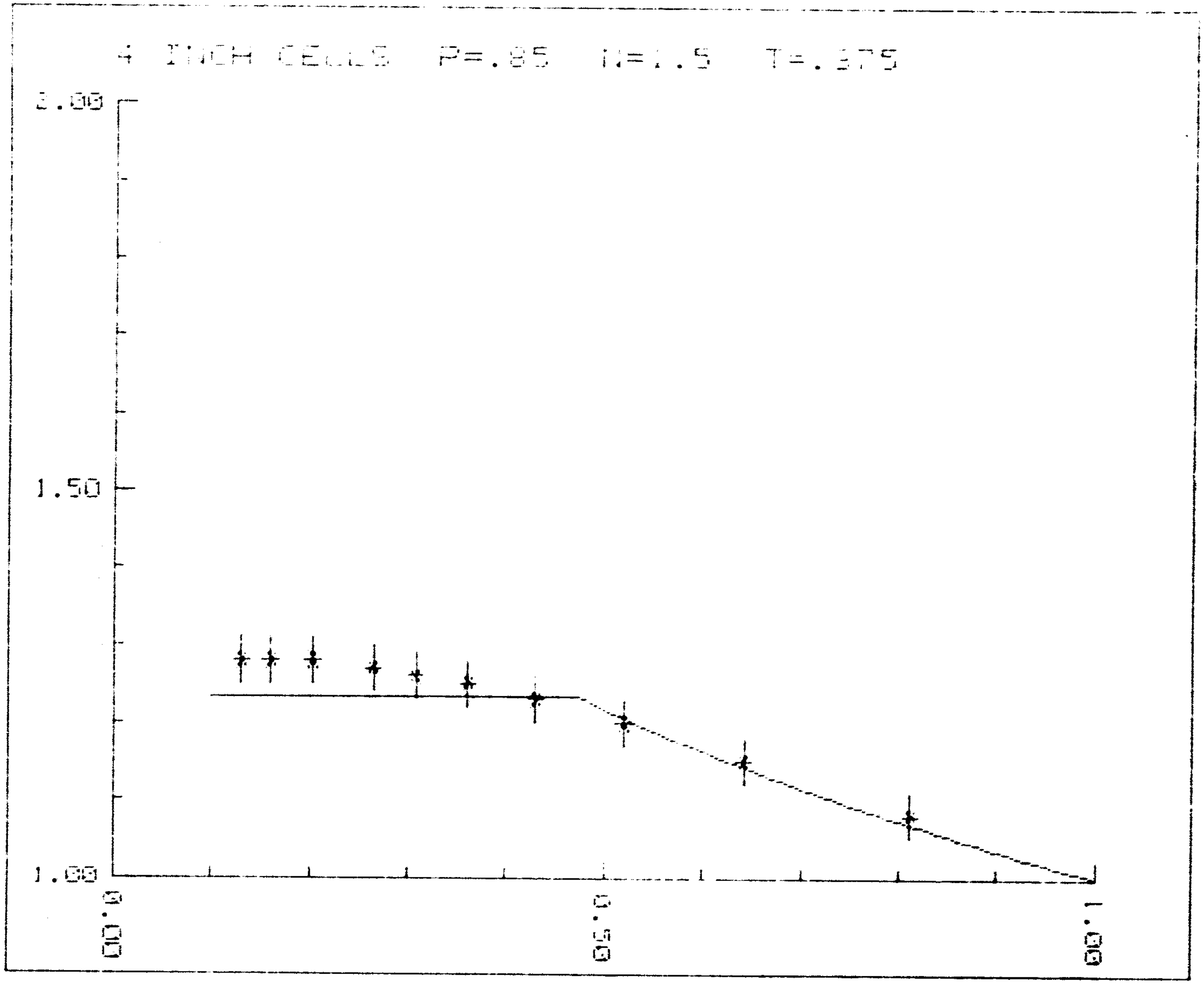


Figure 2-24 Results From Equations Plotted Against Monte Carlo Results

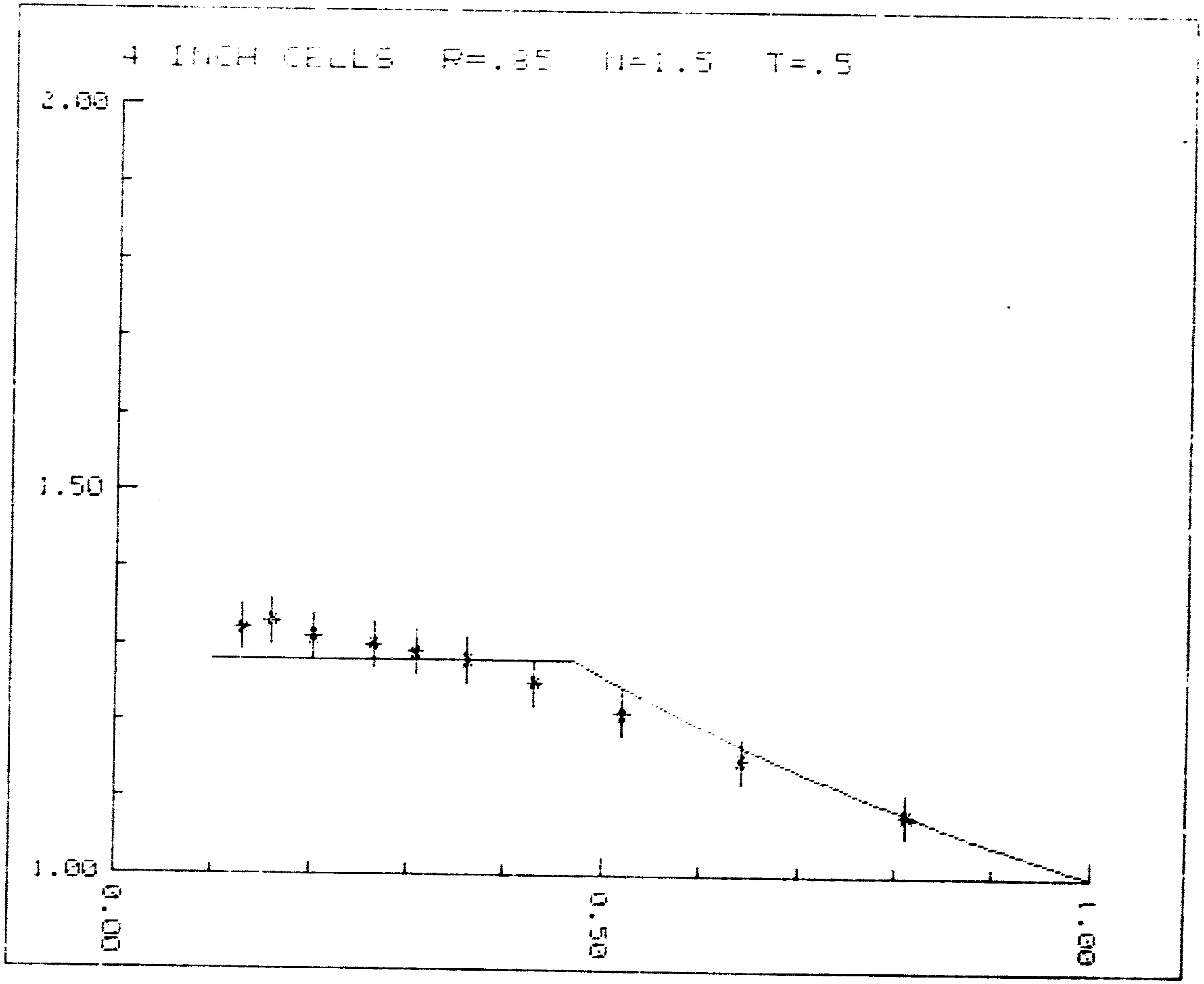


Figure 2-25 Results From Equations Plotted Against Monte Carlo Results

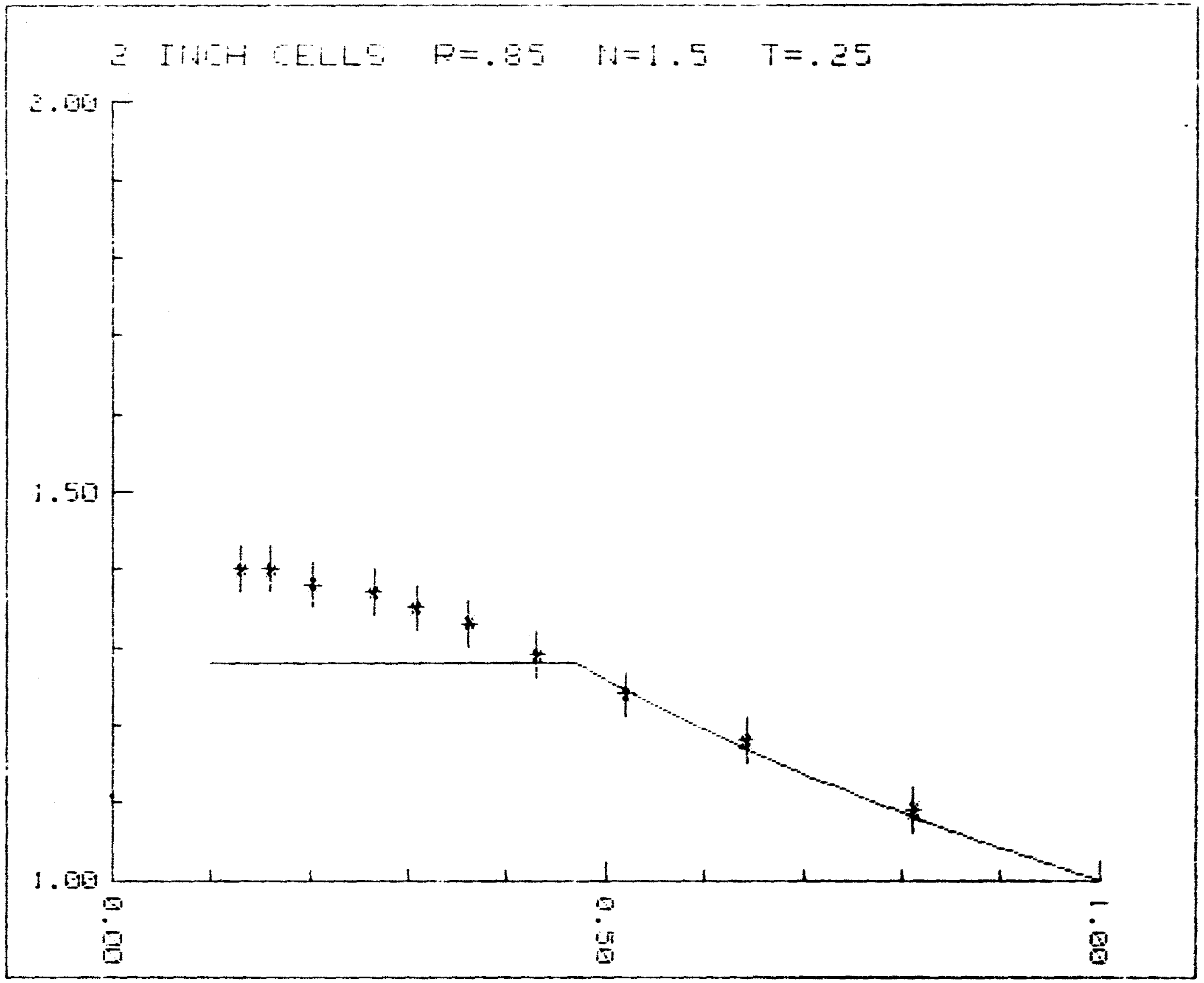


Figure 2-26 Results From Equations Plotted Against Monte Carlo Results

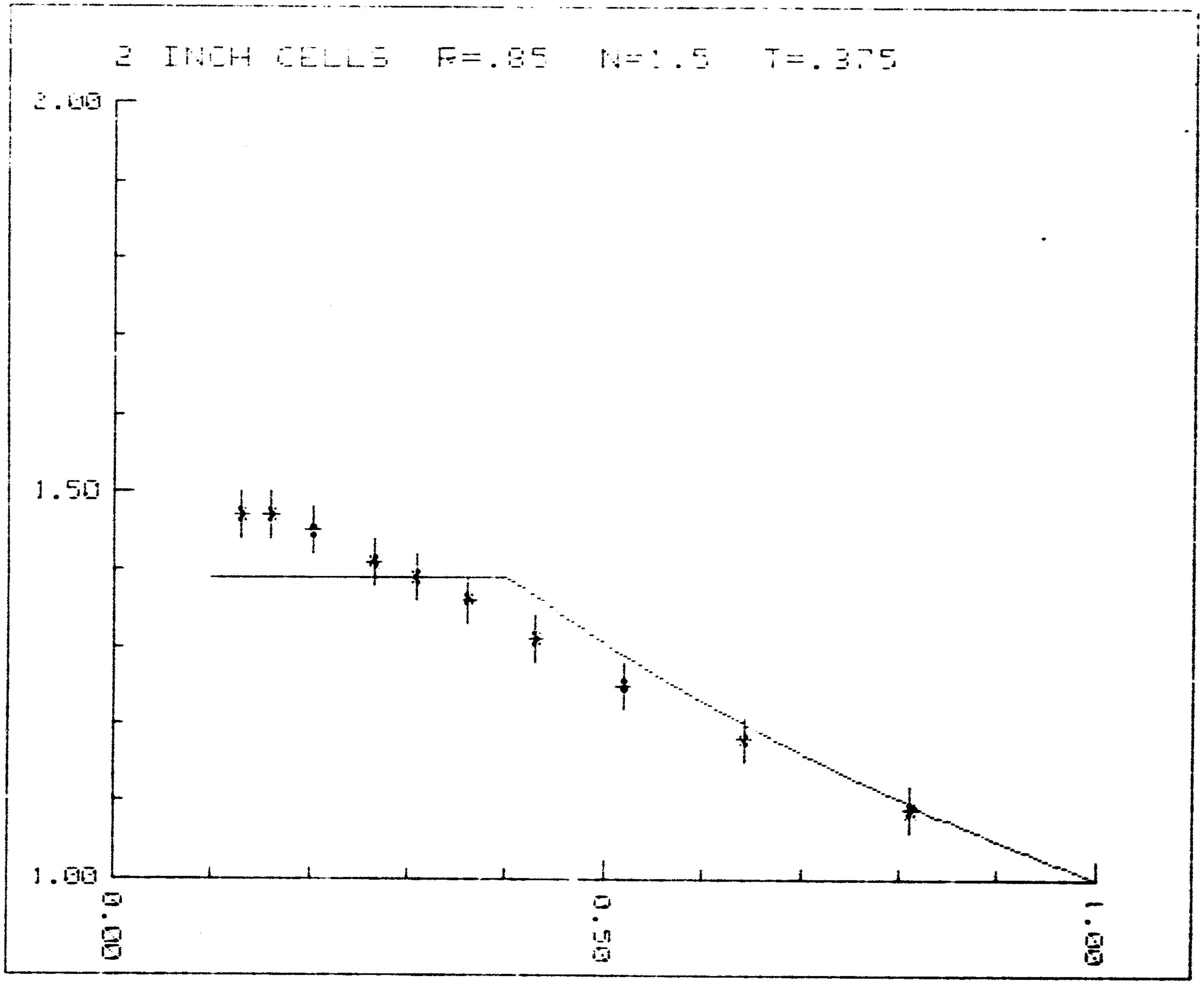


Figure 2-27 Results From Equations Plotted Against Monte Carlo Results

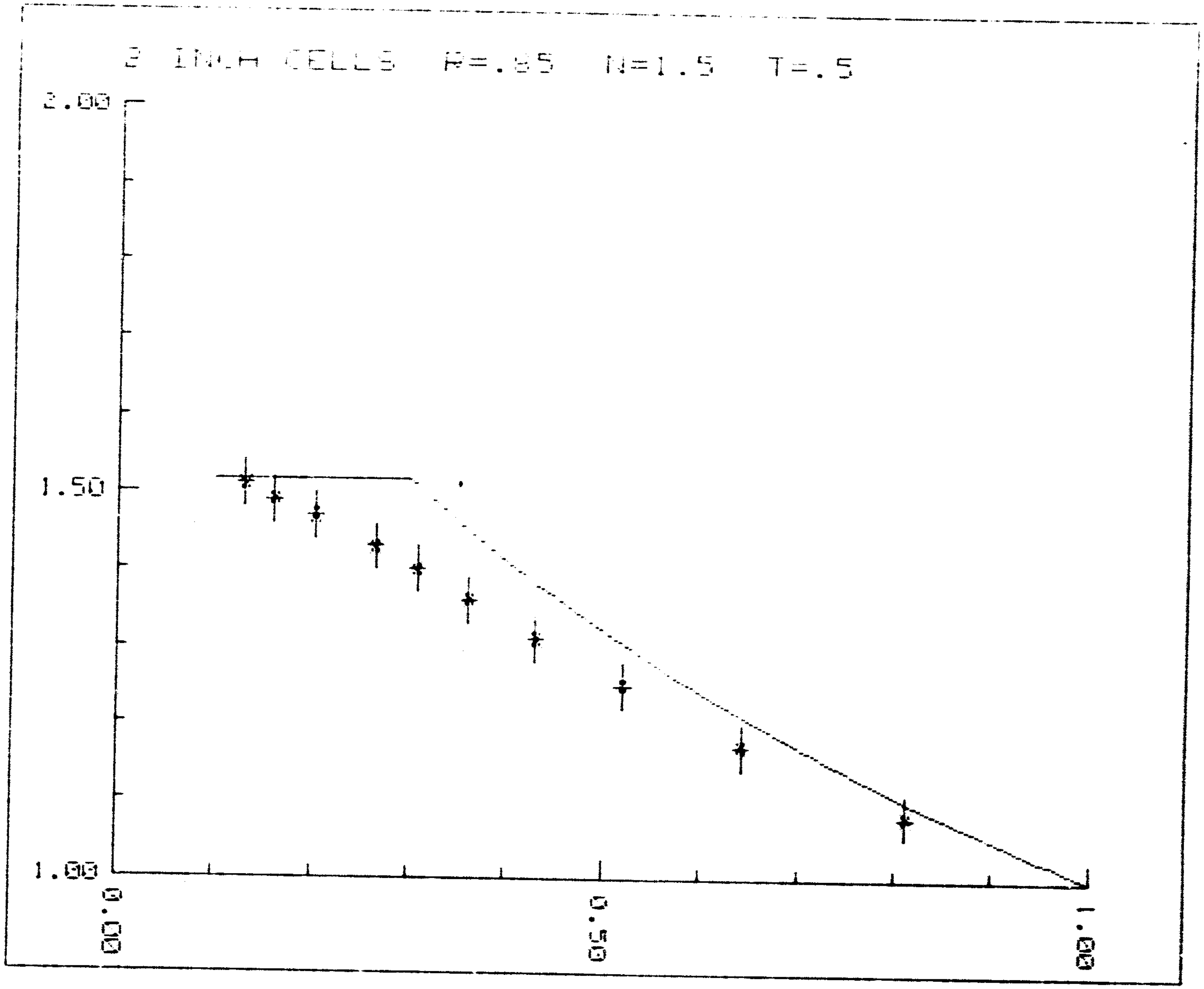


Figure 2-28 Results From Equations Plotted Against Monte Carlo Results

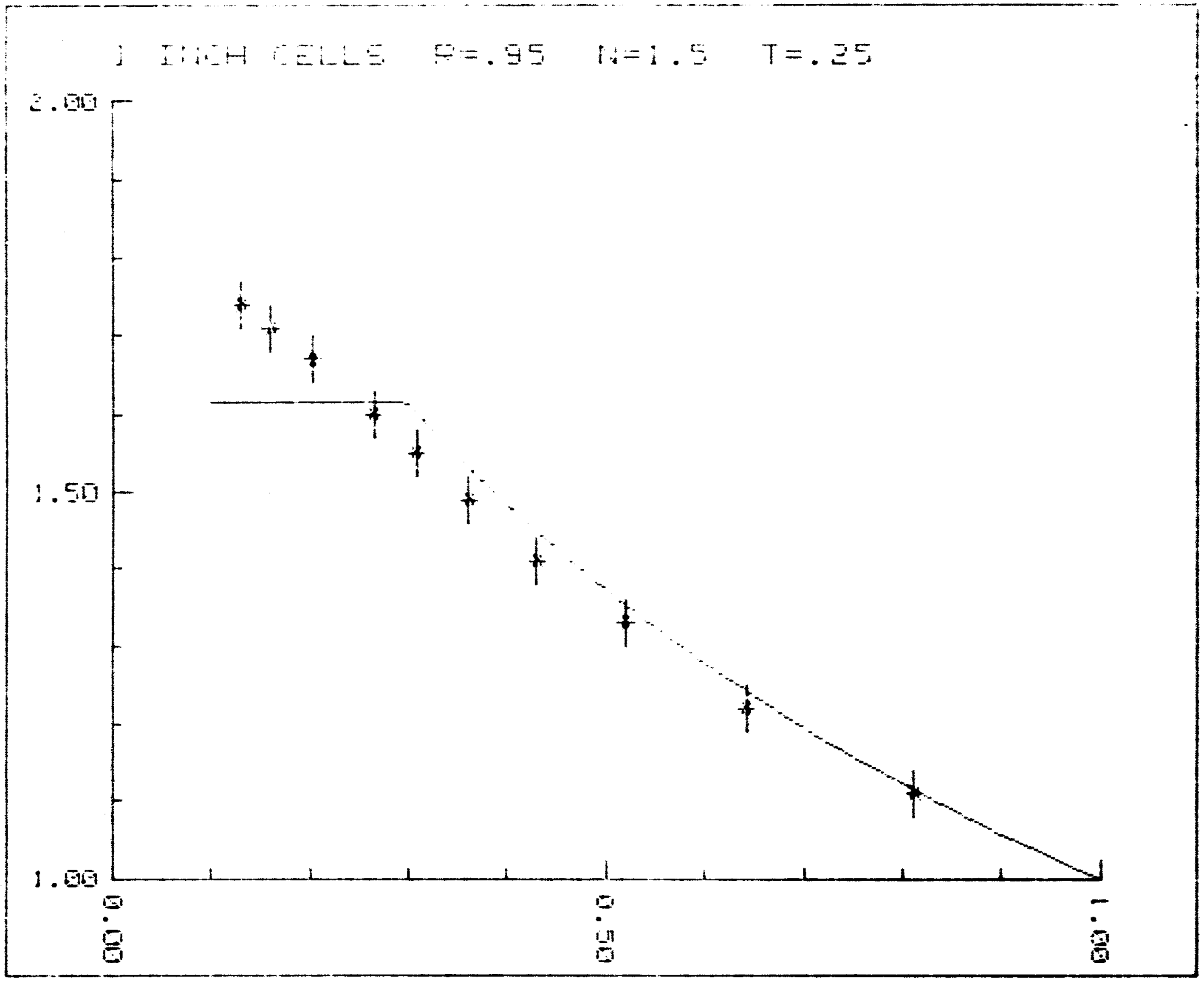


Figure 2-29 Results From Equations Plotted Against Monte Carlo Results

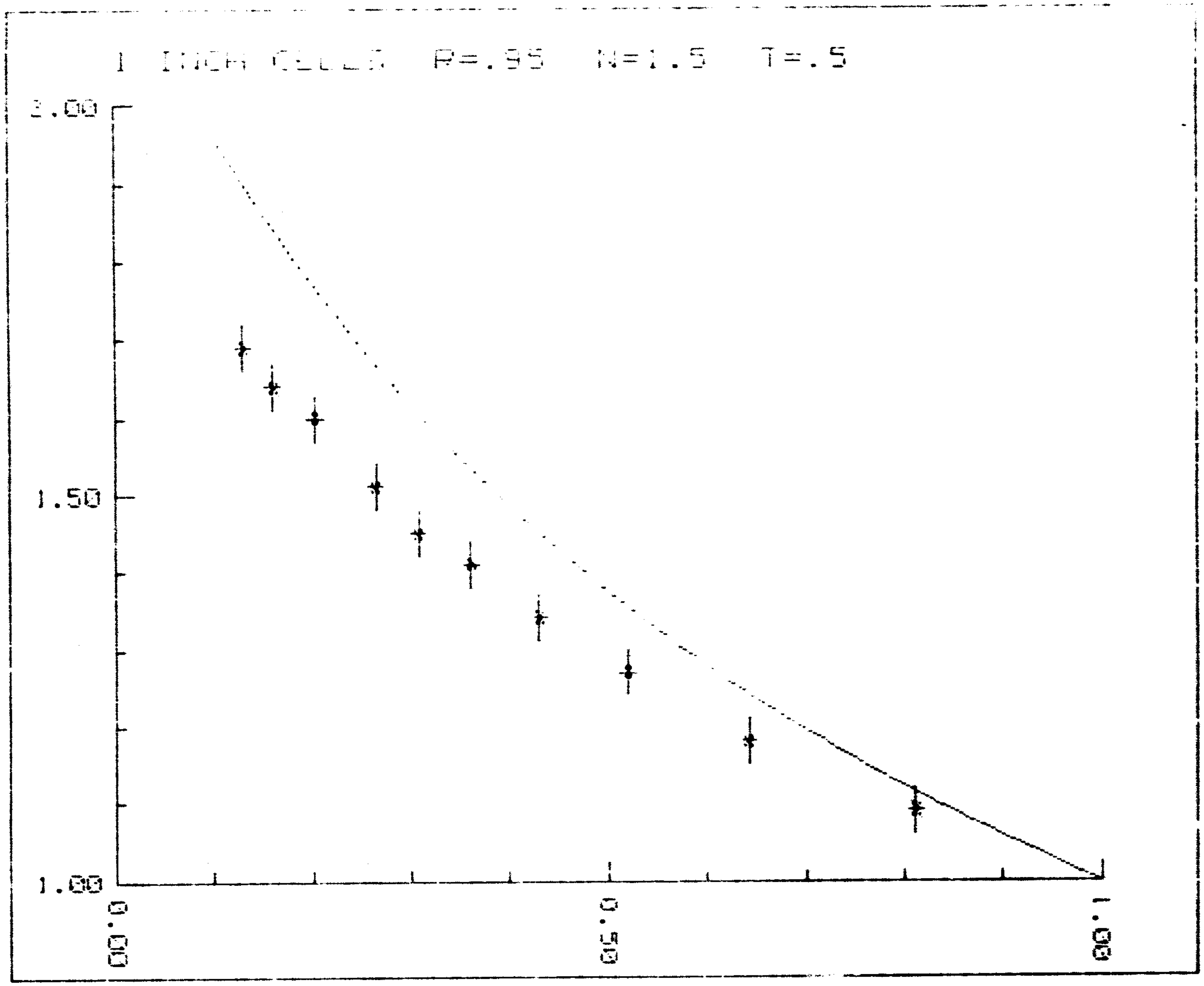


Figure 2-30 Results From Equations Plotted Against Monte Carlo Results

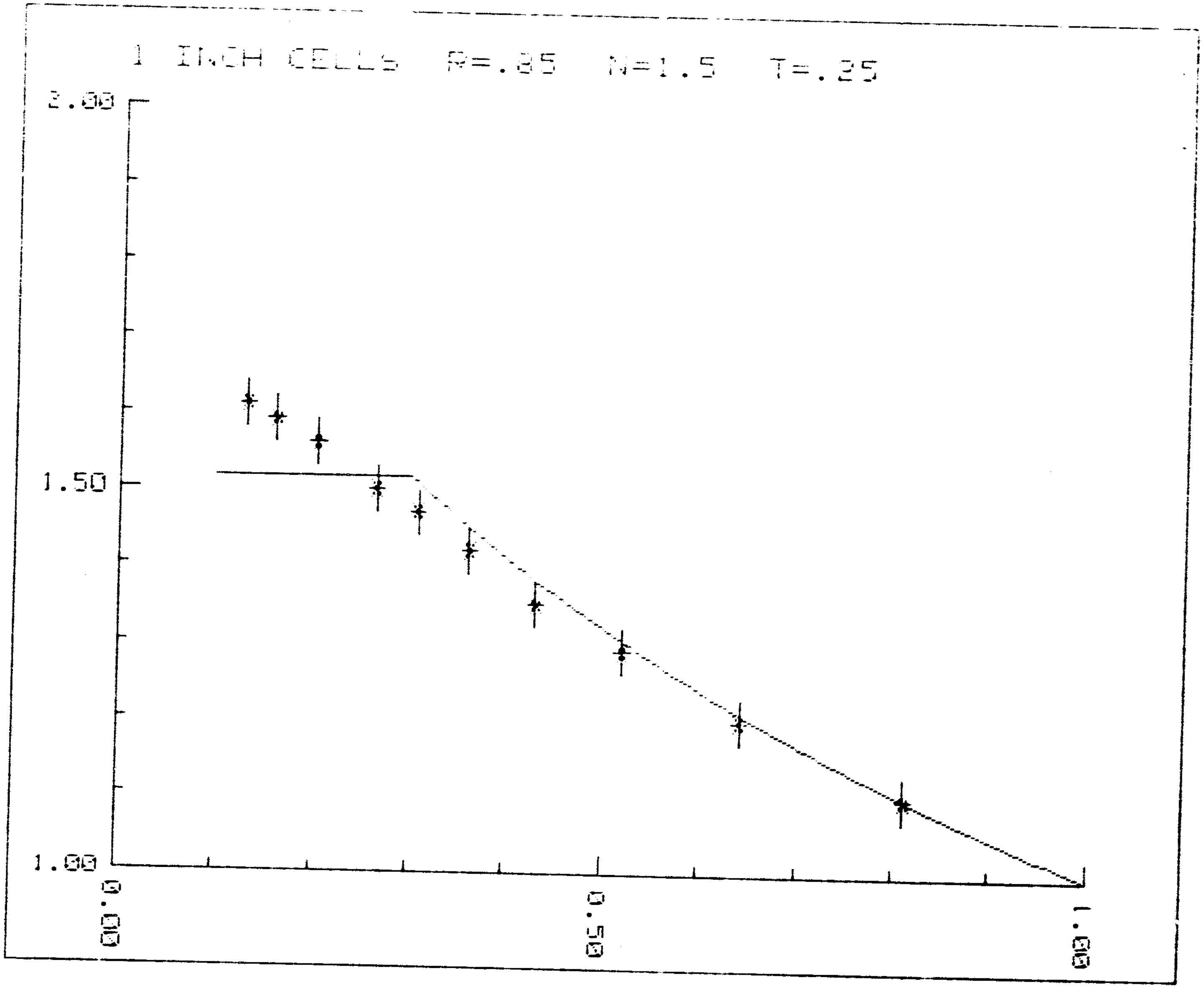


Figure 2-31 Results From Equations Plotted Against Monte Carlo Results

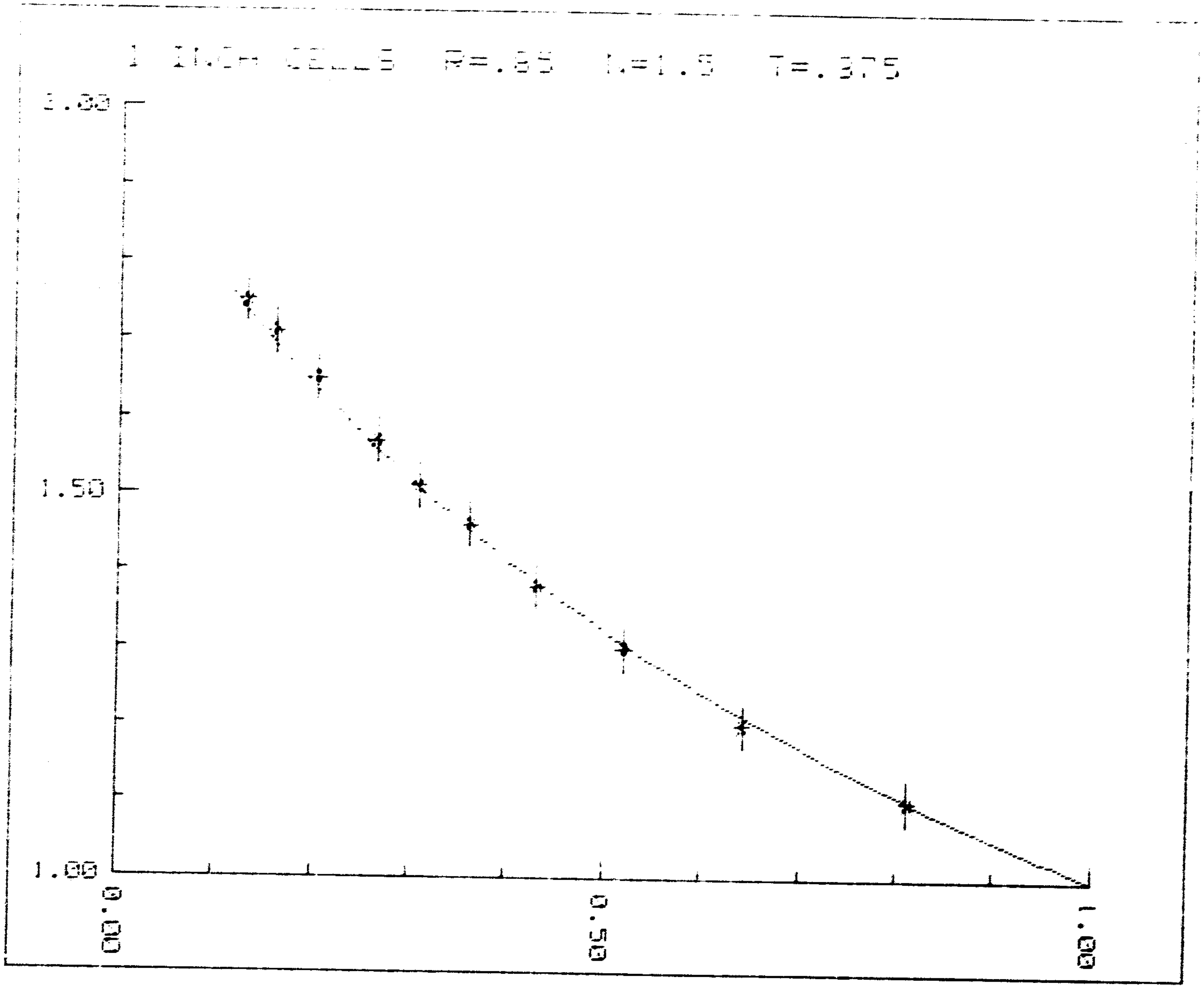


Figure 2-32 Results From Equations Plotted Against Monte Carlo Results

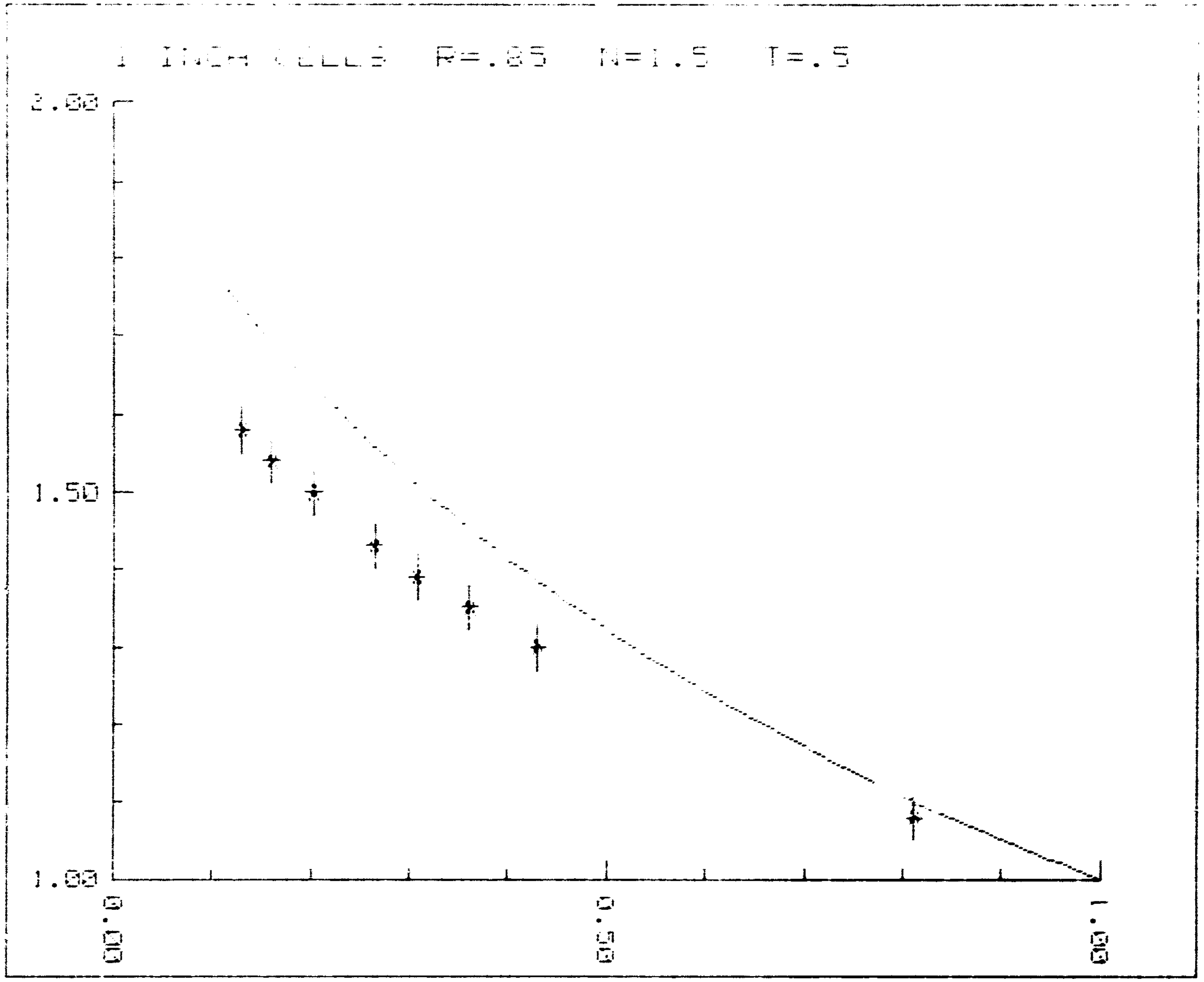


Figure 2-33 Results From Equations Plotted Against Monte Carlo Results

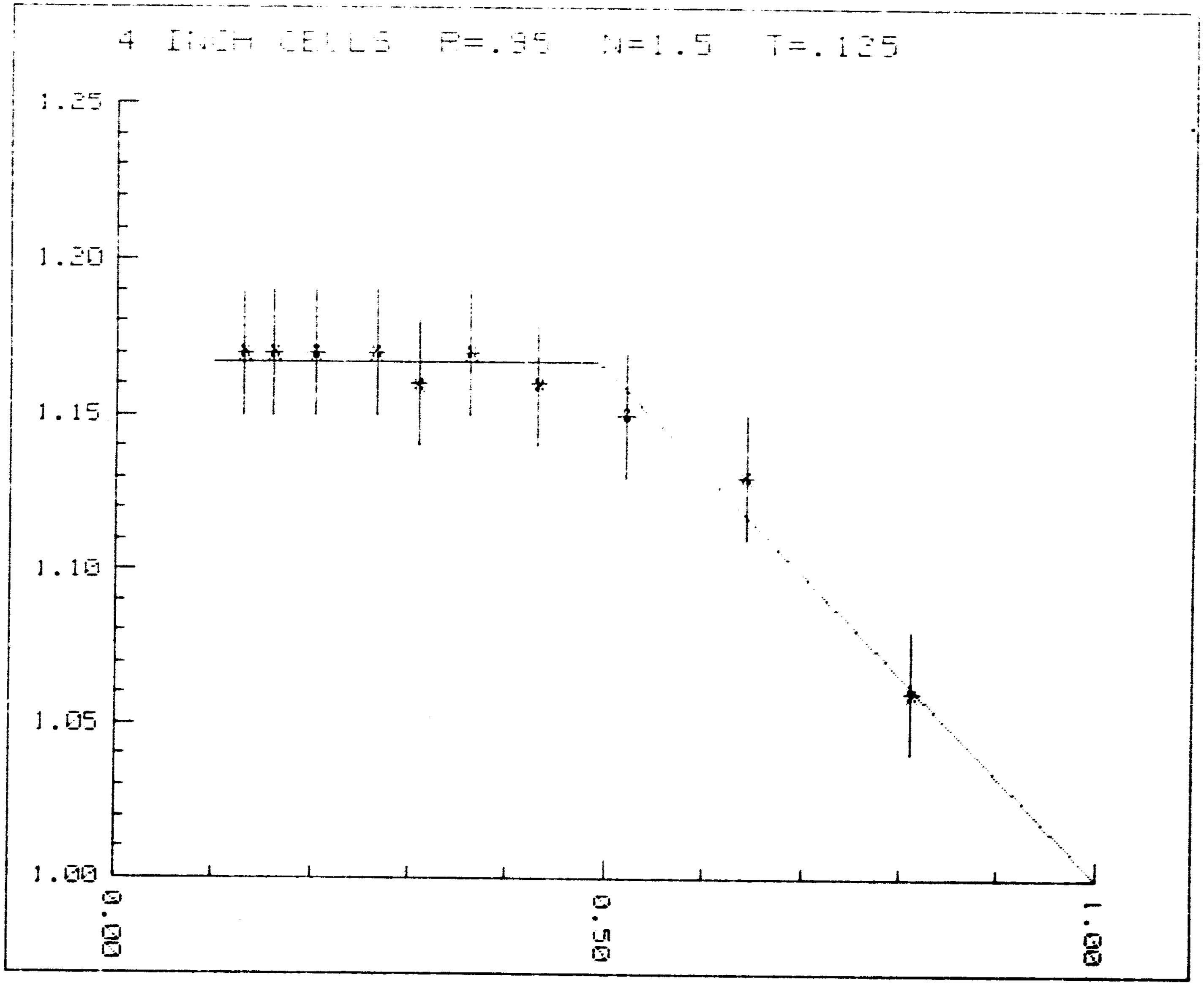


Figure 2-34 Results From Equations Plotted Against Monte Carlo Results. 4" Diameter, 1/8" Trapping Layer, R = .95

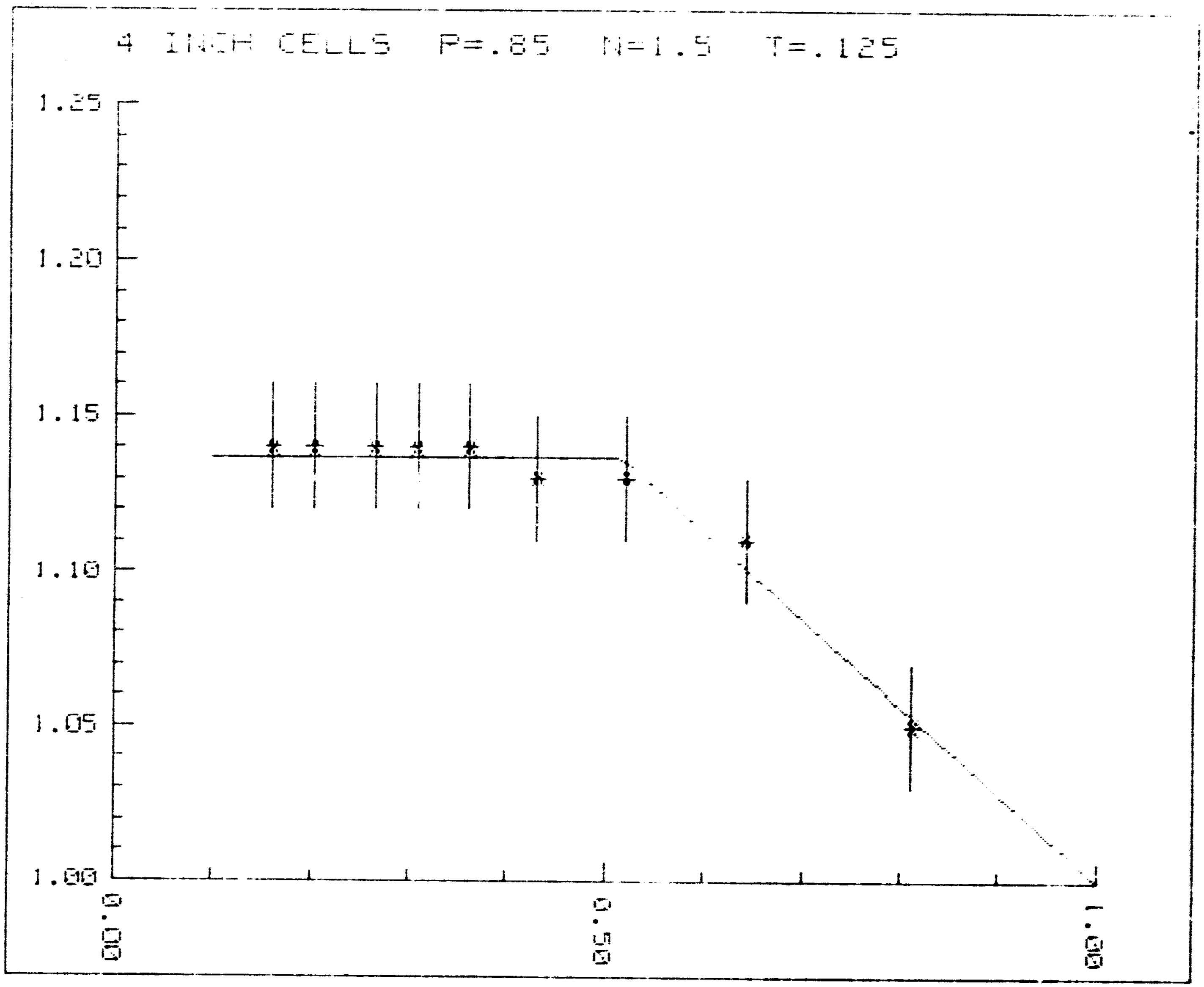


Figure 2-35 Results From Equations Plotted Against Monte Carlo Results. 4" Diameter, 1/8" Trapping Layer, R = .85

$$R = 0.85 \qquad G = \begin{cases} 1.137 & C < 0.515 \\ 1.282 - 0.282C & C \geq 0.515 \end{cases}$$

$$R = 0.95 \qquad G = \begin{cases} 1.167 & C < 0.493 \\ 1.329 - 0.329C & C \geq 0.493 \end{cases}$$

Figure 2-36. Data Fits

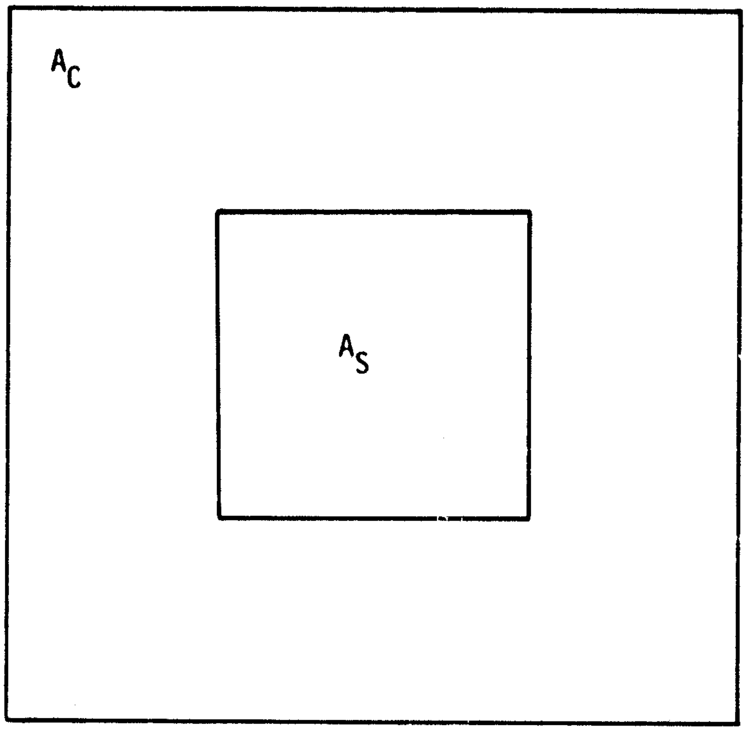


Figure 2-37. Section of Concentrator Containing One Solar Cell

The gain (G) that can be expected is related to the packing fraction (ratio of cell area to panel area). SAI has determined the G of one typical configuration for several different packing fractions. Figure 2-38 summarizes this information.

This example set of gains is representative of a good performance module, but any set can be used in the cost benefit methodology to be described.

For a given power output P_o and without gain or augmentation the area of required solar cells A_s can be determined by:

$$A_s = \frac{P_o}{\eta I} \qquad (1)$$

where

η = solar cell efficiency

I = peak local solar insolation

Now if the output of the solar cells is augmented, the solar cell area required is reduced. The new area $A_{s(c)}$ is given by:

$$A_{s(c)} = \frac{P_o}{\eta G I} = \frac{A_s}{G} \qquad (2)$$

where

G = gain.

The area of the module/array (A_c) is given by:

$$A_c = \frac{A_{s(c)}}{PF} \qquad (3)$$

where

PF = packing factor = the percentage of module/array covered with solar cells.

Using equations (2) and (3), the values for PF and G from Figure 2-38 and using $\eta = 0.13$, and $I = 800\ \mathrm{w/m^2}$ the cell area $A_{s(c)}$ and panel area A_c for an output P_o = 1.0 watt can be calculated.

Packing Fraction	Gain
0.09	1.97
0.16	1.90
0.25	1.73
0.49	1.40
1.00	1.00

Figure 2-38. Packing Fraction - vs - Gain

When G = 1.97 and PF = 0.09

$$A_{s(c)} = \frac{1.0 \text{ watt}}{0.13(1.97)(800)\text{watts/m}^2} = 0.0048 \text{ m}^2$$
$$= 48.8 \text{ cm}^2$$

$$A_c = \frac{0.00488}{0.09} = 0.05422 \text{ m}^2$$
$$= 542.2 \text{ cm}^2$$

Figure 2-39 summarizes the values of $A_{s(c)}$ and A_c for other Figure 2-39 values of PF and G.

The total cost (C_T) of the module/array augmented system can be estimated as follows:

$$C_T = A_{s(c)}(C_s) + A_c(C_c + C_F + C_L) \quad (4)$$

where

C_s = Cost/M^2 of solar cells

C_c = Cost/M^2 of module less solar cells

C_F = Cost of supporting structure per M^2

C_L = Cost/M^2 of land

Costs of electronics/switchgear, storage, and controls not included since there would be the same for all packing fractions.

Substituting from equations (2) and (3) into equation (4):

$$C_T = \frac{P_o}{nG(PF)I} C_s + \frac{1}{PF}(C_c + C_F + C_L) \quad (5)$$

Case	P.F.	G	$A_{s(c)}$ cm^2	A_c cm^2
1	0.09	1.97	48.8	542.2
2	0.16	1.90	50.6	316.5
3	0.25	1.73	55.6	222.4
4	0.49	1.40	68.7	140.2
5	1.00	1.00	96.1	96.1

($A_{s(c)}$ and A_c scale linearly with P_o)

Figure 2-39. Required Cell and Panel Areas for Different Packing Fractions

When PF = 1; $G_{(PF)} = 1$ and the array degenerates into a conventional one and cost is

$$C_T = \frac{P_o}{\eta I}(C_s + C_c + C_F + C_L) \qquad (6)$$

These equations have been used to calculate cost effective situations when light trapping systems can be used to advantage. These will be identified in the next subsection, and in more detail in Section 3.

2.6 SELECTION OF CASES

Light trapping in a photovoltaic panel can be beneficial. Benefits can be in the form of reduced cost per watt of output power, improved reliability, improved output characteristics, a built-in potential for system growth or some combination of these. Another benefit is the ability to get more power from the limited number of cells that can be produced, or the provision of a panel that is optimized for some total energy system or multitechnology energy system. Based on SAI research, cases have been selected to illustrate these potential benefits. These include:

- A panel concept requiring minimum design change. This concept may have immediate application to existing systems, and systems that are now in the design stage.
- A ground-mounted upgradable growth system. This system uses photovoltaic panels that are designed so as to exploit light trapping.
    - To minimize cost per watt output in a current design.
    - To maximize power out for a given solar cell area.
    - To minimize cost per unit of energy output over the life of the system. This may involve a modest start (providing an evaluation period) with a built-in capability for growth should the results of the evaluation warrant.

- A wall-integrated system. This system uses the array to generate electrical power. Reflected sun radiation is used for lighting and heating. This is accomplished by locating the panels on a south facing wall inside atrium portions of buildings and houses. Requirements for electrical power, lighting, heating, and a pleasing interior combine to control system design.
- Dense packed module using light trapping from the cell grid and associated peripheral area surrounding the cells for enhanced output, and diffusion of sharp shadows that fall on the array.
- A minimum design change panel where the performance of a panel with trapping is compared to that of a panel without trapping.
- A ground mounted upgradable growth panel. The panel will be defined and evaluated.
- A wall integrated system. The system will be defined and evaluated.
- A module using light trapping from the cell grid for increased output.

Thus the following section discusses each of these cases.

3.0 STUDY RESULTS

In this section SAI discusses the ways to use and to exploit light trapping, describes methods to use simplified design and costing equations to predict performance and cost benefits.

Several factors combine to represent the value or projected value of electrical power systems. These include cost of product, projected cost of product as compared to other systems, and environmental and societal acceptability. To reduce costs in photovoltaic panels significant funds have been expended by DOE and other organizations to improve cell and array efficiencies. Light trapping technology will provide a step increase in effective cell efficiency. The question is: "Can this step increase be provided cost effectively?" If so, the panel will be able to provide significantly (1.9 to 2.0 times) more power from the current limited numbers of available solar cells.

3.1 THE USE OF LIGHT TRAPPING-VS-THE EXPLOITATION OF THE CONCEPT

Most solar photovoltaic panels use round cells because these are easier to make. Trimming off the edges to make round cells square is wasteful of silicon material. When round cells are packed on panels so that cell touches cell the packing fraction PF = $\pi/4$ = 0.785. If cells are separated slightly to isolate them and to provide space for interconnections, PF would normally be no more than 0.70. Analysis indicates that a gain of as much as 12% may be realized by the incorporation of trapping. Example calculations based on preliminary cost data for cells, encapsulants, structures and land costs has indicated that for many combinations of costs optimum packing fractions may be 50% or considerably less. Thorough panel cost studies taking into account all the performance and cost variables will allow panel designs to not only take advantage of light trapping but to exploit the concept. Watts out per dollar invested can be maximized. The sensitivities of cost of output power to this new set of cost and performance variables may create a new base for the establishment of priceallocation guidelines of the low-cost solar array project, and could affect application of research and development dollars.

3.2 PANEL DESIGN CONSIDERATIONS TO USE LIGHT TRAPPING

A thorough analysis of the potential use of light trapping has identified several options for exploiting the effects. These include trapping in a single transparent layer, in multiple transparent layers of graded index of refraction, trapping in the intercell area in the panel, and trapping in the optically inactive intracell area on the cell itself (the front conductive grid). The full matrix of choices is illustrated in Figure 3-1.

3.3 SCREENING OF COST EFFECTIVE CONCEPTS

The options in design include:

- Trapping region
  - -- Inter-cell, that is the inactive region adjacent to the cells nominally effective for tightly packed round cells, and not effective for tightly packed square cells.
  - -- Intra-cell, inactive regions within the cells themselves (due to front grids) will provide a nominal gain for all array packing densities.
- Trapping technique
  - -- Single homogeneous layer of sufficient thickness
  - -- Multi-layer, graded set of layers to increase trapping layer efficiency

Cost and performance parameters of the graded set of layers must be better understood before a selection between the two layers is possible. There may be applications for both.

- Design philosophy
  - -- Minimal design changes to existing panels, cells, etc.
  - -- Optimum redesign of cell or module to exploit the light trapping techniques.

It is likely that there is an optimum packing fraction for arrays based on trapping layer, the year, and local real estate and labor costs.

MATRIX OF STUDY CASES	PANEL PERFORMANCE IMPROVEMENT DUE TO TRAPPING FROM	
COMPLEXITY OF TRAPPING LAYER	INTER-CELL REGION	INTRA-CELL REGION
Single Layer	(BASELINE CASE)	
● Existing Design	Use Commercial Module Design	Use Commercial Cell Design
● Optimal Design	Design is a Function of Time as Cell Costs Decline with Time	Optimize Cell Grid Layout
Multiple Layers		
● Existing Design	Use Commercial Module Design	Use Commercial Cell Design
● Optimal Design	Design is a function of Time as Cell Costs Decline with Time	Optimize Cell Grid Layout

Figure 3-1. Design Options to be Considered in this Study

3.4 GENERAL TRENDS DETERMINED

The computer program described earlier has been utilized to gain insight into the interplay of performance factors. From analysis of test cases it has become obvious that the key variables in the analysis are:

- cell irradiation gain
- index of refraction of encapsulant layers
- photovoltaic cell area to total panel area ratio
- encapsulant thickness to cell average dimension ratio
- cell grid area to cell area ratio
- cell temperature as a function of irradiation on cell, and on panel.

The SAI proprietary code allows simulation of arrays so that the effect of the variation of these key parameters on array performance is determined.

3.4.1 Minimum Design Change Module

The initial use of light trapping (and the only use so far commercialized) is in what SAI calls the minimum design module. This module is designed and built without regard to any light trapping gain, but minimal materials may be added (e.g., white paint, or white plastic sheet) to provide some enhancement. Even this last step may have degrees of effectiveness, off white color, glossy material, etc., can reduce the effect of light trapping. At present most manufacturers appear to use some type of light trapping considerations in at least one model module they produce. There has never been any data presented as to how consistently this is done, or the optical properties of the materials utilized.

The gain for the minimum design change modules can be estimated by the simplified design equations presented in Section 2. Using these equations for the most recent set of modules for which data is available--the Block III JPL purchases, gains for these configured modules, and for modules for which the thickness was increased to ½ inch, are presented in Figure 3-2. From this one

SUPPLIER	AS CONFIGURED	WITH T = 1/2"
A	1.08	1.17
B	1.10	1.20
C	1.12	1.24
D	1.06	1.13
E	1.13	1.26

Figure 3-2. Typical Gains for Block III Modules Using Simplified Design Equations

can conclude that light trapping can be worth from 6 to 13% increased output with little or no design or manufacturing impact. At $10/w module prices and a world market of about 10 MW/year average over the next decade this relates to an economic value in excess of $90 million dollars. Thicker encapsulation materials produce more gain but cost more. Their worth could be substantial (see Section 4).

A second design consideration in the minimum design change module is the question of cell shape, should one use round, shaped, square or rectangular cells. The trade off normally is between packing factor and cell efficiency. With light trapping the non=cell area can be effective. To illustrate using the simplified design equations, a calculation was made of the equivalent efficiencies of round and square cells that were required to produce the same size and power output module, assuming one used a light trapping design with the round cells only. These results are shown in Figure 3-3.

3.4.2 Change in Layer Thickness

The change in thickness of the encapsulant layer from zero produces a dramatic increase in gain, from zero to close to the maximum available for thickness dimension in the range $t/\ell = 0.2$ to 0.3, where l is the characteristic size of the photovoltaic cell. This effect was well described in Section 2 and will not be further discussed here.

3.4.3 Changes in Layer Index of Refraction

The maximum gain was shown to increase as n^2 where n is the ratio for the index "step" ($n=N_2/N_1$). For practical gains, in the PF = 0.5-0.8 vicinity, the effect is beginning to saturate at $n=1.5$. Figure 3-4 and 3-5 plots gain as a function of index for two packing factor and several t/ℓ ratios. The reason that the gains saturate rather than rising as n^2 (as would be indicated from the general considerations given in Section 1) is that the Fresnel loss at the front face becomes more and more severe as the mismatch between the air and the

ROUND CELL EFFICIENCY P.F. = .70	EQUIVALENT SQUARE CELL EFFICIENCY PF = .95
10	8.9
12	10.7
14	12.5
15	13.4
16	14.3

Case: Round cell P.F. = .70
light trapping module, gain 1.22 (other conditions as in Figure 1).

: Square cell, P.F. = .95, no light trapping used.

Figure 3-3. Comparison of Cell Efficiencies for Equivalent Power

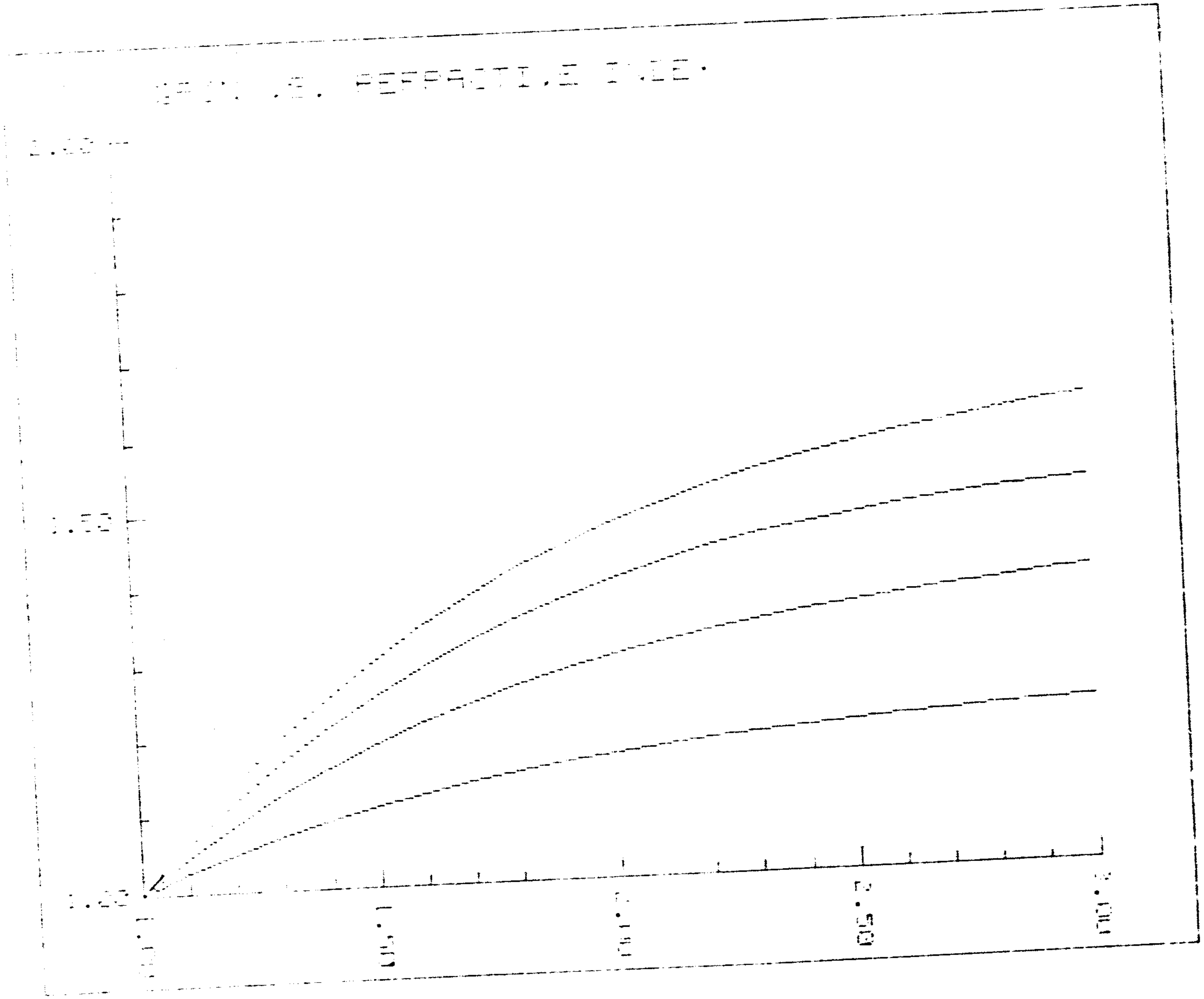


Figure 3-4. Gain as a Function of Index for a 0.5 Packing Factor, R=0.95 and Πℓ Ratios. .031 in Steps of .031 to .125.

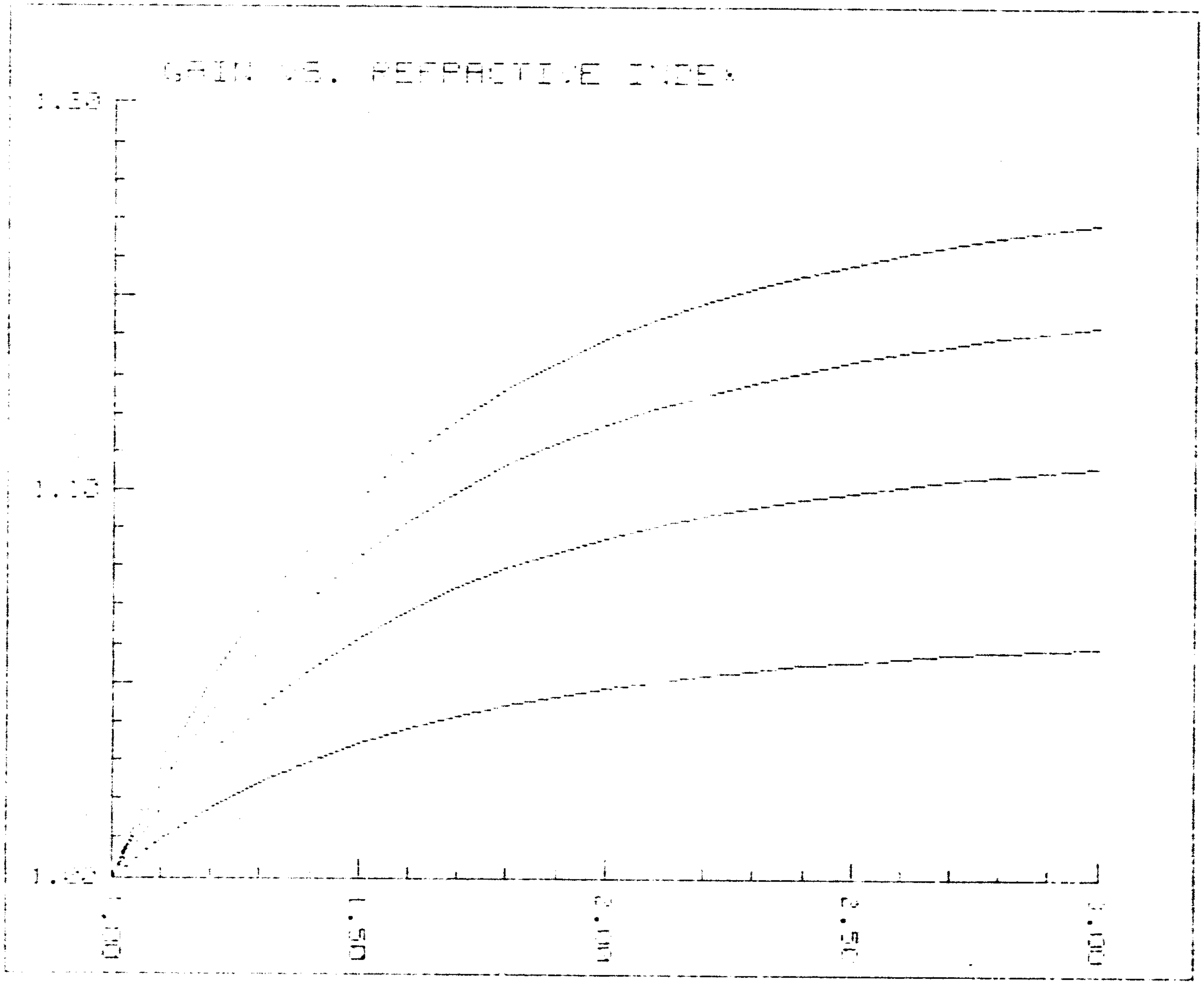


Figure 3-5. Gain vs. Refractive Index
Same conditions as Figure 3-4,
but PF=0.80

high index becomes larger. It is based on these arguments that one is directed toward multilayered graded index layer stacks.

3.4.4 Multilayer Trapping Layers

The addition of a second layer of higher index of refraction in contact with the diffusing layer improves performance. There are three reasons for this. At the top the graded layers provided a better optical match. At the bottom the higher index increases the angular spread of the diffuse reflected light that would reach the top if the module and be lost--thus less is best. Third, the total stack of layers is thicker and thus more effective. However, some trapping occurs only in the higher index layer and this may not be effective if that layer is too thin. Finally, there is internal Fresnel reflection which can lead to suboptimal trapping.

Two, calculations were performed with sets of the SAI Monte Carlo computer program to illustrate the effects. In Figure 3-6 SAI calculations for the case of a 4" diameter round cell, rectangular packing, PF = .70, 130 mil, n = 1.5 superstrate the gain with thickness and index of an additional layer varied. A maximum gain 1.428 is indicated for this case.

In Figure 3-7 another case is studied. Here the overall layer thickness is constrained and the variation is in the relative amount of layer one to layer two. A surprising result is indicated, after a thickness ratio of 20% for layer 2 to the total, the gain available saturates. Similar results for a 3 inch round cell square packed array of PF = 0.67, and for 3 inch quarter cells. Notice that with the quarter cell at the same packing--gains of 1.28 are indicated, higher than the 1.24 gain of full round cells. This is due to the non random orientation of the quarter round cells. Further ordering of the cell may produce higher gains. This is a general conclusion not restricted to the two layer case.

3.4.5 Example Calculations with Two Trapping Layers

In this subsection SAI presents two design calculations to illustrate the general results of the work described in this report. The first case is of square

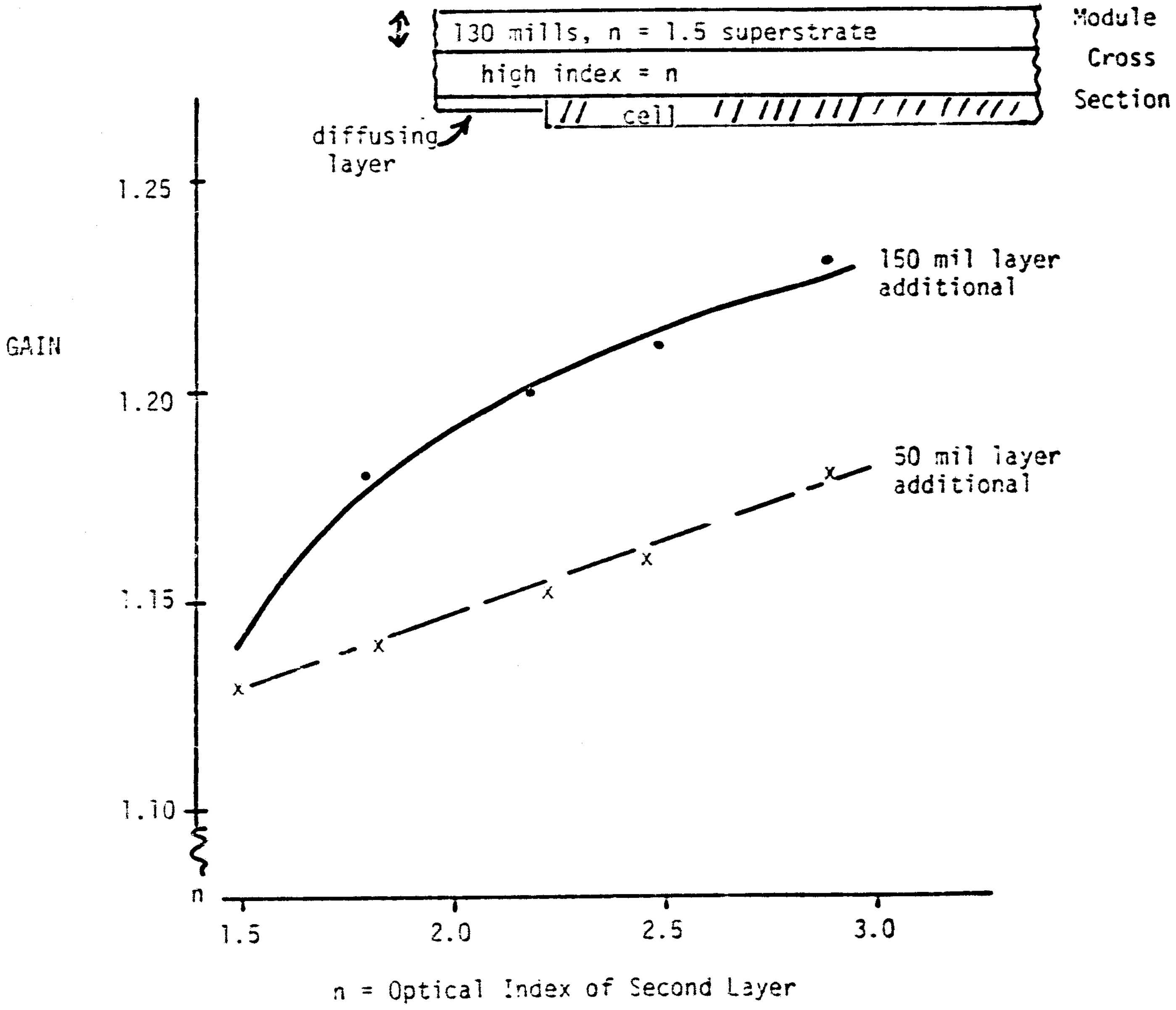


Figure 3-6. Gain Variations in a Two Layer Trapping Geometry, Depending on the Index and the Thickness of the Second Layer

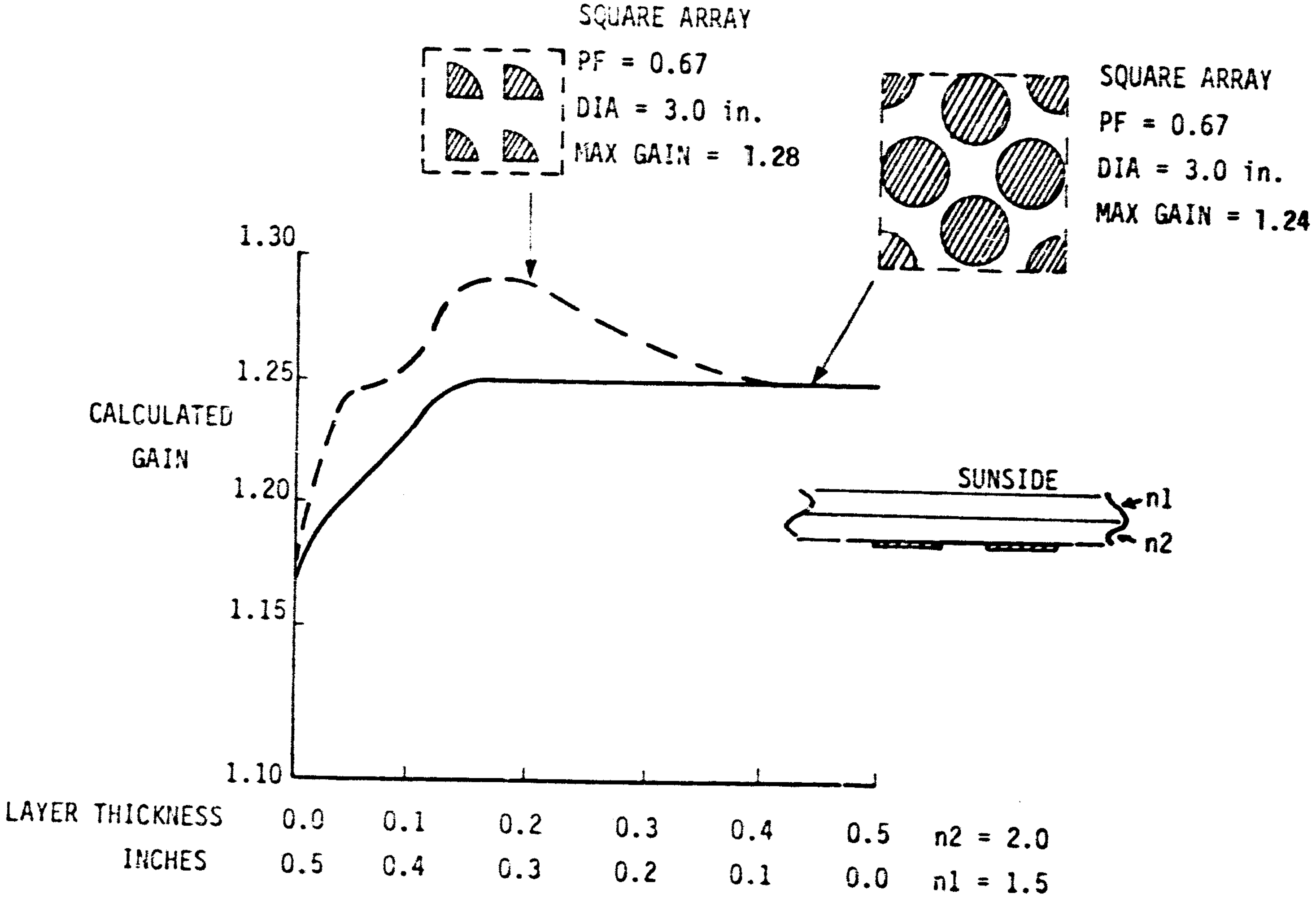


Figure 3-7. Variations in Gain for Two Trapping Layer Structures

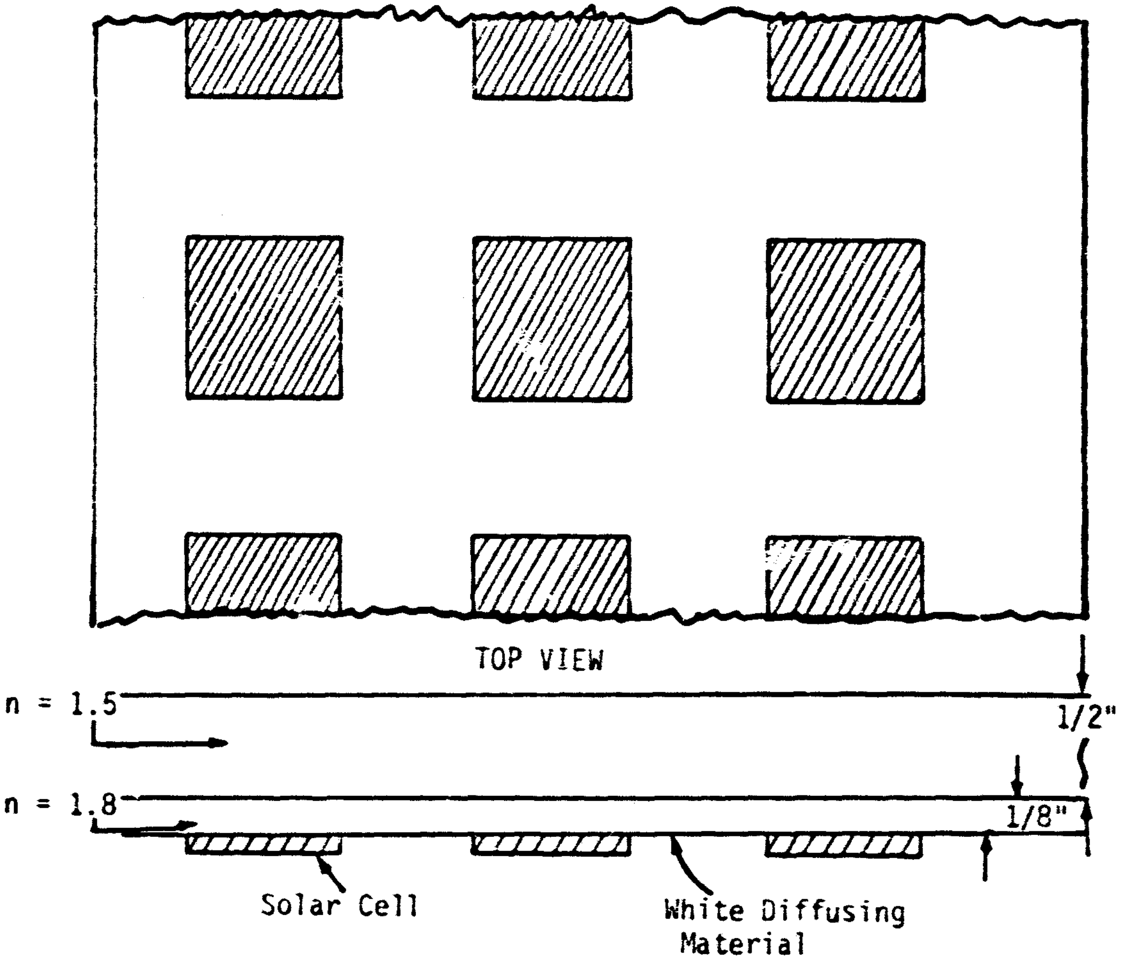
inch cells with an encapsulant of one-half inch $n=1.5$ and 1/8 inch $n=1.8$. See Figure 3-8 for the cross sections of the module and calculated gains. In this case nearly a factor two on cell power out can be obtained. Figure 3-9 shows more details for this case, and illustrates an important trend. Plotted are several variables versus packing factor. The geometric maximum gain (G_{GEO}) is the inverse of the packing factor and this value dominates the maximum gain for PF = 0.4. The maximum optical gain G_{max} is plotted. G_{max} dominates for PF = 0.4 and asymptotes at a value given by n_{max}, where n_{max} is the largest index in the stack (should be lowest layer). G, the practical gain was tabularized on Figure 3-7, except for PF approaching unity, G is always less than the lower limit of either G_{GEO} or G_{max}.

The ratio of G to G_{max} is plotted along with the G to G_{GEO} ratio. Note that (for this case) the gain achievable is never less than 60% of the theoretical maximum. For designs in the PF=0.6 to 0.8 area gain ratios of 70 to 80% of maximum are indicated. Another way to look at this is to note that at the maximum geometric gain limit (PF 0.5) the white diffusing area is equally efficient in capturing light as the solar cell. Thus for PF = 0.6 to 0.8 the white diffusing layer is 70 to 80% as effective in light collection as the cells.

Figure 3-10 illustrates the design for quarter round (3 inch diameter) cells in a square array with a total of 3/16 inch incapsulant. The gain values are not as high as those of the prior figure but are still interestingly high.

3.5 CONCLUSIONS

A multi-layered encapsulant with increasingly higher index from sun side to cell is a preferred design concept from performance considerations. The cross section of a module is indicated in Figure 3-11. One approach to achieving such a layered structure is to mix differing amounts of finely divided highly refracting transparent materials in a lower index binder. Generally the index of the composite is given by the volume weighted averages of the indices of the constituents. For this to be true the material must be very finely dioded (dimensions near or less than the wavelength of light) no layered products of this



PERFORMANCE

PACKING FACTOR	GAIN
.12	1.94
.15	1.87
.19	1.80
.25	1.72
.29	1.65
.34	1.58
.41	1.50
.49	1.41
.60	1.29
.77	1.16
1.00	1.00

Figure 3-8. Square One Inch Cell Example Two Trapping Layers

Case See Figure 3-7.

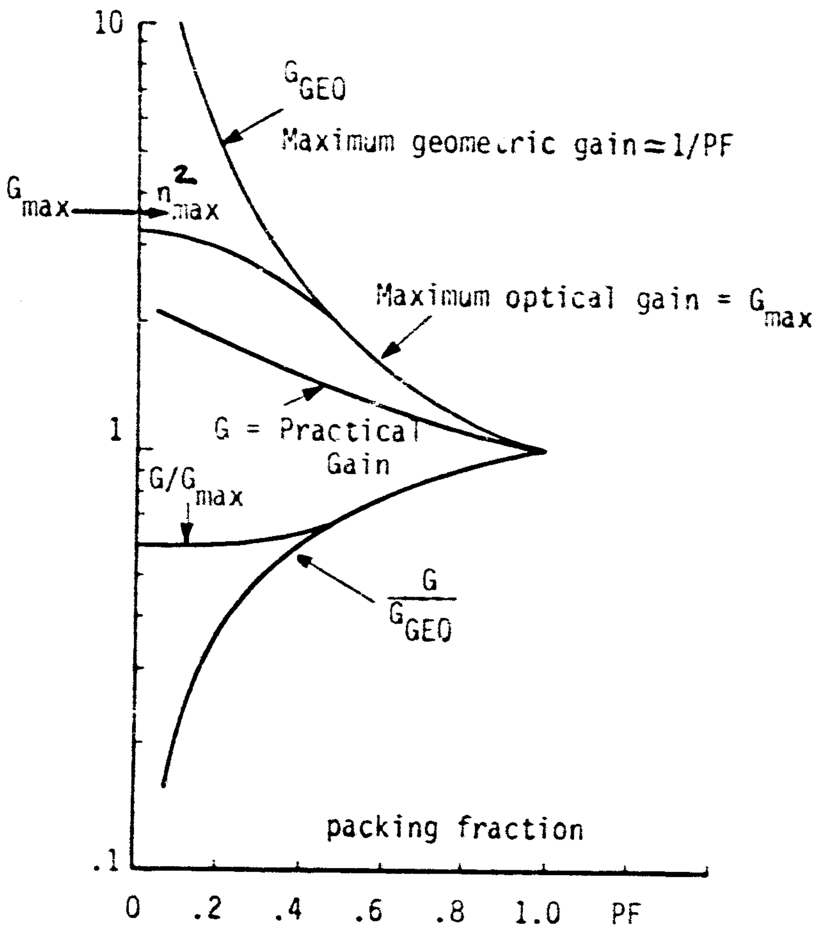
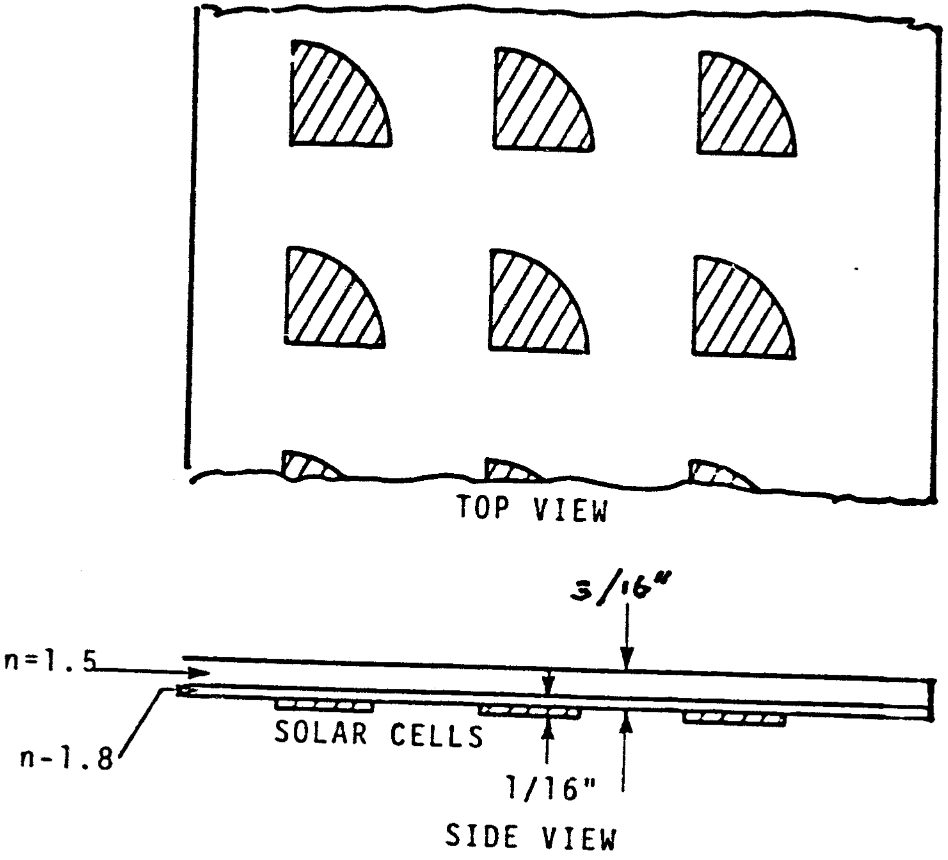


Figure 3-9. Gain and Gain Ratios as a Function of Packing Factor



PERFORMANCE

PACKING FACTOR	GAIN
0.13	1.54
0.16	1.53
0.20	1.52
0.27	1.49
0.31	1.48
0.36	1.45
0.43	1.41
0.52	1.34
0.64	1.25
0.81	1.11
1.00	1.00

Figure 3-10. Quarter Round Cell Example Two Trapping Layers

C-2

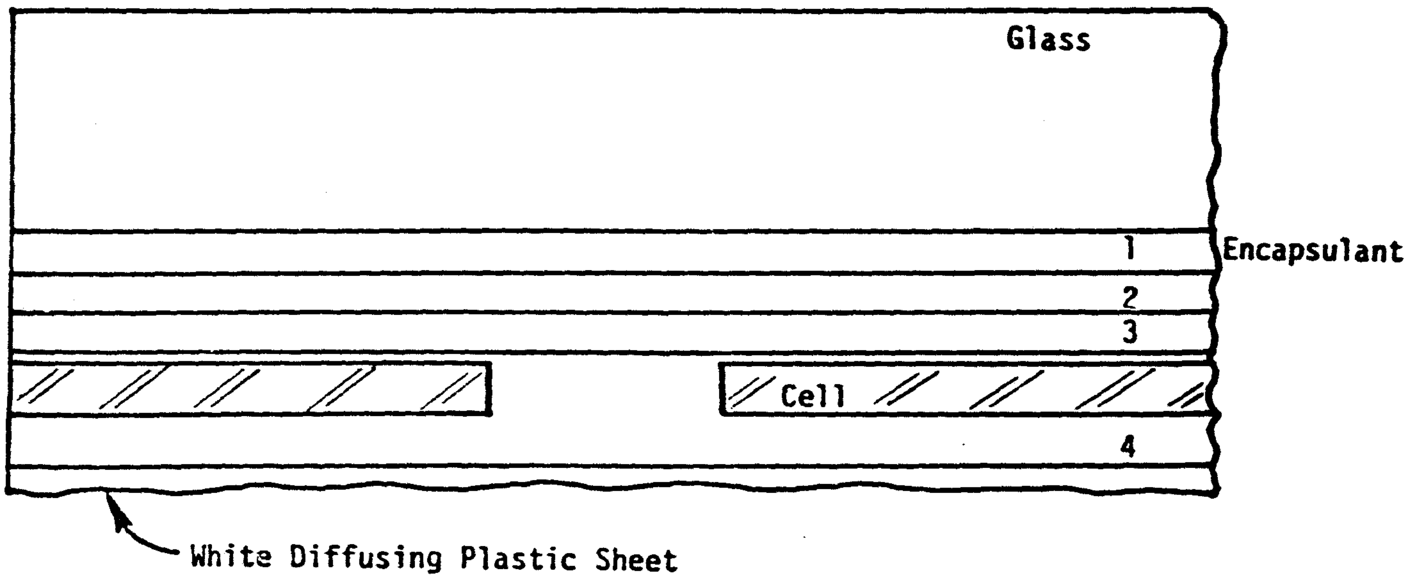


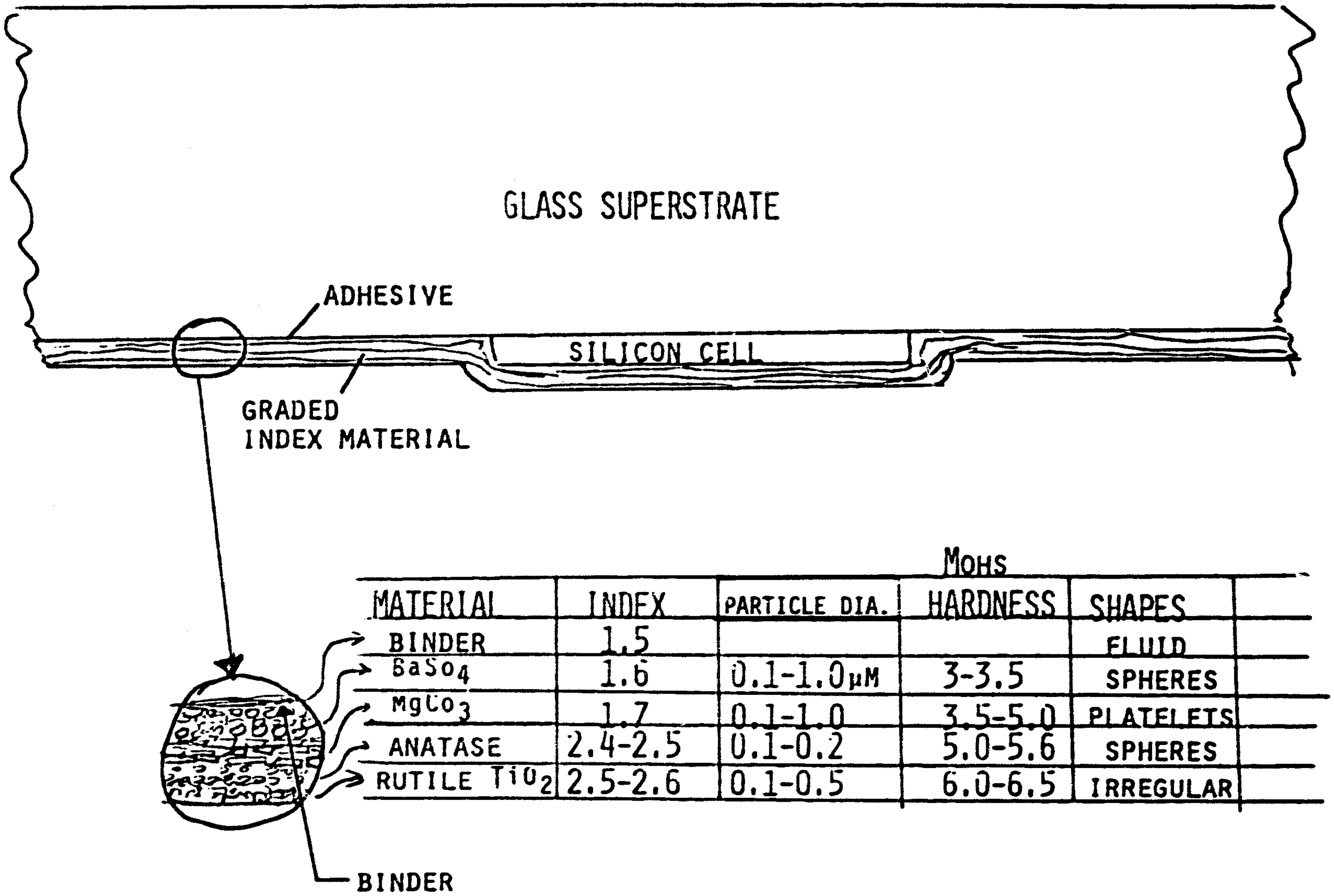
Figure 3-11. Laminated Encapsulant Layers with High Index Used Over Cell

type are presently on the market but SAI believes they could be readily developed, and inexpensive in large quantities. Figure 3-12 illustrates a graded index layer.

Finally it has been learned that the following steps will produce an optically efficient PV module:

- AR coating
- Add diffuse reflector
- Optimize superstrate thickness based on cell size
- Utilize two or more trapping layers
- Use diffusing layer on cell grids
- Add reflectors to super- and sub-strate edges
- Optimize load

In the next section example applications that illustrate these points will be explained.



MATERIAL	INDEX	PARTICLE DIA.	MOHS HARDNESS	SHAPES
BINDER	1.5			FLUID
$BaSO_4$	1.6	0.1-1.0μM	3-3.5	SPHERES
$MgCO_3$	1.7	0.1-1.0	3.5-5.0	PLATELETS
ANATASE	2.4-2.5	0.1-0.2	5.0-5.6	SPHERES
RUTILE TiO_2	2.5-2.6	0.1-0.5	6.0-6.5	IRREGULAR

APPLICATION OF HEAT CAUSES BINDER TO SURROUND PARTICLES AND CREATES A COMPOSITE LAYER WITH GRADED INDEX.

Figure 3-12. Double Layer Cell Encapsulant

4.0 DESIGN APPLICATIONS

In this section SAI described four significant ways to use and to exploit the findings presented in this study. These are:

- a minimum design change module
- an optimum packing factor module concept
- roof or wall integrated panels
- modules using light trapping from cell grids.

These will be explained in detail in the following subsections.

4.1 A MINIMUM DESIGN CHANGE MODULE CONCEPT

The minimum design change module concept is defined as those changes that would be easy for a manufacturer to implement. While this concept calls for the modification of existing designs, the modification can result in only minor changes, for example, painting the under side of a panel white. In more recent conceptual designs, a relatively thin layer of material having a graded index of refraction (going from $N=1.5$ to 2.6 or higher) may be used. The bottom surface of this layer will be a reflector/diffuser (white paint or its equivalent). These changes will provide a gain in output power. The actual gain produced will be a function 1) the diffusivity and reflection of the painted surface, 2) the characteristics of the panel layers (materials, stacking order, optical index and thicknesses), 3) module packing fraction (PF), and 4) size and shape of cells. The simplified design equations of Section 2 can be used to evaluate the gain caused by light trapping of a specified panel. The use of a lower index layer covering a higher index layer is shown to improve light trapping -- much as in the case of clouded fiber optical links.

When two layers are used, the simplified design equation has a modification of the refractive index. Assume two layers have index N_2, and thickness t_2 and N_3, and t_3. N_3 is always closer to the diffusing side and is higher in value than N_2. Studies have determined that the index N to be used is approximated by

$$N = N_2 + \frac{t_3(N_3 - N_2)}{t_2 + t_3}$$

Thus $N \rightarrow N_2$ when $t_3 \rightarrow 0$ and $N \rightarrow N_3$ when t_3 is larger compared to t_2. Under these conditions, the values of gain clearly approach those given by the simplified Monte Carlo model.

Taking a standard module design of packing factor 0.7, thickness of 1.5, index layer 0.13 inches using 4 inch diameter cells, a study was made of adding a second layer of thickness .05 inches. Figure 4-1 shows the effect of increasing the index from 1.5 to 3. A gain of 1.13 rises to 1.17 under these conditions. In Figure 4-2, the gain where a $n = 2.5$ index material is added to the same module described above is shown as a function of that layer thickness. Gains rise from 1.09 at thickness increase of zero to over 1.20 at thickness increase of .15.

Modules can be augmented up to 20% at nominal packing factors (PF = .70) and to even higher levels if less than the maximum packing is used. Each manufacturer has to evaluate the ease of reducing the cell spacing, and calculate the benefits from the equations provided. It appears that measurable savings in cells will result from adopting this design approach.

Materials, number of layers, packing fraction have all been considered in this minimum change design. It is unlikely that changes in trapping layer thickness and cell sizes would ever be considered as modification to installed panels. Revisions to panel designs in production could conceivably include all three changes.

4.2 GROUND MOUNTED UPGRADABLE GROWTH SYSTEM

The studies at SAI have increased the knowledge and the level of the technology behind a concept that will improve the performance efficiency of panels of solar cells. The concept traps light in transparent plates of materials used to mount and to cover solar cells and channels this light to the cell. Now,

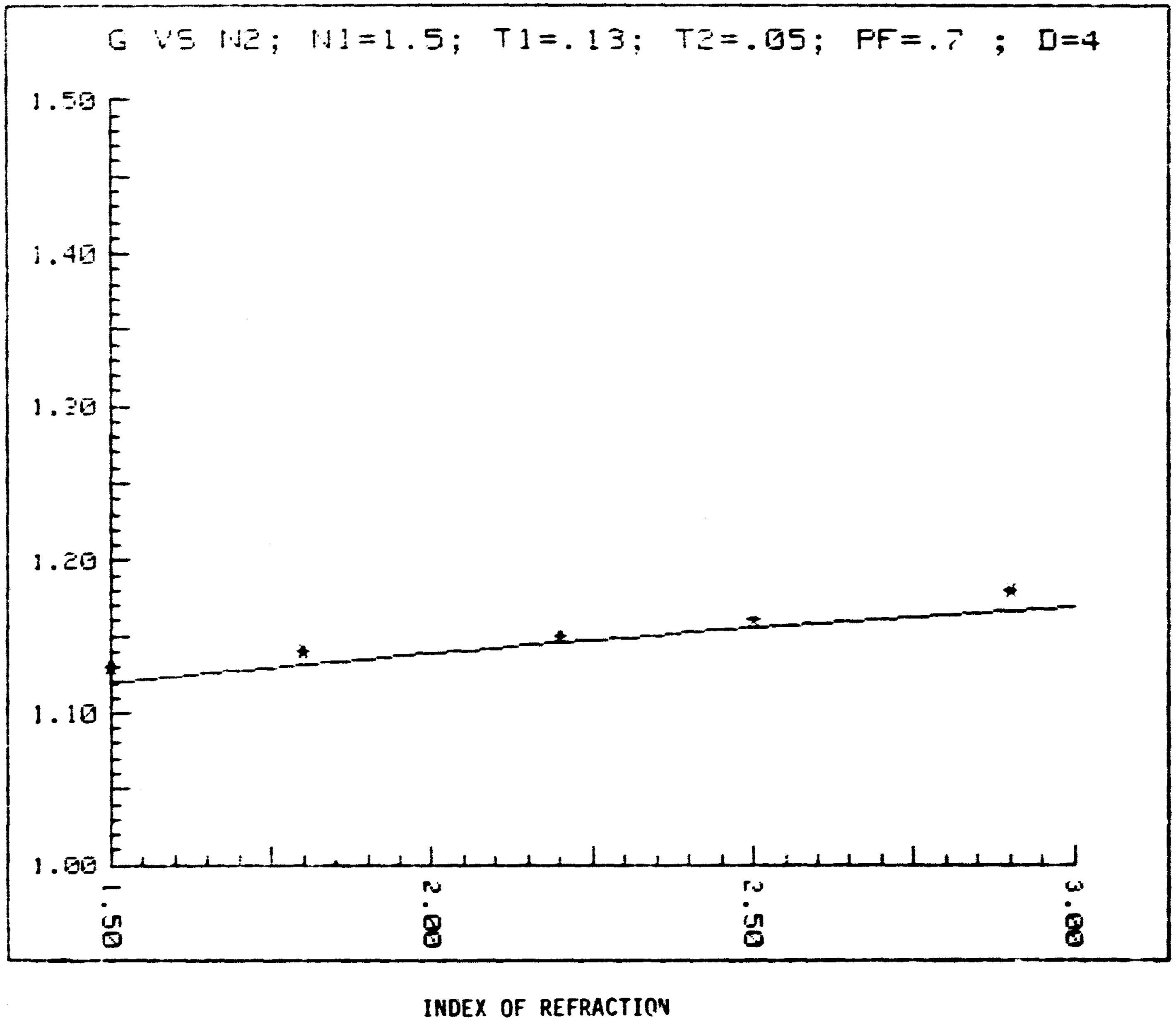


Figure 4-1. Module Gain -vs- Index of Refraction

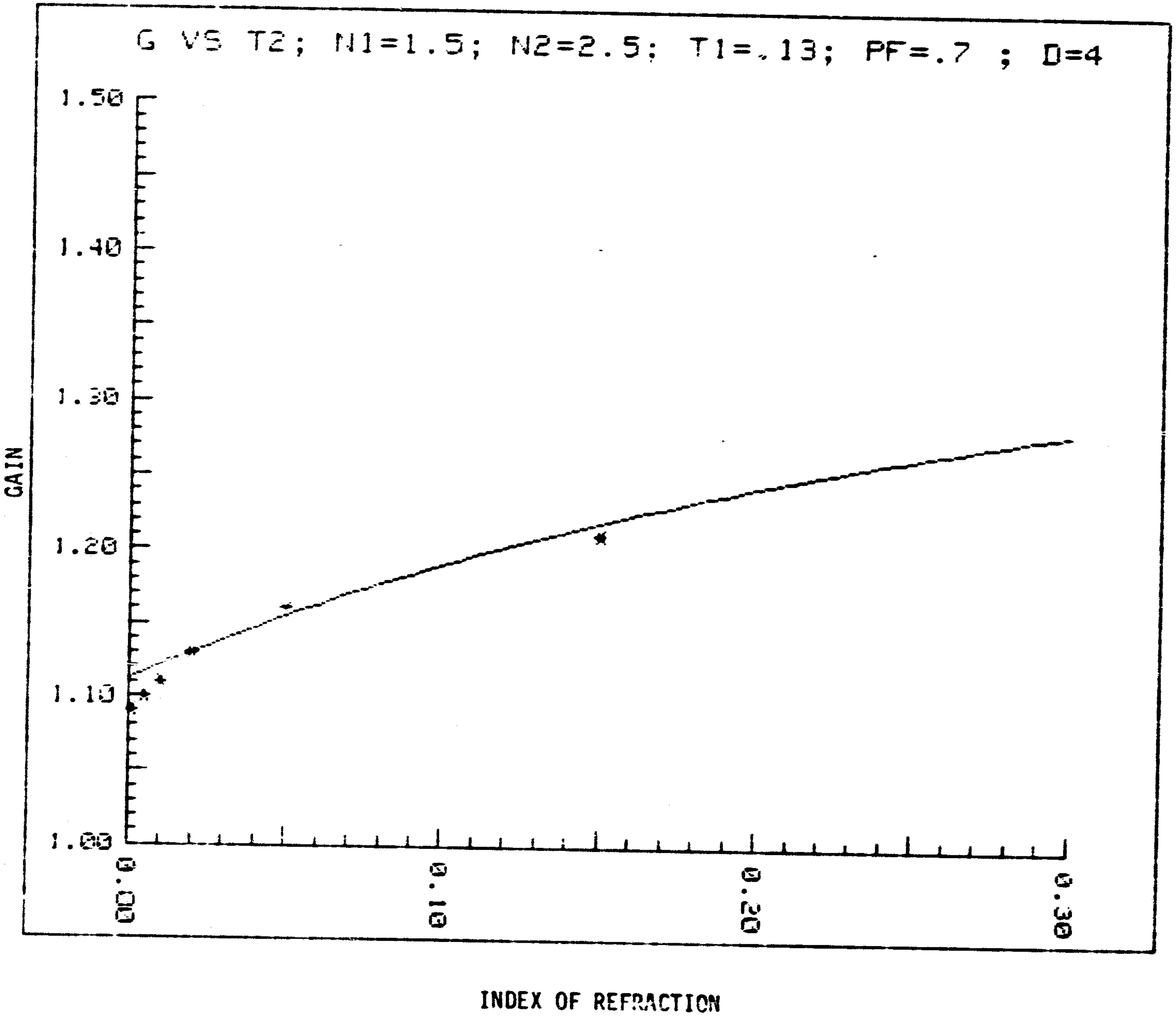


Figure 4-2. Module Gain -vs- Index of Refraction

when photovoltaic cells are costly, the concept allows gains in solar cell panel performance that are approximately a factor of two. The additional cost is that of increasing panel size approximately a factor of five. As cells decrease in cost this panel structure can be used to mount additional new denser modules to increase power output up to approximately a factor of 2.5 over the initial output power. Light trapping therefore provides PV system purchasers with the option of buying growth systems that:

- allows each current PV cell to do the job of approximately two cells, and
- may encourage energy conscience individuals and business managers to get into photovoltaic systems earlier.

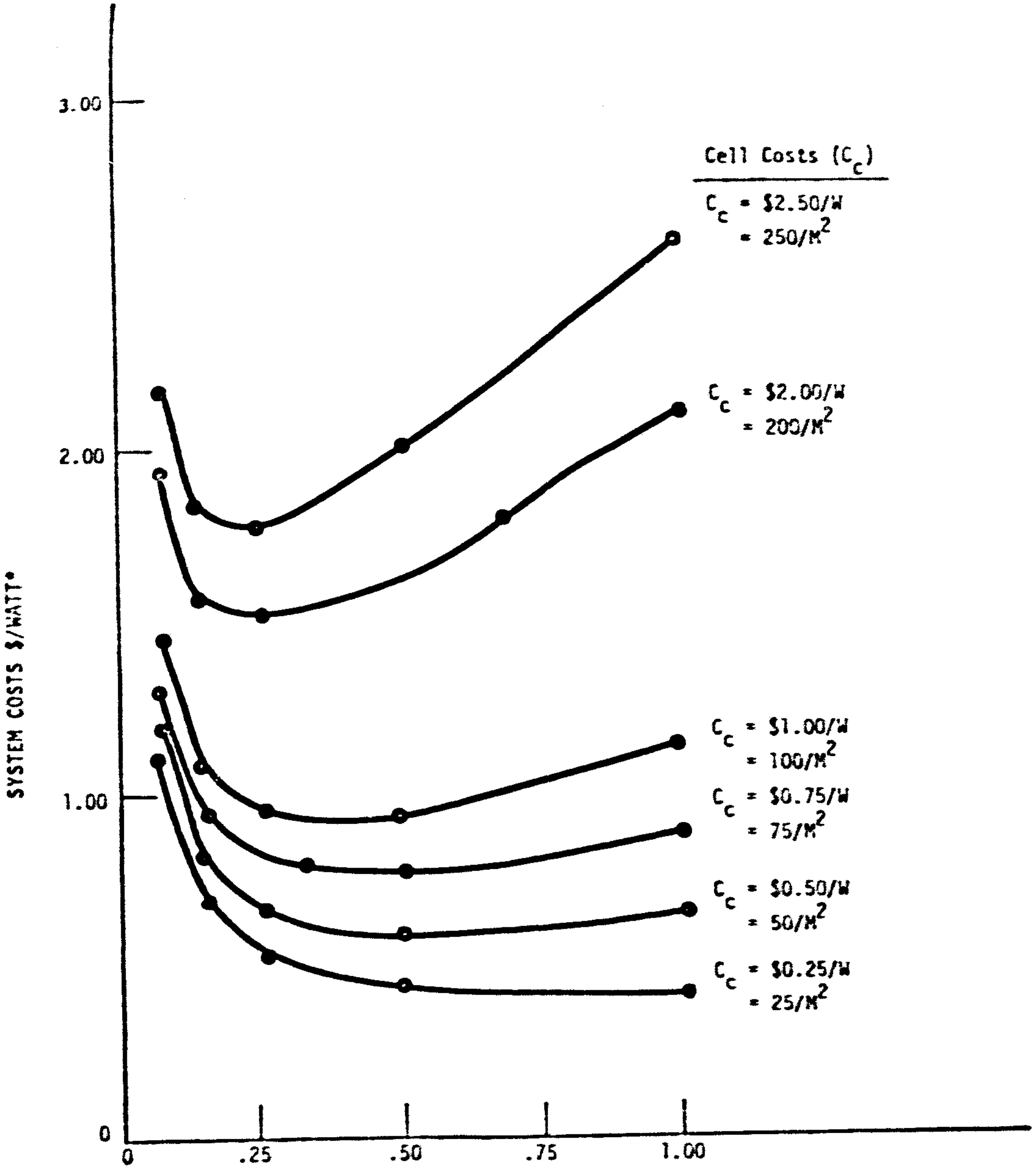
For example, a business could install a 10kW system now and expand it to approximately 25kW in one or more increments on a schedule determined by:

- increasing power requirements
- increasing local power costs
- reducing solar cell costs.

The costs of materials, land and labor will drive the design, and scheduling of the fabrication and demonstration of growth photovoltaic system. Performance and installation cost equations were developed in Section 2.

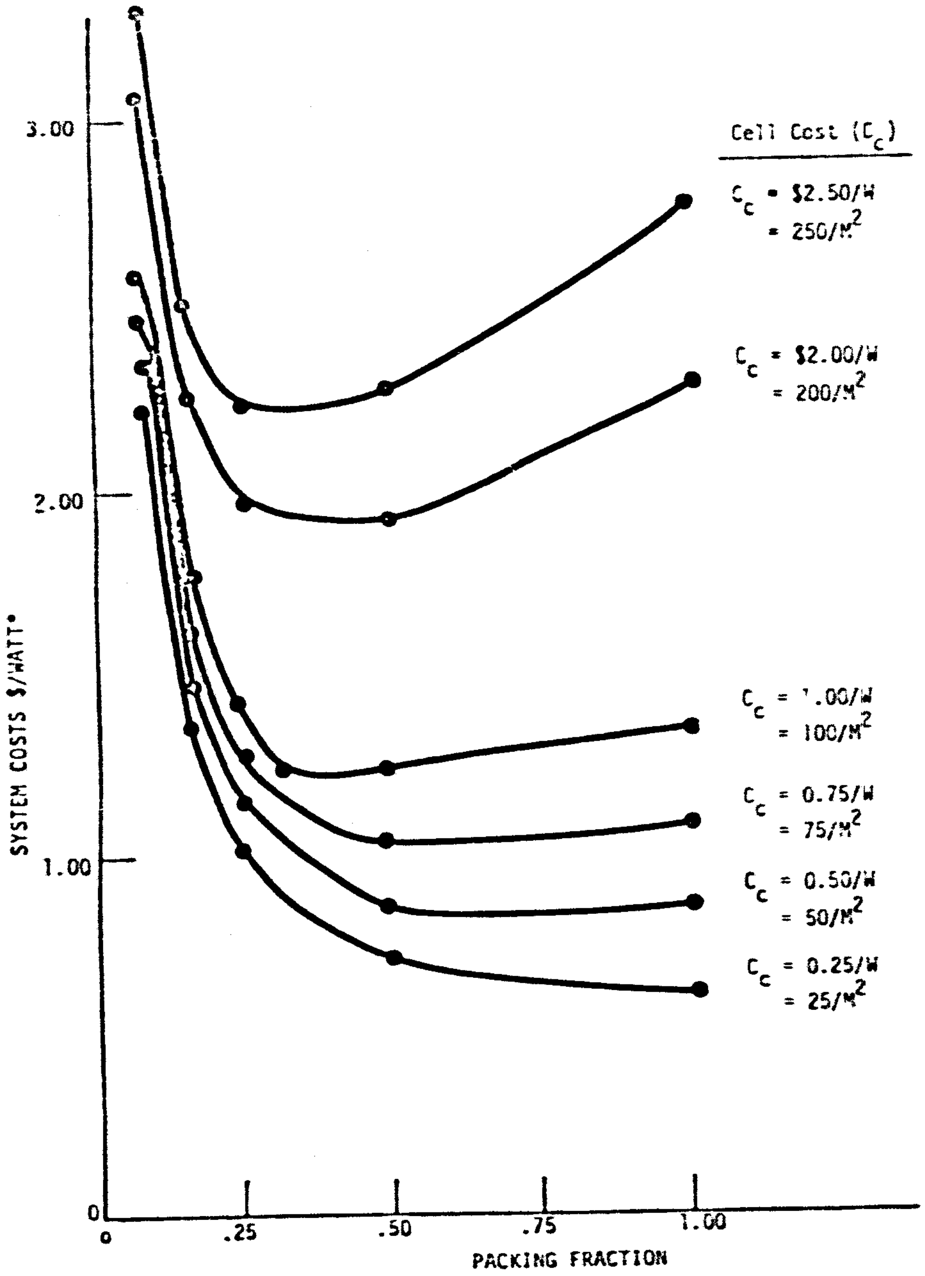
Figures 4-3 and 4-4 show the results of the solution of equation (5) for a system using estimated costs for 1979, 1982 and 1986 respectively. Based on this information for lowest installation costs the 1979 panels should have used a packing frction of 0.16, the 1982 panels should use a PF of 0.25 and the 1986 panels will use a PF of 0.49.

Using this methodology a plot of PF vs time for lowest installation cost can be developed. This will allow a user to select the PF that will given him the power he needs at lowest installation costs and will provide needed data when planning a retrofit schedule. Note that cell costs in Figures 4.3 and 4.4 will have to go below \$50/m^2 (~50¢/watt) before packing factor should go above 0.50.



*Power conditioning and cabling considered to be same for all cases.

Figure 4-3. Example for Land/Structure Cost $10/M^2



*POWER CONDITIONING AND CABLING CONSIDERED TO BE SAME FOR ALL CASES.

Figure 4-4. Example for Land/Structure Cost $31/$M^2$

SAI will be glad to define the demonstration program in detail, to layout a schedule for its completion, and to provide costs.

The electrical power generated by each panel will be absorbed in a resistive load during tests. A load adjust and power meter that monitors the output of each panel can be designed to allow the load to be trimmed so that the cell operates at that point on the IV curve for maximum power output. This will allow a real time comparison of panels at varying levels of insolation and will make it possible to use the sun as the test source. Materials costs will be a function of number of panels, and PF range demonstrated and the power output of each panel.

The gain that can be experienced in a photovoltaic panel is a function of packing fraction, trapping layer material, trapping layer thickness, layer transmission characteristics, and cell dimensions.

Calculations using the SAI developed Monte-Carlo analysis program for the case of a module consisting of:

- Top cover, 125 mils, n=1.50 (glass)
- Pottant and spacer, 5 mils, n-1.5 (EVA and Craneglas)
- High index layer, 50 and 150 mils treated, and n-1.8 to 2.8 in steps
- Cells
- Diffusing layer

These cases where gain was studied as a function of layer thickness and refractive index n gave the results plotted in Figure 4-5. The gains achieved reach 1.20 or higher. For this packing fraction PF (0.70) the highest permissible gain is 1.43, so that about half of the previously lost energy is trapped.

A comparative estimate of the equivalent cell efficiencies required for a round cell packed at 70% density in a well designed module (gain = 1.22) and a square cell efficiency in a 95% dense packed module was made. Table 2-3 shows the results. A slightly more efficient round cell competes well on a per unit power basis with a square cell.

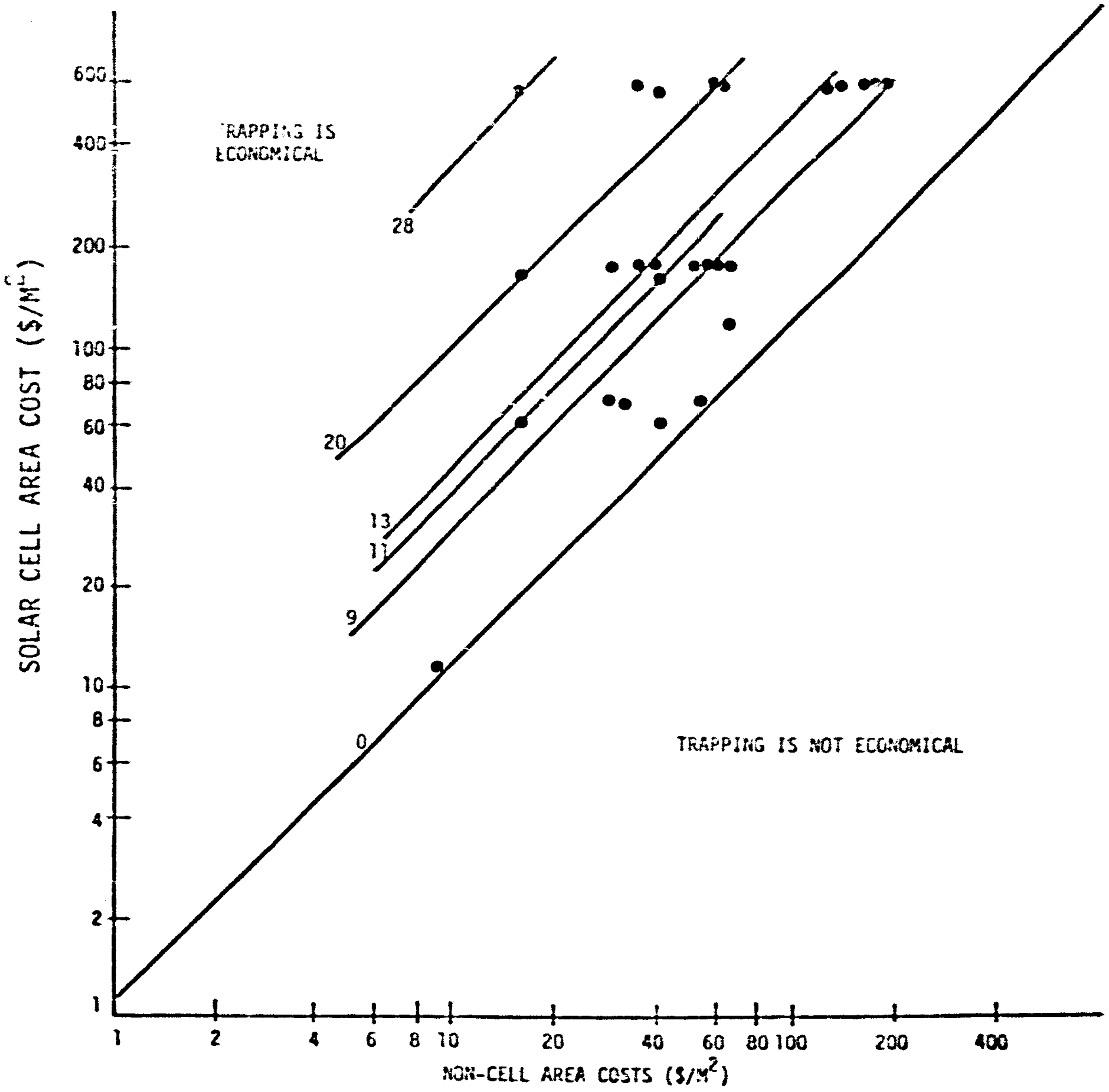


Figure 4-5. Regions of Cost Savings

4.3 ANALYSIS TECHNIQUES

To evaluate light trapping three cases have been selected. These include review of a large number of cases and parameterizing of the results in % of cost saving (diagonal lines) plotted for cell area cost versus non-cell area costs is given in Figure 4-5. In Figure 4-6 is presented the % savings as a function of the cell area to non cell area cost ratio. Naturally where the ratio is unity, no cost savings can be achieved by a substitution. For higher ratios the line is relatively straight and is approximately 1% per unit of the ratio for this set of calculations.

In order to develop a cost estimate of a near standard module, SAI surveyed the volumetric costs of module materials (units $\$/ft^2$ mil) and report these in Figure 4-7. The most cost effective optically thick module uses a glass superstrate and Craneglas-EVA as a spacer between the cell and glass. Figure 4-8 shows the cost function for a module suitable for a residential application, with costs developed for three cases (see Figure 4-9). The basic residential array area cost is taken as $\$7/m^2$ consistent with JPL cost estimates. This includes an area credit. Three cell price scenarios as listed in Figure 4-10 are employed. Finally three encapsulation thicknesses in each year are studied, using the cost estimating formula displayed in the figure. The result of the calculation is given in Figures 4-11 to 4-12.

The 1/4 t/ℓ case is the optimum at PF = 0.5 for 1980 cell prices. This remains true with 1982 scenario cell prices, however by 1986 DOE goals, the advantage of light trapping is lost, as cells are as cheap as the encapsulation materials.

4.4 A WALL-INTEGRATED SYSTEM

A design for the light trapping PV panel to be integrated into the wall of a home has been developed. Following paragraphs describe this system, present modeling assumptions and give modeling results.

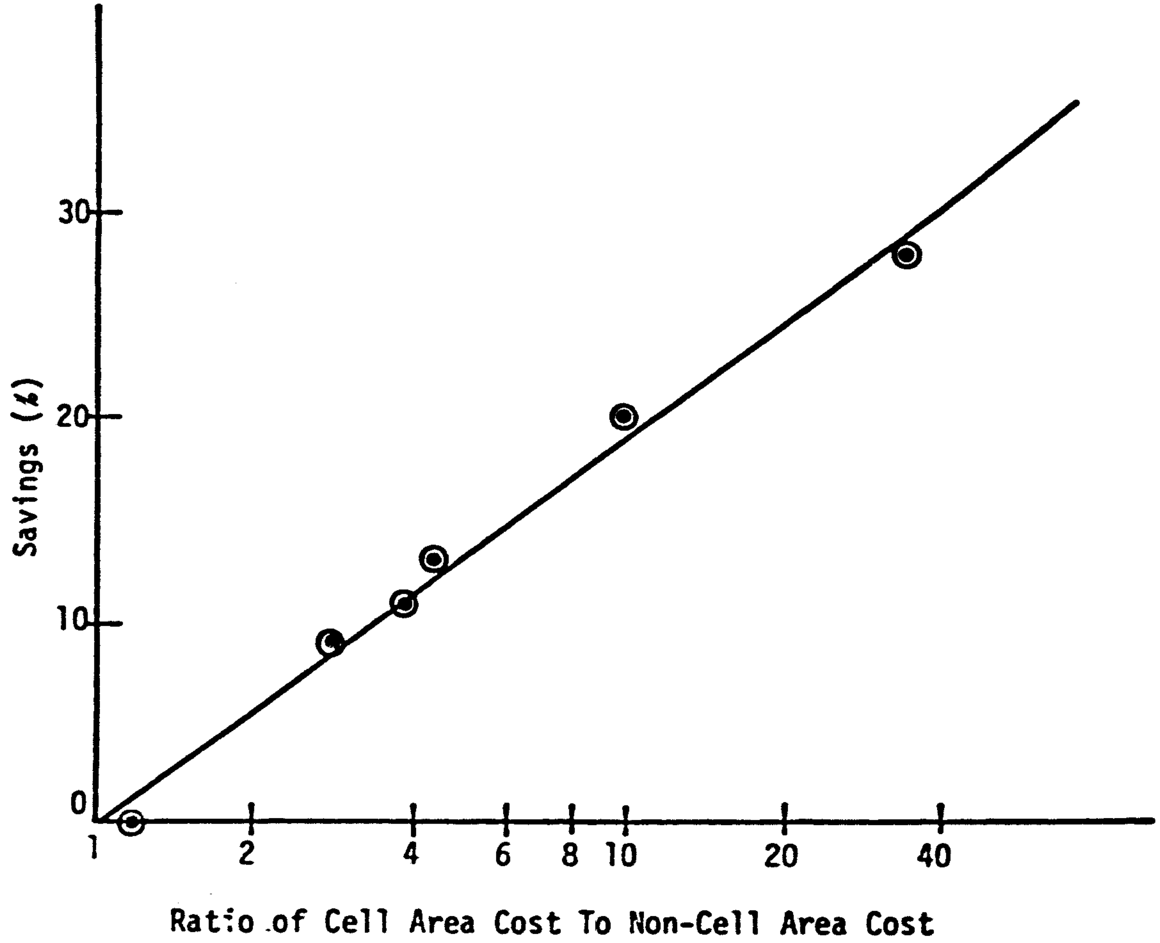


Figure 4-6. Savings as a Function of Cost Ratios

USAGE	MATERIALS	MATERIALS VOLUMETRIC COST $(\$/\text{FT}^2\text{MIL})$
TOP COVERS	SODA-LIME GLASS	.002*
	TEDLAR	.050
	KORAD	.020
	SILICON/ACRYLIC	.035+
POTTANTS	EVA	.005+
	EPR	.005+
	PBA (PMMA)	.010+
	PCP	.005+
SPACER	CRANEGLASS (200)	.0015
BACK COVER	METALIZED MYLAR	.01 TO .70 RANGE

ENCAPSULANT

ALLOWANCE AVERAGE COST .0057 BASED ON 130 MIL MODULE

---

* AT 125 MIL THICKNESS

\+ IN DEVELOPMENT

Figure 4-7. Data on Encapsulant Costs

RESIDENTIAL

MODULE SUPERSTRATE AND ARRAY AREA COSTS = C_A

$$C_A = \left[21 + .048\ (t - t_{MIN})\right] (\$/M^2) \quad (t \text{ IN MILS})$$

RESIDENTIAL MODULE, t_{MIN} = 130 MILS, CRANEGLAS + 20% EVA FILLER USED, 1.8 MATERIAL BURDEN

EXAMPLE CALCULATIONS:

t (MILS)	Δt (MILS)	C_A ($\$/M^2$)
130	0	21.0
155	25	22.2
180	50	23.4
230	100	25.8
280	150	28.2
330	200	30.6
430	300	35.4
630	500	45.0

Figure 4-8. Minimum Cost Superstrate Thickness Increase

- THREE CASES REVIEWED: 1980 CELLS AT $\$5.75/M^2$
  1982 CELLS AT $\$1.73/M^2$
  1986 CELLS AT $\$0.69/M^2$

  INCLUDES CELL STRINGING COSTS.

- THREE ENCAPSULANT THICKNESSES: 125 MILS
  250 MILS
  375 MILS

  USING ENCAPSULANT COST FORMULA DEVELOPED EARLIER

$$C_C = \left[14 + .048\,(t - t_{MIN})\right]\ (\$/M^2);\ t \geq t_{MIN}$$

t = THICKNESS IN MILS

t_{MIN} = 130 MILS

Figure 4-9. Example Calculations—Case of Four Inch Circular Cells with varying N=1.5 Encapsulant Thickness

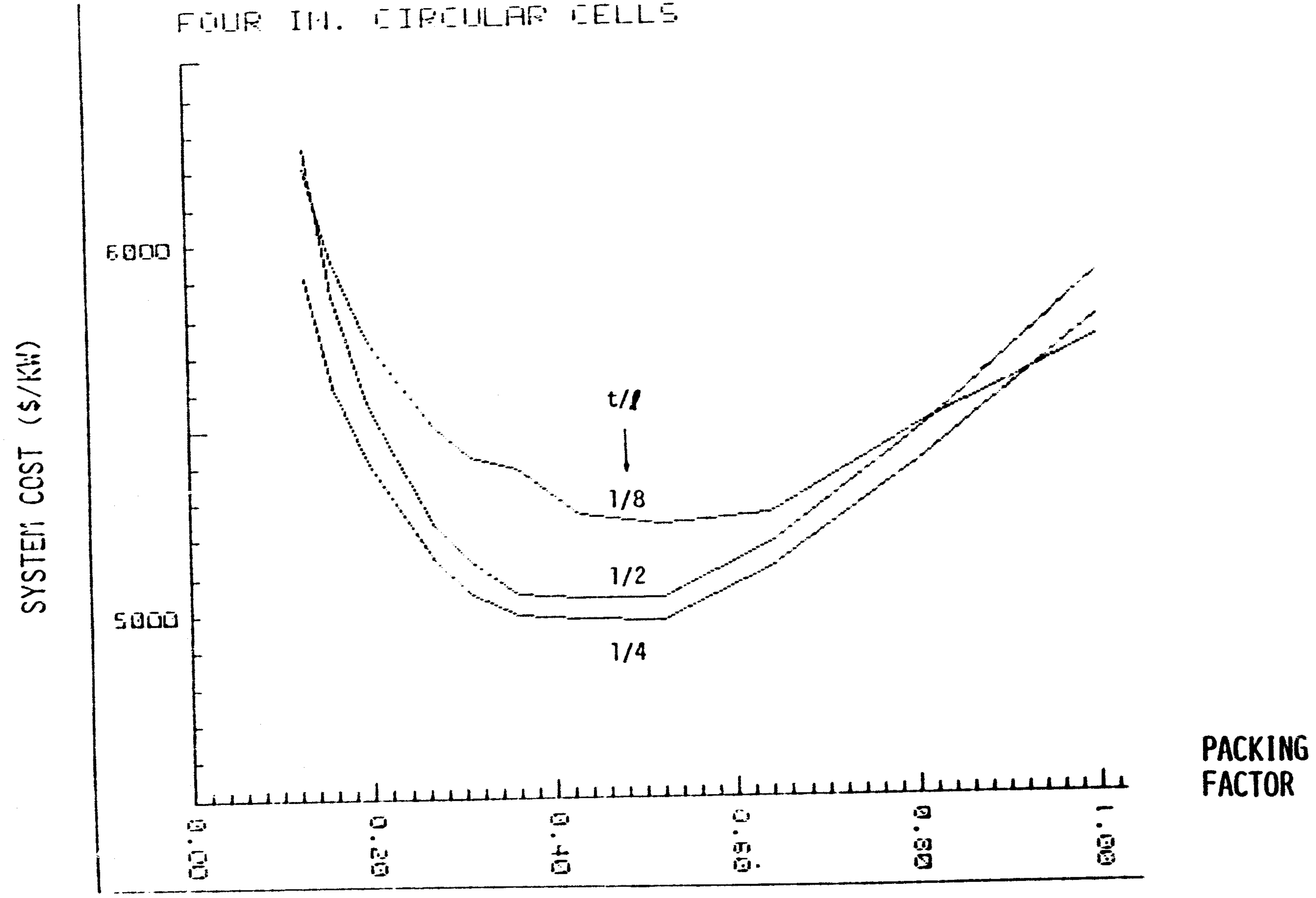


Figure 4-10. Example: 1980 Cell Prices, Three Encapsulant Thickness

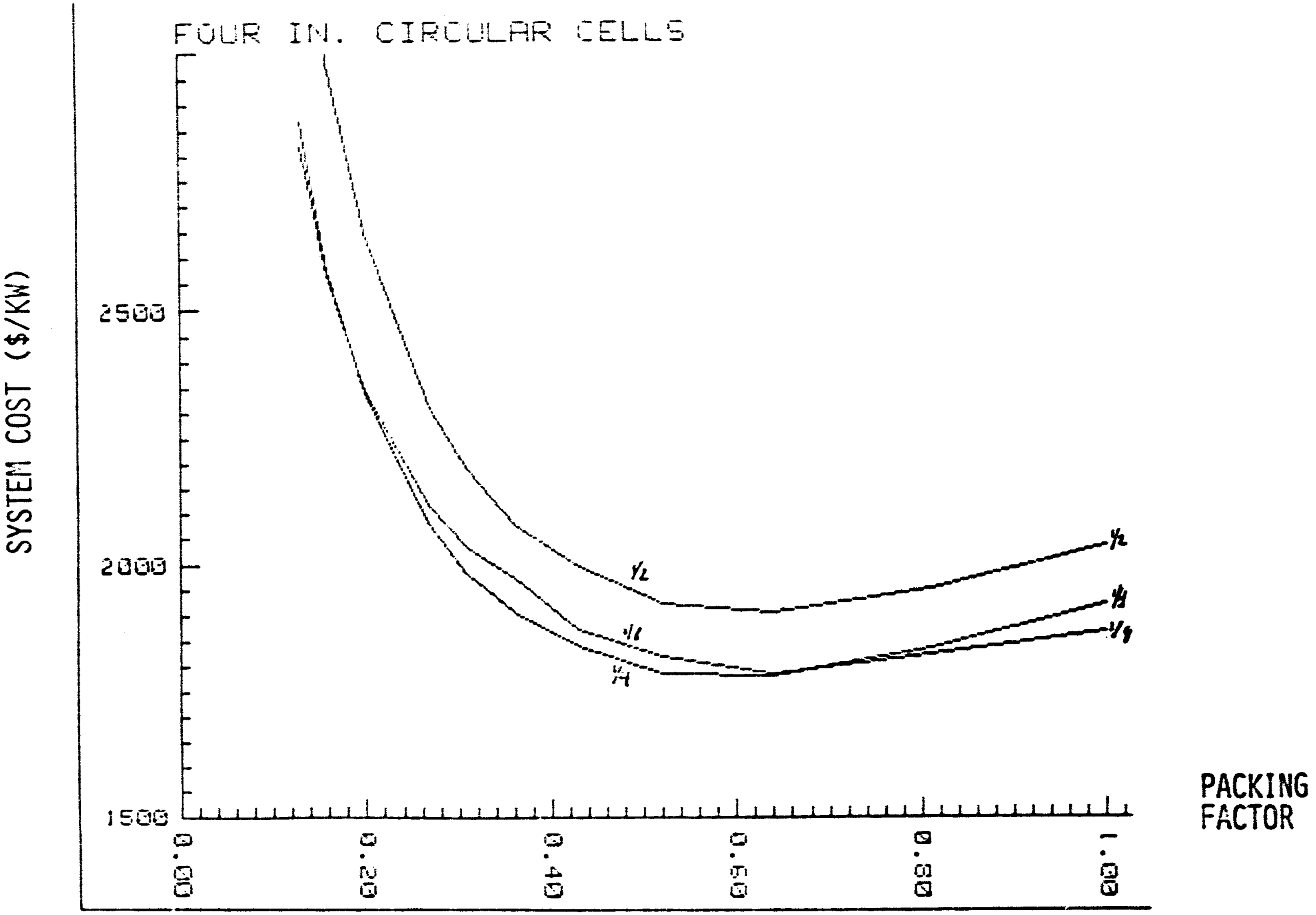


Figure 4-11. Example: 1982 Cell Prices, Three Encapsulant Thickness

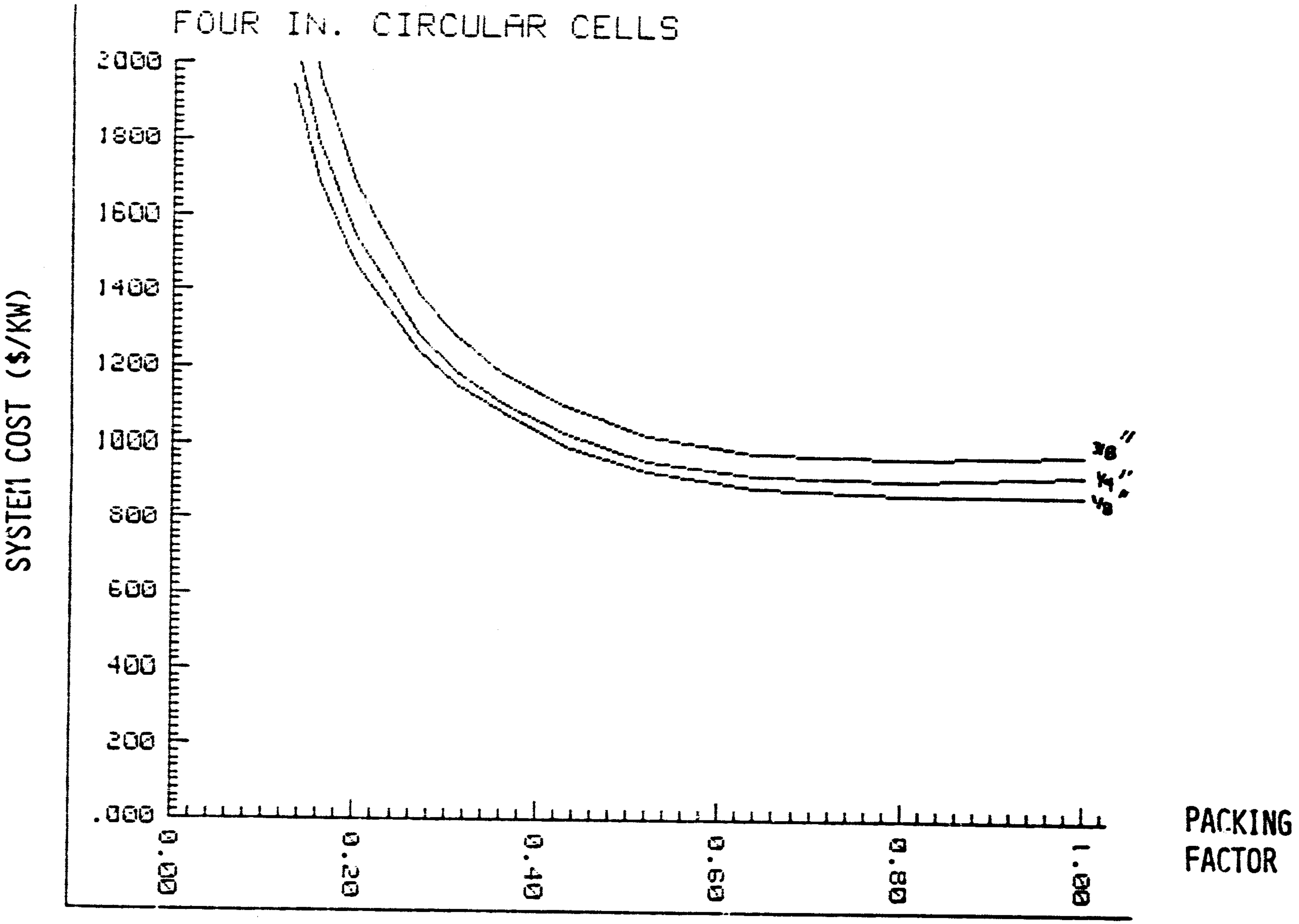


Figure 4-12. Example: 1986 Cell Prices, Thr-e Encapsulant Thickness

4.4.1 System Definition

It has been shown that light trapping techniques can increase the amount of solar energy incident on a photovoltaic cell by up to a factor of two. This increase is without any loss in acceptance angle. The overall panel is larger than one that does not utilize light trapping, and a significant amount of light (about 50%) is reflected back. Despite these facts the overall cost of power from a light trapping panel will be significantly lower than from a conventional panel. Further cost reductions could be achieved if the two detrimental features (large area and reflected light) could be turned into advantages.

A way to exploit all the characteristics of the light trapping panel is suggested by the requirements of double shell passive building design when interior south facing walls are exposed to sunlight. By use of the light trapping panel a credit for wall construction material could be taken as the panel would replace the wall. The interior space in front of the panel (an atrium) would be light and airy due to the reflected sunlight. The panel could be translucent, diffusely transmitting a fraction of the sunlight to interior rooms. Thus all light would be utilized either for illuminator, heating or for production of electricity. The concept is applicable to new energy efficient construction in sunny areas. The basic design would be equally applicable to commercial buildings, houses, multifamily dwellings, military buildings and barracks, hotels, etc. The atrium lobby that is created would particularly lend itself to hospitals, motels, military BOQ's, shopping malls and the like. The concept has additional advantages in that the panels are interior and are protected from long term degradation. Additionally the panels require none of the usual wall maintenance such as painting. Figure 4-13 summarizes the concept.

4.4.2 Modeling Assumptions

The basic panel has three functions. It is a wall, and must integrate with construction material and practices. It is a partially optically reflecting and transmitting barrier and must be capable of design adjustments for various uses. Finally it converts light to d.c. electricity, and must do so in a safe and effective way.

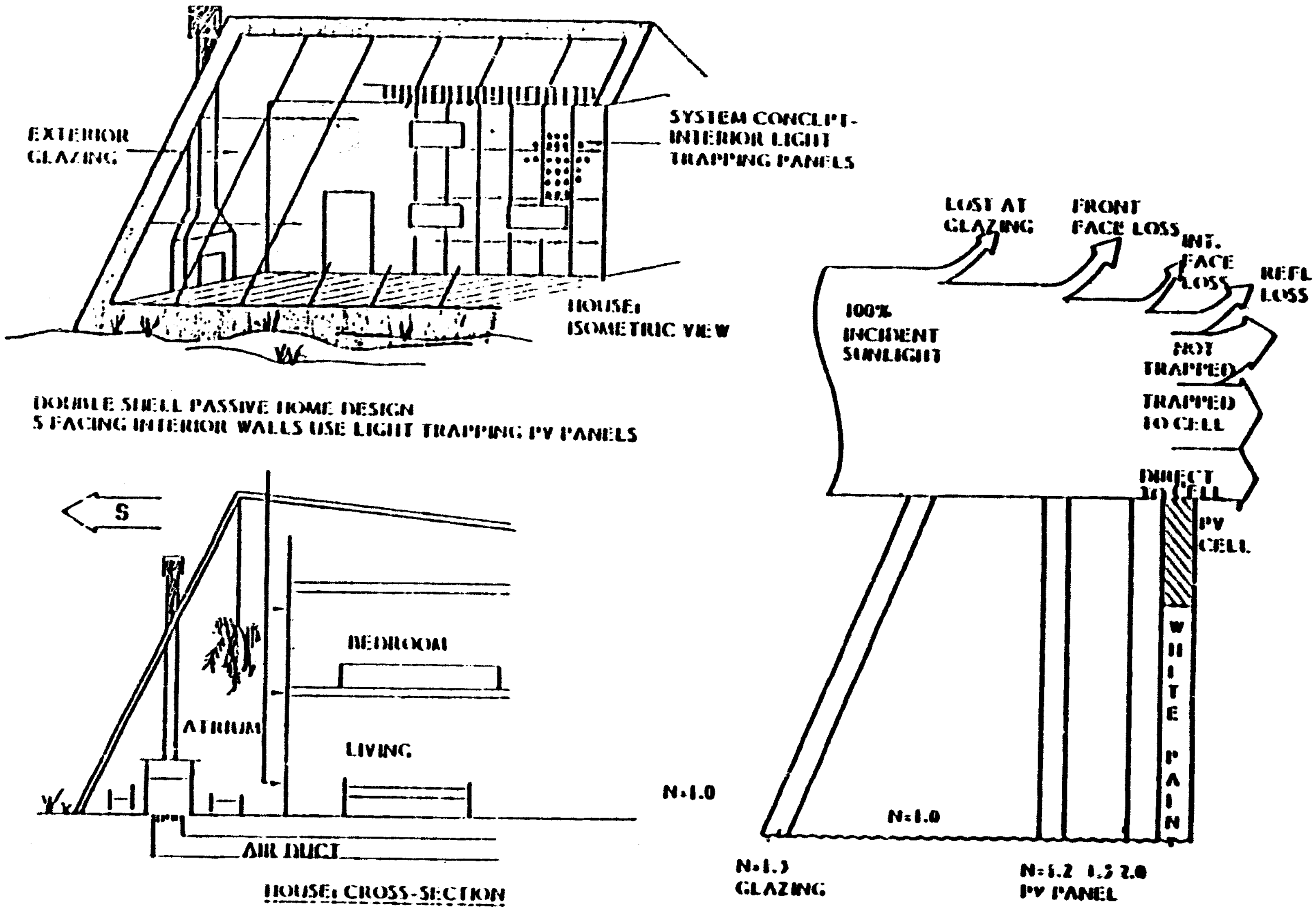


Figure 4-13. Wall Integrated System

The preferred design concept would utilize standard wall panel sizes. A framework provides mechanical connection to ceiling, floor and other panels, and electrical interconnection. Ease of replacement of panels would be provided also. Light trapping is increased when smaller cells are used. Figure 4-14 shows a scheme to use a large round cell effective in an attractive pattern design. For durability, and light weight, either a single glass or plastic sheet is the basic structural material. Glass would provide less light absorption and be of lower cost but for some applications the impact resistance of plastics are useful. Thin film coatings would be applied in a factory to the basic sheet. These would consist of a stack of anti-reflection (AR) coatings at the front face, and high index coatings at the rear for trapping. Figures 4-15 and 4-16 show a cross section view of a typical design with reflection, transmission and trapping layers indicated. The optimum values can be altered by changing the film stack and/or by altering the cell packing fraction. The design displayed represents optimum values for current cell prices. As cell prices are reduced the optimum packing fraction will increase. When economically advantageous the entire replaceable panel will be taken out and a new higher density unit (providing more power) will be inserted. This provides more power for additional occupants or loads in the building.

4.4.3 Results

The design concept was analyzed with computer programs developed during the IRD project and the results are shown in Figures 4-17 and 4-18. The cell gain of the system is about 2. In other words, besides the light falling directly on the cell, another nearly equal amount is diffused through the light trapping panel. This additional light provides increased electrical output proportional to the gain and causes the cost of cells per power output to decrease also in proportion. As can be seen from Figure 4-17, the outer double glazed window reflects some of the incident sunlight and drops a small fracton of that reflected from the panel. Its main function, of course, is to provide thermal insulation for the dwelling structure, while allowing sunlight to enter.

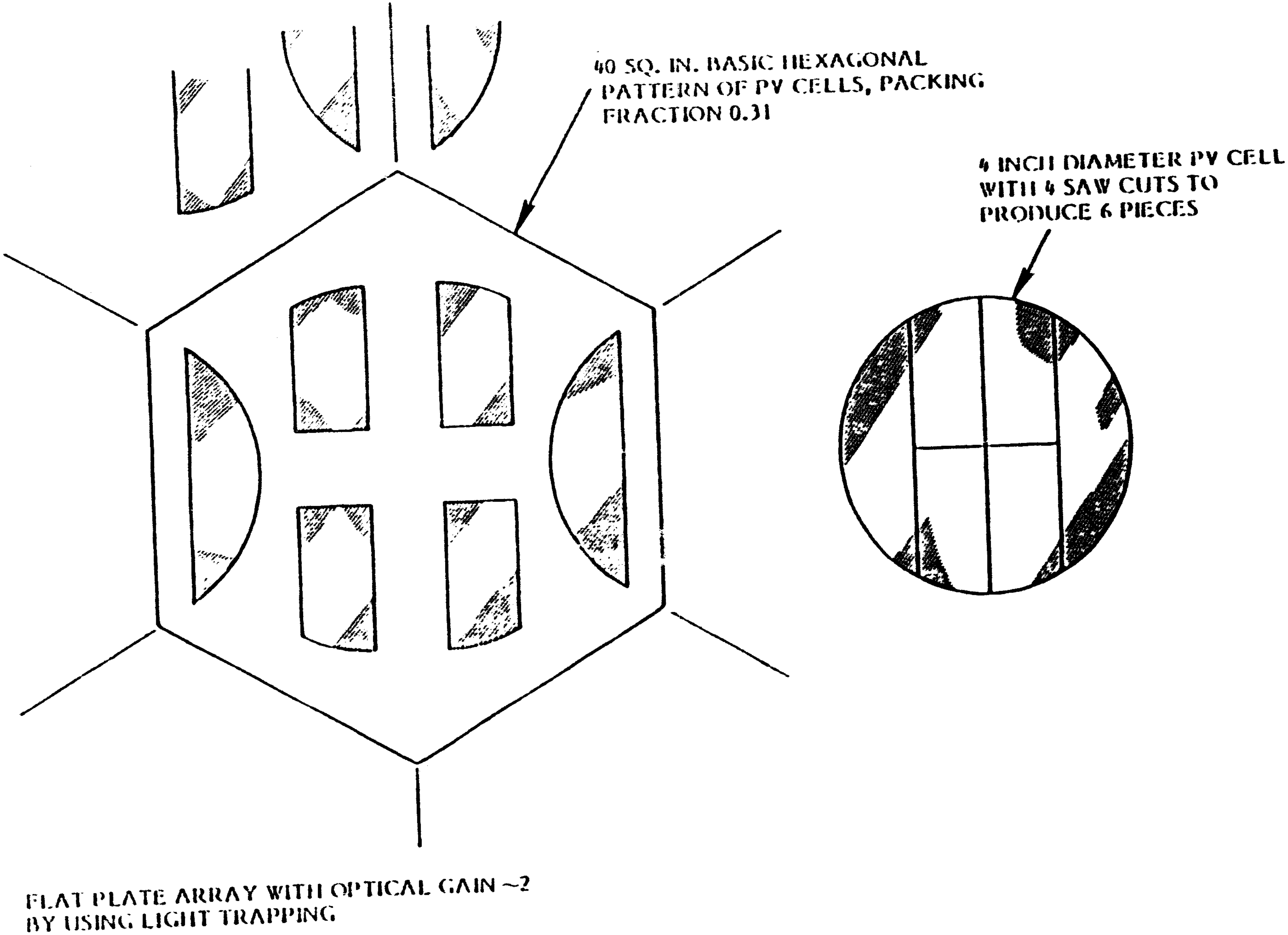


Figure 4-14. Plan View

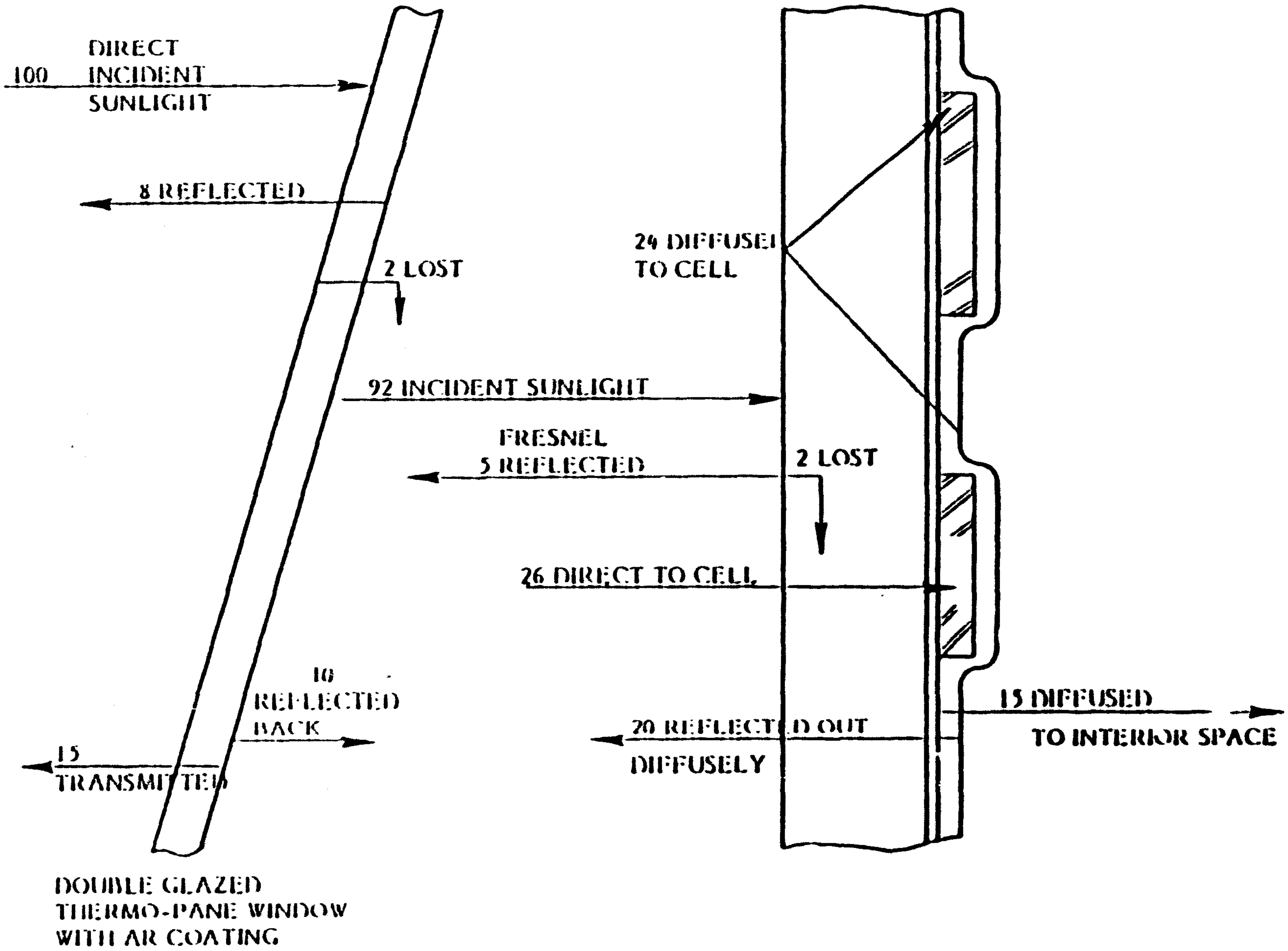


Figure 4-15. Detailed Result of Performance Calculations

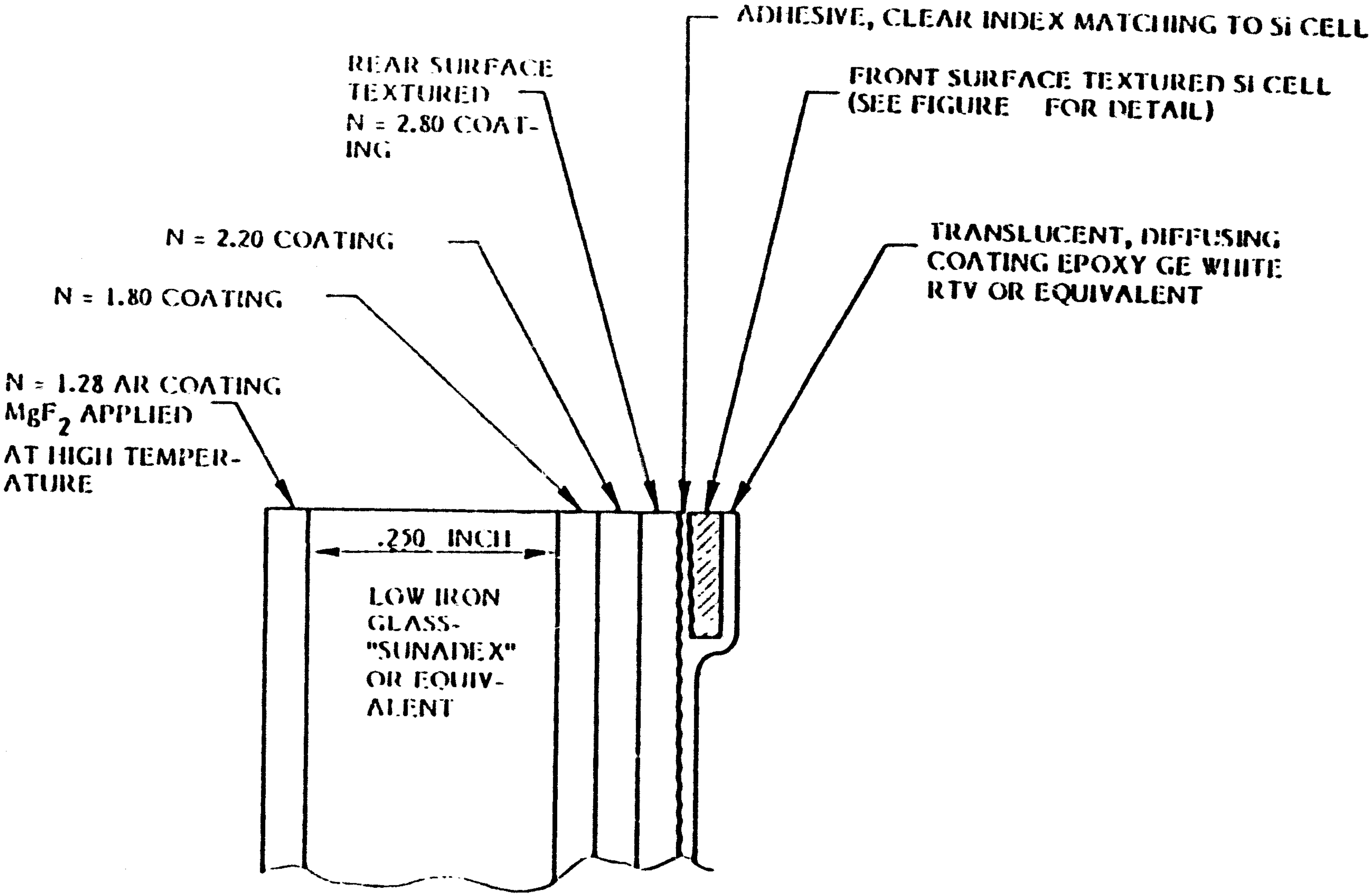


Figure 4-16. Cross-Section View

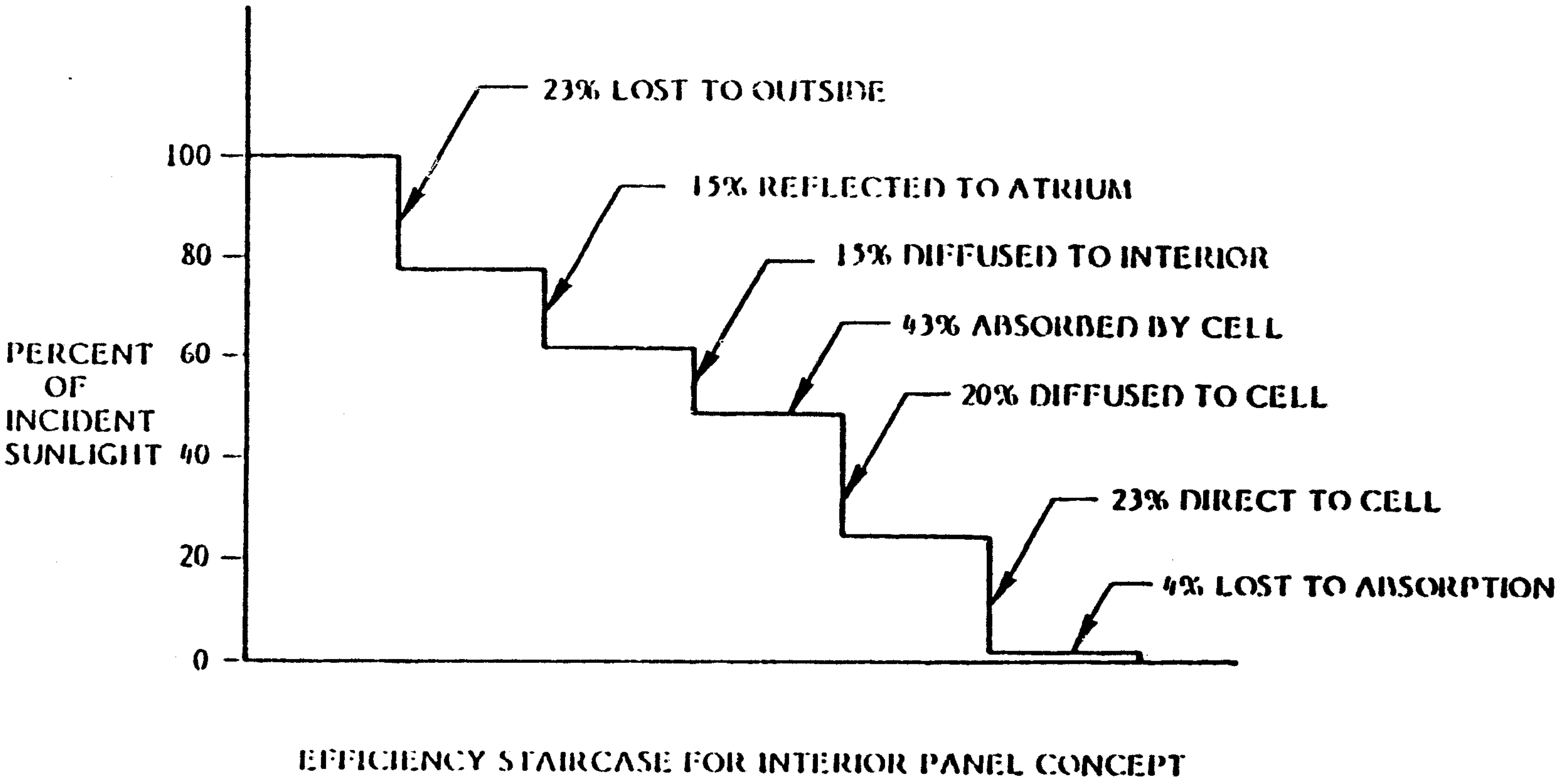


Figure 4-17. Summary Result of Performance Calculations

	$1980 COSTS PER m^2			
	1980	1984	1986	
Cells/Assembled	10,000	2000	500	
Glass	20	15	10	
Coatings	10	5	2	
Framework	10	10	8	
Electrical	10	10	8	
System Assembly, Transportation, etc.	500	200	100	
Total:	10,550	2240	628	100% packing
Area Costs ($1980/$m^2$)	3,880	700	283	31% packing
Power Costs ($/w)	10.6	2.24	0.63	100% packing
	6.5	1.17	0.47	31% packing

Figure 4-18. Cost Estimates for Flat Plate System

The panel reflects or transmits most of the light not absorbed on the cells. The transmitted light into the interior is about 15% of normal daylight privides background interior room illumination although electric lights would be required for spot illumination for reading or performing tasks. The reflected light in the atrium provides fairly uniform intense illumination, and passive heating/cooling. In total about 4% of the light is "lost", but this is used to heat the walls which is a desirable gain in winter.

The highest cost item in the system is the photovoltaic cells, the glass supporting frame and itnerconnections being minor elements. A summary of the anticipated cost elements in present and future costs (1980 dollars) is given in Figure 4-18.

4.5 INTERCELL TRAPPING

Even when cell prices are so inexpensive that the value of intercell areas are diminished, the intracell areas (those areas on the cell itself devoted to grids) that provide blockage, are likely areas to exploit light trapping. The distinction between the two types of trapping is as follows:

- Intercell trapping traps light by diffuse back reflection from the regions between cells.
- Intracell trapping uses a diffusing layer on the cell grid itself to recover a large part of grid blockage losses.
- In both cases light trapping works over the entire hemisphere thus providing concentration of the sky diffused component of solar radiation.

Light trapping from the cell grid can be provided by a white diffusing material applied over the grid. This can be part of the cell manufacture and represent little or no extra cost. Figure 4-19 illustrates grid trapping.

EVEN IN THE CASE OF THE SUBSTRATE DESIGN AND/OR WITH NEARLY 100% PACKING FRACTION CELL GRID REGIONS ARE ATTRACTIVE FOR OPTICAL TRAPPING.

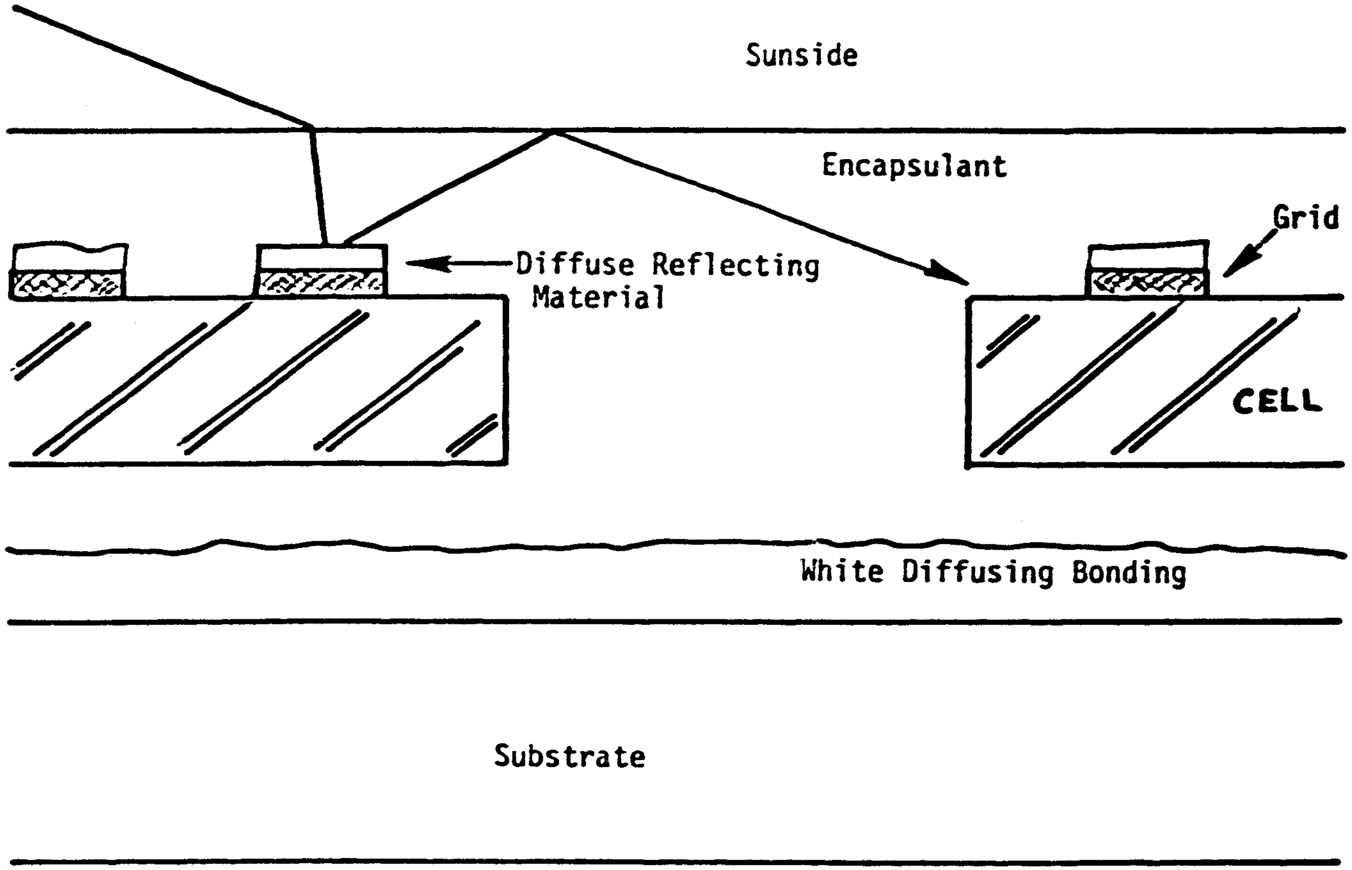


Figure 4-19. Light Trapping From a Cell Grid

5.0 CONCLUSIONS

Based on a six month study of cost effective photovoltaic module design conducted for the Low Cost Solar Array project of the Jet Propulsion Laboratory, Science Applications, Inc. has determined that

1. Optical designs of PV panels using light traping introduce a host of new parameters that must be considered in PV module design and new research and development avenues that promise to provide early dividends. Among the most promising areas are higher index materials for encapsulants, and modules with somewhat different design than those produced at present in such areas as packing factor and encapsulant thickness.

2. Light trapping can be used to:
   - Improve efficiency in standard PV modules.
   - Optimize PV module designs based on cost using current and projected material, labor, money and real estate costs.
   - Improve the efficiency of solar systems architecturally integrated into buildings to provide PV electric power generation, space heating and diffuse lighting.

3. Light trapping PV modules using trapping layers made of currently available materials is already a viable proposition. The development of higher index materials can improve this situation even as cell costs decline.

4. Design method has been developed that illustrate to the engineer the correct approach to design. The following steps were illustrated in the report.
   - Familiarization with concepts - examples.
   - Obtain data on materials: optical properties and costs to augment data on module.

- -- Use design nomographs or simplified design equation to obtain gain as a function of packing factor and thickness of encapsulant above cell.
- -- Use costing nomograph or simplified costing equations to determine gain for various packing factor and thickness values, find a cost minimum.
- -- Estimate cost savings obtained at minimum and compare with standard design.
- -- Repeat with other material choices.

5. Based on this study it is recommended that designers consider light trapping designs in situations where

   - Round cells (full or partial) are to be utilized.
   - Silicon is costly and/or in short supply.
   - Cells are roof and/or wall integrated (residential).
   - Module thickness is important - (hail areas is an example).
   - Rapid power requirement growth is anticipated at site.
   - Thin or sharp shadows fall on array.
   - Array area costs are low.

Finally it is important to realize that there are a wide variety of ways to use light trapping in a cost effective way. Several ways were illustrated in Section 4, including standard module design improvements, new module designs, new ways to employ modules and use of the cell grid to trap light.

6.0 REFERENCES

Section 1

1-1. T.M. Knasel, System Designs for Low Cost-Low Ratio Solar Concentrators SPIE Vol. 161, Optics Applied to Solar Energy IV (1978).

1-2 United States Patent No. 4,246,042, "Fixed Solar Energy Concentrator" (assigned to Science Applications, Inc.).

1-3 United States Patent No. 4,162,928, "Solar Cell Module", Neal F. Shepard, Jr., July 31, 1979, (assigned to NASA).

1-4 N.F. Shepard, "Development and Testing of Shingle-Type Solar Cell Modules-Final Report", DOE/JPL-954607-79/4, February 28, 1979.

1-5 J.G. Mark and C.H. Volk, "The Zero Depth Concentrator Phenomenon", JPL 5101-13b.

1-6 United States Patent No. 4,116,718, "Photovoltaic Array Including Light Diffuser", J.W. Yerkes and J.E. Avery, September 26, 1978, (assigned to Atlantic Richfield Co.).

Section 2

2-1 Springborn Labs DOE/JPL-954527-79-10, Investigation of Test Methods, Material Properties and Processes for Solar Cell Encapsulants.

2-2 Spire Corp. DOE/JPL 95421-78/4, Integral Glass Encapsulation for Solar Arrays, Quarterly Progress Report No. 10, June 1979.

2-3 Solar Cell Array Design Handbook

2-4 James W. Stultz, "Thermal and Other Tests of Photovoltaic Modules Performed in Natural Sunlight," J. Energy 3, p. 363, Nov-Dec 1979.

2-5 T.M. Knasel, System Designs for Low cost-Low Ratio Solar Concentrators SPIE Vol. 161, Optics Applied to Solar Energy IV (1978).

APPENDIX A

Optical Design Guide
for
Light Trapping
in
Flat Plate Photovoltaic Modules
(JPL Contract 955787)

SCIENCE APPLICATIONS, Inc.
1710 Goodridge Drive
P.O. Box 1303
McLean, VA 22102
(703) 821-4300

APPENDIX "A"

OPTICAL DESIGN GUIDE
FOR
LIGHT TRAPPING
IN
FLAT PLATE PHOTOVOLTAIC MODULES

(JPL CONTRACT 955787)

PRESENTED AT THE

DEPARTMENT OF ENERGY - LOW COST SOLAR ARRAY PROJECT
17TH PROJECT INTEGRATION MEETING
4 - 5 FEBRUARY 1981
PASADENA, CALIFORNIA

PRESENTED BY:
T.M. KNASEL
SCIENCE APPLICATIONS, INC.
1710 GOODRIDGE DRIVE
McLEAN, VIRGINIA 22102
(703) 821-4499

TITLE: ORGANIZATION OF DESIGN GUIDE

PURPOSE: PRESENTS THE FOUR DESIGN GUIDE SECTIONS

DEFINITIONS:

DISCUSSION: THE GUIDE STARTS WITH THE GENERAL BACKGROUND, DEVELOPS DESIGN TECHNIQUES AND PRESENTS EXAMPLES, CONCLUSIONS AND REFERENCES.

ORGANIZATION OF DESIGN GUIDE

- BACKGROUND - MATERIAL TO FAMILIARIZE READER WITH BASIC PHYSICAL CONCEPTS, GOALS AND PURPOSES OF THIS GUIDE
- SIMPLIFIED DESIGN TECHNIQUES - TO ALLOW A DESIGN ENGINEER TO DEVELOP EFFECTIVE OPTIONS AND STUDY TRADE-OFFS
- EXAMPLES - TO ILLUSTRATE THE TECHNIQUES PRESENTED
- CONCLUSIONS AND REFERENCES - FOR FOLLOW UP IN MORE DETAIL ON FACTS PRESENTED HERE

TITLE: TABLE OF CONTENTS

PURPOSE: PROVIDES A QUICK OVERVIEW OF THE DESIGN GUIDE

DEFINITIONS: THE SEVERAL TECHNICAL TERMS THAT APPEAR IN THE TABLE OF CONTENTS WILL BE DEFINED AS THEY ARE FIRST USED IN THE BODY OF THE GUIDE.

DISCUSSION: CONTENTS ARE GIVEN IN THIS AND THE NEXT THREE SLIDES.

TABLE OF CONTENTS

BACKGROUND

PAGE #

A) OPTICAL DESIGN GUIDE

TITLE: TABLE OF CONTENTS (Continued)

PURPOSE:

DEFINITIONS:

DISCUSSION:

TABLE OF CONTENTS

SIMPLIFIED DESIGN TECHNIQUES

TITLE: TABLE OF CONTENTS (Continued)

PURPOSE:

DEFINITIONS:

DISCUSSION:

TABLE OF CONTENTS

EXAMPLES

TITLE: TABLE OF CONTENTS (Continued)

PURPOSE:

DEFINITIONS:

DISCUSSION:

TABLE OF CONTENTS

TITLE: ACKNOWLEDGEMENTS

PURPOSE: IDENTIFIES MAJOR CONTRIBUTORS

DEFINITIONS:

DISCUSSION:

ACKNOWLEDGEMENTS

- SCIENCE APPLICATIONS, INC. APPRECIATES THE ASSISTANCE OF THE LOW COST SOLAR ARRAY PROJECT OF THE JET PROPULSION LABORATORY, PARTICULARLY DON BICKLER AND PAUL ALEXANDER OF PPE AND ED CUDDIHY OF THE ENCAPSULATION TASK.

- THE DESIGN GUIDE WAS PREPARED BY C.N. BAIN, BRUCE GORDON, BOB MALINOWSKI, AND T. MICHAEL KNASEL (PROJECT MANAGER) OF SAI McLEAN, VIRGINIA.

TITLE: INTRODUCTION

PURPOSE: PRESENTS AN OVERVIEW OF THE INTRODUCTORY REMARKS

DEFINITIONS:

DISCUSSION:

A.1 INTRODUCTION

- CONTRACT DETAILS
- GOALS OF DESIGN GUIDE
- DEFINITIONS

TITLE: CONTRACT DETAILS

PURPOSE: TO GIVE THE MAJOR CONTRACT DETAILS

DEFINITIONS: LIGHT TRAPPING WHEN USED IN CONNECTION WITH PHOTOVOLTAIC PANELS IS THE ACTUAL TRAPPING OF LIGHT IN THE PLASTIC OR GLASS SUPERSTRATE THROUGH INTERNAL REFLECTION AT SUPERSTRATE SURFACES. THIS ACTION IS INITATED BY PLACING A DIFFUSING REFLECTING COATING (SUCH AS WHITE PAINT) ON THE UNDERSIDE OF THE SUPERSTRATE.

DISCUSSION: BECAUSE THE POTENTIAL OF LIGHT TRAPPING APPEARS TO BE SIGNIFICANT THIS CONTRACT WAS ESTABLISHED TO INVESTIGATE AND DEVELOP DESIGN RULES FOR THE USE OF LIGHT TRAPPING AND TO EVALUATE THE COST BENEFITS OF LIGHT TRAPPING.

CONTRACT DETAILS

TITLE: ANALYSIS OF COST-EFFECTIVE PHOTOVOLTAIC PANEL DESIGN CONCEPTS USING LIGHT TRAPPING

SPONSOR: JET PROPULSION LABORATORY

CONTRACT NO: 955787

OBJECTIVES:

1. DEVELOP OPTICAL DESIGN RULES FOR EFFICIENT USE OF LIGHT TRAPPING IN FLAT PANEL PHOTOVOLTAIC MODULES

2. PERFORM A COST BENEFIT STUDY OF OPTIMUM DESIGNS TO DETERMINE ECONOMIC VALUE OF LIGHT TRAPPING

TITLE: GOALS OF DESIGN GUIDE

PURPOSE: THIS CHART SUMMARIZES THE GOALS THAT WERE SET UP FOR THE DESIGN GUIDE

DEFINITIONS:

DISCUSSION: THE GUIDE IS DEVELOPED FOR THE PRACTICING ENGINEER. THEREFORE, GRAPHS AND SIMPLIFIED EQUATIONS ARE USED INSTEAD OF A DETAILED ANALYTICAL TREATMENT.

GOALS OF DESIGN GUIDE

TAKING THE POINT OF VIEW THAT A PHOTOVOLTAIC MODULE IS A OPTICAL THICK FILM - THREE DIMENSIONAL OPTICAL SYSTEM IN WHICH TRAPPING OF LIGHT CAN AND DOES TAKE PLACE:

- DEVELOP GRAPHICAL RELATIONSHIPS BETWEEN CELL/MODULE EFFICIENCIES AND OPTICAL VARIABLES
- VARIABLES SHALL INCLUDE:
  - CELL SPACING
  - COVER PLATE MATERIALS
  - ENCAPSULATION THICKNESS
  - INDEX OF REFRACTION OF ALL OPTICAL MATERIALS
  - REFLECTIVITY (ANGULAR PATTERN) OF BACK LAYER
- MODLING EFFORT SHALL ADDRESS SINGLE AND MULTIPLE TRAPPING LAYERS
- SIMPLIFIED EQUATIONS SHALL BE DEVELOPED AS APPROXIMATIONS TO FULLY DETAILED CALCULATIONS
- PICTORIAL DISPLAYS AND CROSS-SECTIONING OF OPTICAL MATERIALS SHALL BE USED AS APPROPRIATE

THE DESIGN GUIDE WILL ENABLE THE ENGINEER TO USE LIGHT TRAPPING EFFECTIVELY IN PV PANEL DESIGN.

TITLE: DEFINITIONS

PURPOSE: THIS AND THE NEXT CHART PROVIDE DEFINITIONS OF SOME OF THE TECHNICAL TERMS AND PHRASES USED IN THE GUIDE.

DEFINITIONS:

DISCUSSION:

DEFINITIONS

- THIN FILM OPTICAL SYSTEMS - TWO DIMENSIONAL STRUCTURES THAT REFLECT, REFRACT OR TRANSMIT LIGHT DEPENDENT ON THE WAVELENGTH AND THE OPTICAL PROPERTIES OF THE MATERIALS - OPTICAL RADIATION GOES FORWARD OR BACKWARD ONLY.

- THICK FILM OPTICAL SYSTEMS - THREE DIMENSIONAL STRUCTURES THAT REFLECT AND TRANSMIT OPTICAL RADIATION FORWARD OR BACKWARD, WITH PROPAGATION POSSIBLE TRANSVERSE TO LAYER STRUCTURE.

- LIGHT TRAPPING REFERS TO PROPAGATION IN THICK FILMS WHERE LIGHT IS TRAPPED IN HIGH INDEX MATERIALS BY TOTAL INTERNAL REFLECTION. LIGHT IS NOT NORMALLY TRAPPED UNLESS IT IS SCATTERED IN A DIFFUSE (I.E., NON-SPECULAR) MANNER.

(DEFINITIONS CONTINUED ON NEXT PAGE)

TITLE: DEFINITIONS (Continued)

PURPOSE:

DEFINITIONS:

DISCUSSION:

DEFINITIONS CONTINUED

- MONTE-CARLO - USE OF RANDOM NUMBERS TO DETERMINE THE PATH OF THE SCATTERED. RAYS
- CLOSED FORM SOLUTION - A MATHEMATICAL ANSWER THAT CAN BE EVALUATED EXACTLY.
- FRESNEL REFLECTION - REFLECTION FROM THE SUDDEN CHANGE IN INDEX OF TWO TRANSPARENT MEDIA.
- LAMBERTIAN DISTRIBUTION - A DISTRIBUTION OF SCATTERED RADIATION VARING AS THE SURFACE VIEW FACTOR - AS COS θ WHEN θ IS THE ANGLE TO THE NORMAL.

DIFFUSE SCATTERING, SPECULAR SCATTERING (SEE VIEWGRAPH WHERE IT COVERS THIS).

TITLE: OPTICAL PRINCIPLES

PURPOSE: OUTLINE OF TOPICS TREATED IN THIS SECTION

DEFINITIONS:

DISCUSSION:

A.2: OPTICAL PRINCIPLES

- REFRACTION, REFLECTION IN THICK FILMS
- LIGHT TRAPPING CONCEPT
- THICK FILMS FOR OPTICAL CONCENTRATION
- CLOSED FORM APPROXIMATE SOLUTION
- COMPUTER MODELING
- SIMPLIFIED DESIGN EQUATIONS

TITLE: REFRACTION, REFLECTION IN THICK FILMS

PURPOSE: TO PROVIDE DEFINITIONS

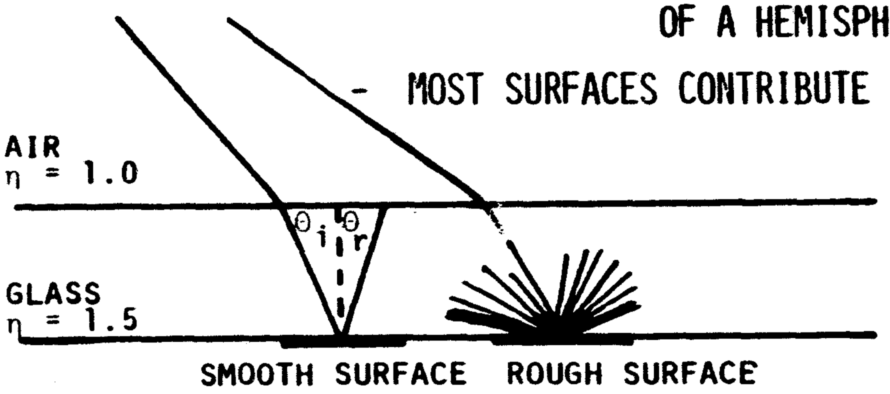
DEFINITIONS: SEE CHART

DISCUSSION: IN THICK FILMS TWO OPTICAL PHENOMENA TAKE PLACE - REFRACTION AND REFLECTION, BOTH OF WHICH ARE DEFINED ON THIS CHART. LIGHT SPECULARLY REFLECTED FROM AN INTERNAL SURFACE OF A THICK FILM OR SUBSTRATE WILL EXIT THE OTHER SURFACE WHICH IS PARALLEL TO IT. HOWEVER, IF REFLECTION IS FROM A ROUGH DIFFUSING SURFACE, SUCH AS FROM A WHITE PAINT COATING, THE LIGHT IS DIFFUSED (OR SCRAMBLED) AND SOME IT CAN BE TRAPPED AND PROPAGATED. A SOLAR PHOTOVOLTAIC PANEL THAT TRAPS LIGHT FROM AREAS NOT COVERED BY CELLS IS FUNCTIONING AS A CONCENTRATOR. LIGHT FALLING AT THE EDGES OF PANELS, BETWEEN THE CELLS AND ON THE ELECTRICAL GRIDS OF CELLS IS SUBJECT TO TRAPPING IN AN APPROPRIATELY DESIGNED PANEL. THE MATERIALS USED IN A PANEL, THEIR ARRANGEMENTS, AND THE GEOMETRIC LAYOUT OF THE PANEL ALL CONTRIBUTE TO THE GAIN THAT CAN BE ACHIEVED.

REFRACTION, REFLECTION IN THICK FILMS

REFRACTION AND REFLECTION ARE THE PRINCIPAL OPTICAL INTERACTIONS IN THICK FILMS:

- REFRACTION: BENDING OF OBLIQUE RAYS AS THEY PASS FROM ONE MEDIUM TO ANOTHER HAVING A DIFFERENT REFRACTIVE INDEX
- REFLECTION: THE RETURN OF RADIATION BY A SURFACE WITHOUT CHANGE IN WAVELENGTH
  - SPECULAR - FROM A SMOOTH SURFACE
    - ANGLE OF INCIDENCE (Θ_i) EQUAL ANGLE OF REFLECTION (Θ_r)
  - DIFFUSE - FROM A ROUGH SURFACE
    - INTO MANY (SOMETIMES ALL) DIRECTIONS OF A HEMISPHERE
  - MOST SURFACES CONTRIBUTE SPECULAR AND DIFFUSE COMPONENTS.



TITLE: THICK FILMS AS OPTICAL CONCENTRATORS

PURPOSE: TO IDENTIFY SOME OF THE FACTORS THAT LIMIT GAIN

DEFINITIONS: GAIN - THE RATIO OF THE OUTPUT POWER OF A PV SOLAR PANEL WITH TRAPPING TO THE OUTPUT OF THE SAME PANEL WITHOUT TRAPPING

DISCUSSION: GAIN IS A FUNCTION OF THE REFRACTIVE INDICES OF THE MATERIALS USED, AND THEIR ARRANGEMENT. GAIN IS ALSO A FUNCTION OF PACKING FACTOR (TOTAL CELL AREA/TOTAL PANEL AREA) AND THE LIGHT ABSORPTION CHARACTERISTIC OF THE THICK FILM MATERIAL. THESE LIMITS ARE TREATED IN DETAIL LATER WHEN PERFORMANCE EQUATIONS ARE DEVELOPED.

NOTE: PACKING FACTOR AND PACKING FRACTION ARE USED INTERCHANABLY BY THE PHOTOVOLTAIC INDUSTRY.

THICK FILMS AS OPTICAL CONCENTRATORS

THE ABILITY OF THICK FILMS TO PROPAGATE OPTICAL RADIATION IN A TRANSVERSE DIRECTION RAISES THE POSSIBILITY THAT OPTICAL CONCENTRATION (CALLED GAIN) CAN BE ACHIEVED. SUCH SYSTEMS WOULD HAVE THE FOLLOWING PROPERTIES:

- MAXIMUM THEORETICAL GAIN FOR ANY RECEIVING ELEMENT WOULD BE LIMITED TO THE SQUARE OF THE RATIO OF INDICIES, $(\eta_{HIGH}/\eta_{LOW})^2$
- MAXIMUM GAIN FOR AN ARRAY OF ELEMENTS THAT TRAP WOULD BE LIMITED TO THE RATIO OF THE TOTAL AREA TO AREA OF RECEIVER, A_{TOTAL}/A_{RCVR}
- THE GAIN WILL BE LIMITED ALSO BY THE ABSORPTION OF THE THICK FILM

TITLE: LIGHT TRAPPING CONCEPT

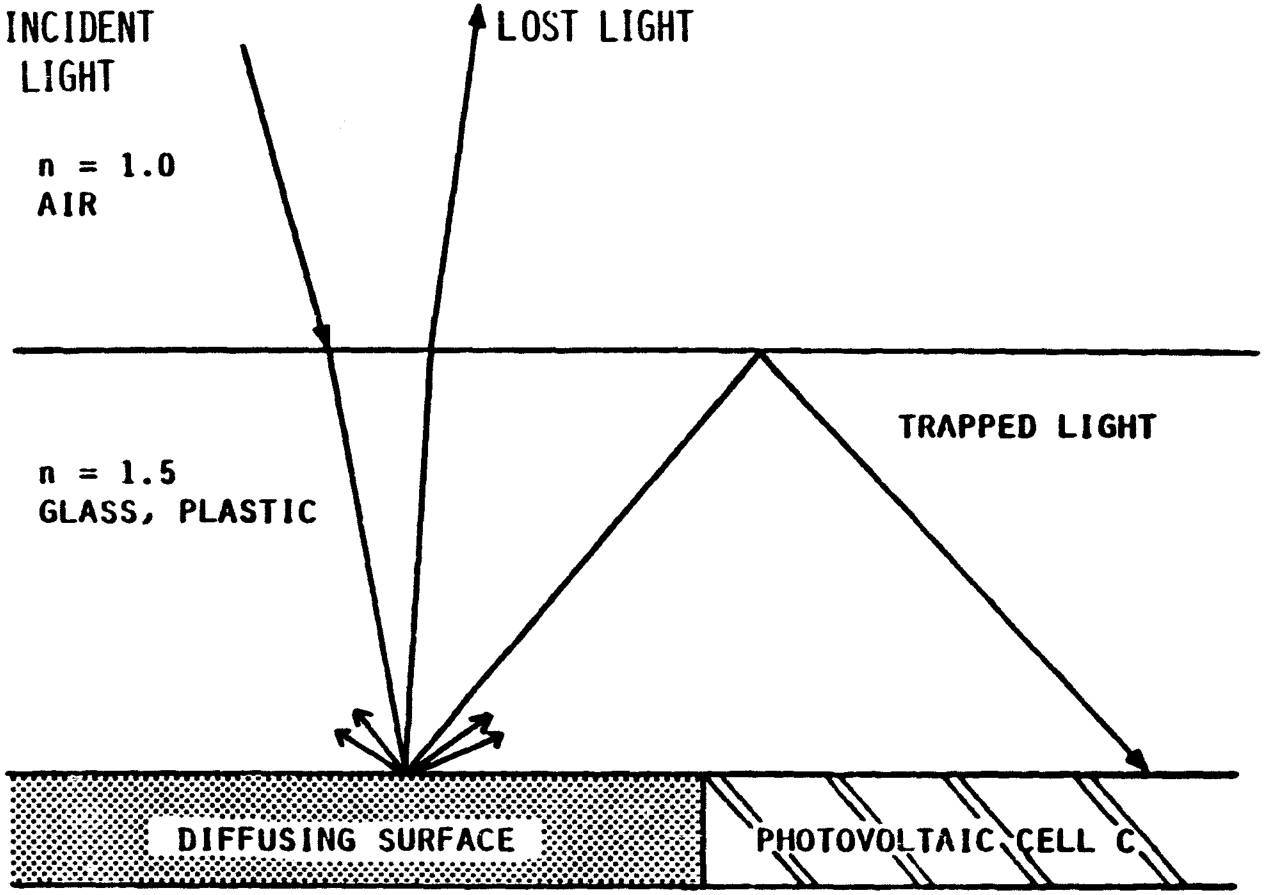
PURPOSE: TO ILLUSTRATE THE BASIC PRINCIPLES OF LIGHT TRAPPING

DEFINITIONS: INTERCELL - THE AREAS OF THE PANEL BETWEEN THE SOLAR CELLS

DISCUSSION: LIGHT FROM THE SUN ENTERS FROM THE "TOP" OF THE PANEL. PART OF THE LIGHT HITS THE CELL DIRECTLY. LIGHT THAT ARRIVES AT POINTS BETWEEN THE CELL IS REFLECTED BY THE DIFFUSING SURFACE. LIGHT REFLECTED AT ANGLES LESS THAN THE CRITICAL ANGLE IS LOST; THE LIGHT REFLECTED AT ANGLES GREATER THAN THE CRITICAL ANGLE IS PROPAGATED, (EACH TIME LIGHT IS REFLECTED FROM A DIFFUSE SURFACE SOME OF IT IS LOST).

LIGHT TRAPPING CONCEPT

- USE OF HIGH INDEX OF REFRACTION MATERIALS
- DIFFUSELY REFLECTING INTERCELL AREA



TITLE: LIGHT TRAPPING BY DIFFUSE REFLECTION IN A THICK FILM

PURPOSE: TO SHOW THE TRAPPING CONCEPT IN A THREE DIMENSIONAL SKETCH

DEFINITIONS:

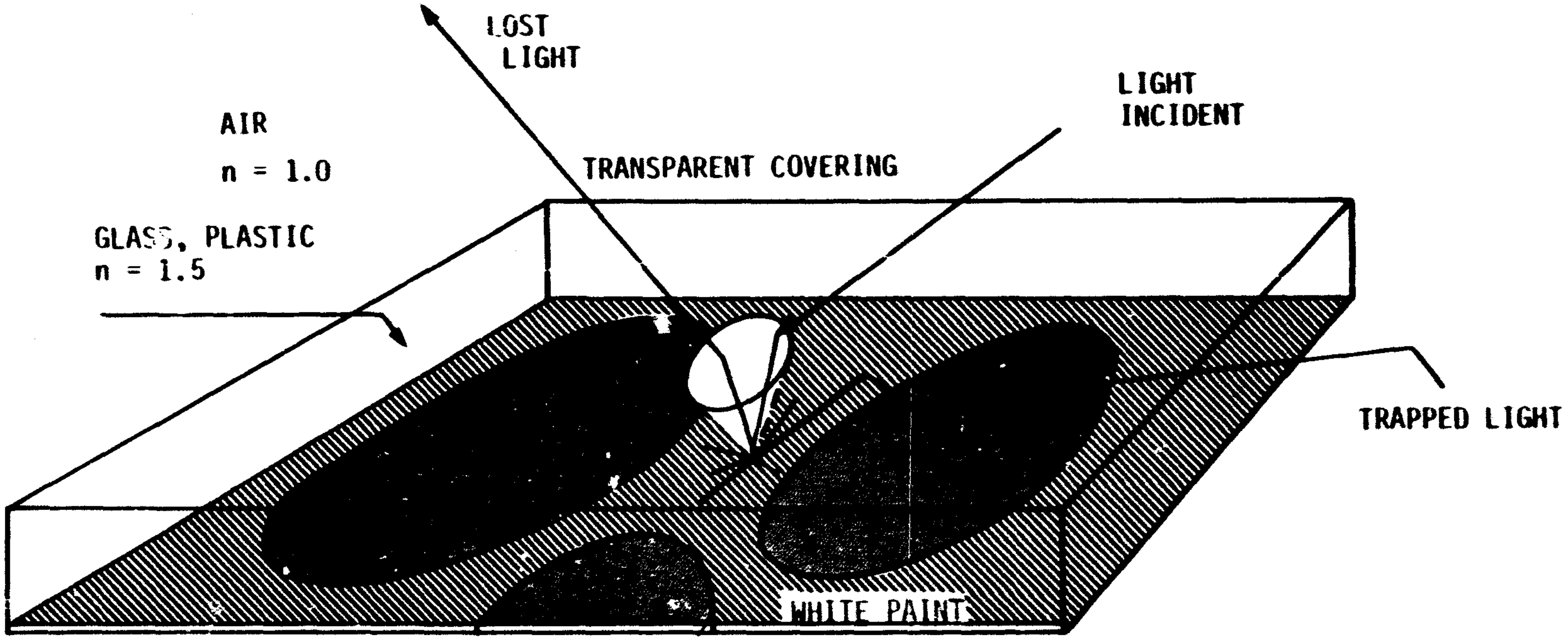
DISCUSSION: LIGHT REFLECTED FROM ANY POINT ON THE DIFFUSLY REFLECTING SURFACE WITHIN A CONE OF THE SIZE INDICATED WILL EXIT THE PANEL. THIS CONE IS DEFINED BY THE CRITICAL ANGLE. FOR EXAMPLE, THE CRITICAL ANGLE (θ_c) IN THIS CASE IS A FUNCTION OF THE INDICE OF REFRACTION OF AIR (1.0) AND THE SUPERSTRATE (GLASS, PLASTIC = 1.5).

$$\theta_c = \text{ARCSIN } (1.0/1.5) = 41.8^{\circ}$$

LIGHT TRAPPING BY DIFFUSE REFLECTION IN THICK FILM

DIFFUSE LIGHT TRAPPING IS ACCOMPLISHED WHEN AN INCIDENT RAY ENTERS A HIGHER INDEX TRANSPARENT LAYER AND IS SCATTERED.

AN EXAMPLE RELATED TO PHOTOVOLTAIC MODULES IS SHOWN BELOW:



TITLE: CLOSED FORM APPROXIMATE SOLUTION

PURPOSE: TO DEFINE GAIN AS A FUNCTION OF PACKING FRACTION AND INDEX OF REFRACTION

DEFINITIONS:

n_1 = INDEX OF REFRACTION OF AIR ($n_1 = 1$)

n_2 = INDEX OF REFRACTION OF TOP (FIRST) LAYER

N = $^{n_2}/_{n_1} = n_2$

C = FRACTION OF MODULE AREA COVERED BY CELLS

L = FRACTION OF ENERGY LOST INSIDE CRITICAL ANGLE

Θ_c = CRITICAL ANGLE

DISCUSSION:

CLOSED FORM APPROXIMATE SOLUTION

- ASSUMPTIONS:
  - SINGLE TRAPPING LAYER, INDEX η_2; PLACED IN AIR, INDEX η_1
  - NO ABSORPTION IN LAYER
  - NO FRESNEL REFLECTIONS
  - HOMOGENEOUS MIXTURE OF DIFFUSING LAYER AND CELLS
  - PERFECT DIFFUSE (LAMBERTIAN) REFLECTION BETWEEN CELLS

- METHOD—SERIES SOLUTION TO RAY PROPAGATION

$$G_0\ (N) = 1/(C+L - LC)$$

$N = \eta_2/\eta_1$

C = CELL PACKING FACTOR

L = FRACTION OF ENERGY LOST DUE TO RAYS EXITING AT LESS THAN CRITICAL ANGLE

$$\mathrm{SIN}\,\theta_c = \frac{\eta_1}{\eta_2} = \frac{1}{N}$$

$$L = \mathrm{SIN}^2\theta_c = \left(\frac{\eta_1}{\eta_2}\right)^2 = \left(\frac{1}{N}\right)^2$$

TITLE: CLOSED FORM APPROXIMATE SOLUTION (Continued)

PURPOSE: TO EXPRESS GAIN AS A FUNCTION OF INDEX OF REFRACTION AND PACKING FRACTION, AND SHOW THE EFFECTS OF CHANGING PACKING FRACTION

DEFINITIONS:

DISCUSSION:

CLOSED FORM APPROXIMATE SOLUTION (CONT'T)

- FOR THE CASE WHERE THE PACKING FRACTION IS SMALL THE EXPRESSION REACHES THE OPTICAL LIMIT FOR GAIN

$$\lim_{C\to 0} G_0\,(N) = \lim_{C\to 0} \frac{1}{C+L-LC} = \frac{1}{L} = \left(\frac{\eta_2}{\eta_1}\right)^2 (N)^2$$

- THIS EQUATION CAN BE REDEFINED IN TERMS OF E, THE FRACTION OF MODULE AREA WHICH IS INTERCELL DIFFUSING MATERIAL

$$E = 1-C \qquad\qquad C = 1-E$$

$$G(N) = 1/\left|1-E+L-L(1-E)\right| = 1/\left|1-E(1-L)\right| \approx 1+E(1-L)$$

- IF THERE IS NO INTERCELL DIFFUSING AREA, THE GAIN APPROACHES 1

- AS THE INTERCELL AREA INCREASES, THE GAIN INCREASES

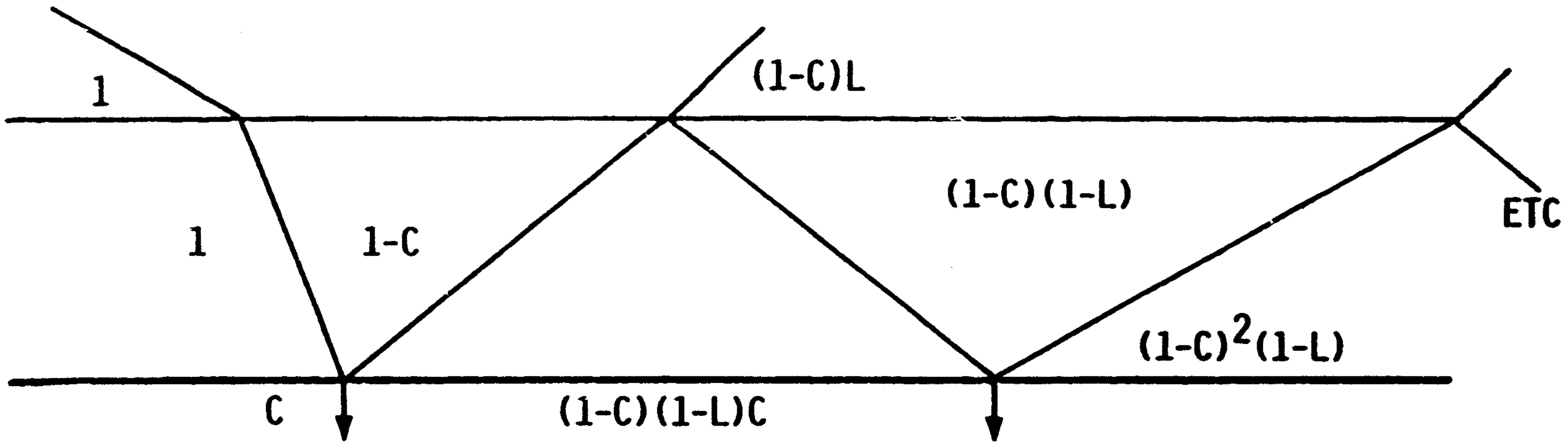
TITLE: DERIVATION OF CLOSED FORM SOLUTION

PURPOSE: TO SHOW RADIATION TRANSPORT AND LOSSES AT ENCAPSULANT SURFACES.

DEFINITIONS:

DISCUSSION:

DERIVATION OF CLOSED FORM SOLUTION



$$G = \left[1 + \underbrace{(1-C)(1-L)}_{1-C-L+LC} + (1-C)^2(1-L)^2 \cdot \cdot \cdot\right]$$

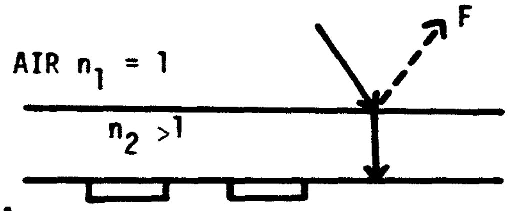
$$G = \sum_{n=0}^{\infty} (1-C-L+LC)^n = \sum_{n=0}^{\infty} X^n = \frac{1}{1-X} = \frac{1}{C+L-LC}$$

TITLE: SIMPLIFIED DESIGN EQUATIONS

PURPOSE: TO SHOW HOW THE SIMPLIFIED DESIGN EQUATIONS ARE DEVELOPED TO INCORPORATE OTHER PROPERTIES SUCH AS LAYER THICKNESS AND DIFFUSE REFLECTIVITY OF INTERCELL AREA

DEFINITIONS: F = FRESNEL LOSS. THIS IS THE REFLECTIVE LOSS AT AN INTERFACE BETWEEN TWO MATERIALS HAVING DIFFERENT INDICES OF REFRACTION

$$F = \left(\frac{n_1 - n_2}{n_2 + n_1}\right)^2 = \left(\frac{n_2 - 1}{n_2 + 1}\right)^2$$



R = DIFFUSE REFLECTIVITY OF INTERCELL AREA

T = TOTAL LAYER THICKNESS

ℓ = LENGTH OF CELL OR DIAMETER

DISCUSSION:

SIMPLIFIED DESIGN EQUATIONS

1) GAIN WITH NO FRESNEL REFLECTIONS

$$G_U = 1/(C+L-LC)$$

2) GAIN WITH FRESNEL REFLECTION AT TOP LAYER

$$G_0 = 1/(C+L-LC-LF+LCF)$$

3) GAIN WITH FINITE REFLECTIVITY $R \leq 1.0$

$$G(R) = 1/\left[1-R(1-C-L+LC+LF-LCF)\right]$$

4) GAIN FOR LESS THAN OPTIMUM THICKNESS $T/\ell < 0.3$

$$G(T) = 1 + \left[G_0 - 1\right]\left(1-(1-3.33T/\ell)^3\right)$$

TITLE: SIMPLIFIED DESIGN EQUATIONS (CONTINUED)

PURPOSE: TO SHOW THAT THE GAIN IS MORE ACCURATELY EXPRESSED AS A FUNCTION OF ℓ, R, N, T AND C AND CAN BE USED TO CALCULATE THE GAIN FOR MULTIPLE LAYERS.

DEFINITIONS:

DISCUSSION:

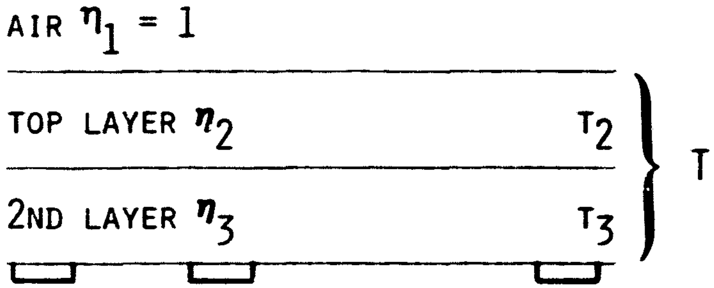
SIMPLIFIED DESIGN EQUATIONS (CONT'D)

5) GAIN CAN BE EXPRESSED AS A FUNCTION OF ℓ, R, N, T, AND C FOR A SINGLE LAYER

$$G = f(\ell, R, N, T, C)$$

6) THE GAIN FOR MULTIPLE LAYER MODULES CAN BE CALCULATED USING THE SINGLE LAYER EQUATION AND NEW VALUES FOR N AND T

$$G = f(\ell, R, f_\eta(\eta_1, \eta_2, \ldots), f_T(\tau_2, \tau_3, \ldots), C)$$



AIR $\eta_1 = 1$

TOP LAYER η_2 τ_2

2ND LAYER η_3 τ_3

$\left.\right\}$ T

FOR EXAMPLE: T = THE SUM OF τ_2 AND τ_3

I.E., $T = \tau_2 + \tau_3$

N = THE THICKNESS-WEIGHTED N FOR EACH OF THE LAYERS

I.E., $N = \eta_2 + \tau_3(\eta_3 - \eta_2)/T$

TITLE: MONTE-CARLO COMPUTER MODEL

PURPOSE: TO EXPLAIN THE DETAILED CALCULATIONAL TECHNIQUES USED.

DEFINITIONS:

DISCUSSION: A DETAILED MODEL USING MANY RANDOM RAYS PROPAGATING IN THE THREE DIMENTIONAL MATRIX WAS CONSTRUCTED AND UTILIZED. THE FEATURES OF THE MODEL ARE ILLUSTRATED. THE PURPOSE OF THE MODEL WAS TO INVESTIGATE THE BEHAVIOR TO THE LIGHT TRAPPING IN COMPLEX SITUATIONS BEYOND THE CAPABILITY OF THE SIMPLIFIED SOLUTIONS. ALSO IN REGIONS OF JOINT APPLICABILITY THE TWO TECHNIQUES WERE COMPARED.

COMPUTER MODEL FOR SIMULATION OF LIGHT PROPAGATION AND DIFFUSION BY MONTE CARLO METHODS

IN ORDER TO CHECK THE CLOSED FORM SOLUTION AND TO PROVIDE MORE DESIGN DETAIL A COMPUTER CODE WAS WRITTEN WITH THESE FEATURES:

- PROPAGATION OF LIGHT IN THREE DIMENSIONS INCLUDES FRESNEL LOSSES, ABSORPTION LOSSES, AND DIFFUSION LOSSES
- DIFFUSED RAYS GIVEN ANGLES WHICH EFFECTIVELY SAMPLE THE REAL DISTRIBUTION OF DIFFUSED LIGHT - A MONTE CARLO TECHNIQUE IS USED
- VARIOUS DIFFUSION PATTERNS INCLUDING LAMBERTIAN DISTRIBUTION ARE AVAILABLE AS INPUT
- A TWENTY BY TWENTY BOX MATRIX IS USED TO DEFINE CELL AND DIFFUSING AREAS

THE ACCURATE COMPUTER PREDICTIONS WERE THEN COMPARED TO THE CLOSED FORM SOLUTIONS.

TITLE: CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION

PURPOSE: TO ILLUSTRATE THE COMPARISON OF THE MONTE-CARLO AND CLOSED FORM SOLUTIONS

DEFINITIONS: LABELS ON GRAPHS

- CELL DIAMETER (INCHES) OR SIDE IF SQUARE
- REFLECTIVITY OF WHITE DIFFUSING LAYER, R
- TOTAL THICKNESS ABOVE CELL, T INCHES
- INDEX OF REFRACTION ABOVE CELL, N

AXES

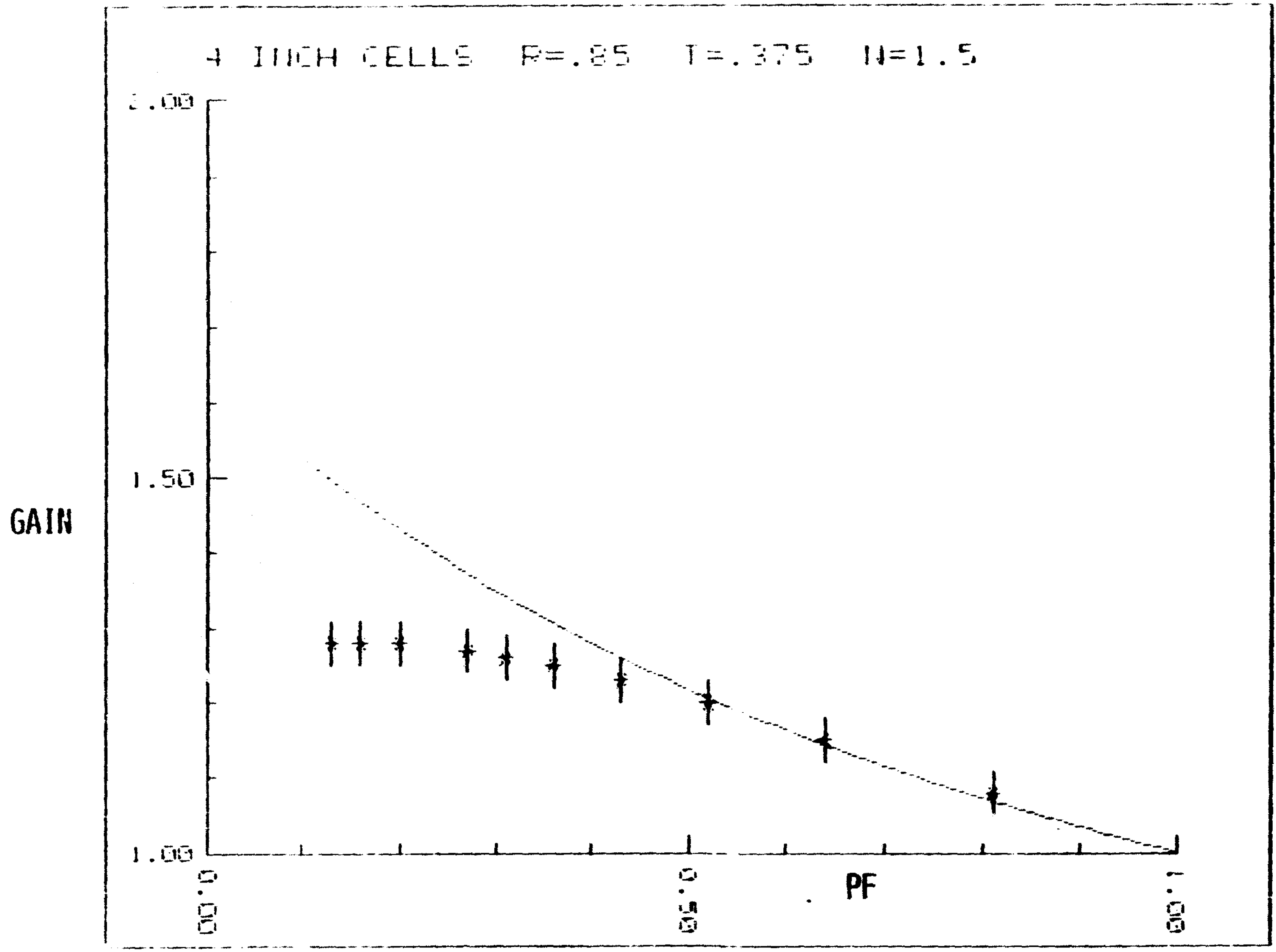
- Y AXIS, GAIN ON CELL, G
- X AXIS, PACKING FACTOR, PF

LINE

- CLOSED FORM EQUATION
- POINTS, MONTE-CARLO MEAN (X) AND ERROR (BAR)

DISCUSSION: THE GRAPHS SHOW THE GAIN THAT CAN BE EXPECTED FOR GIVEN MODULE PHYSICAL AND OPTICAL CONFIGURATION. THE GRAPHS CONTINUE ON NEXT FIVE PAGES.

CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION



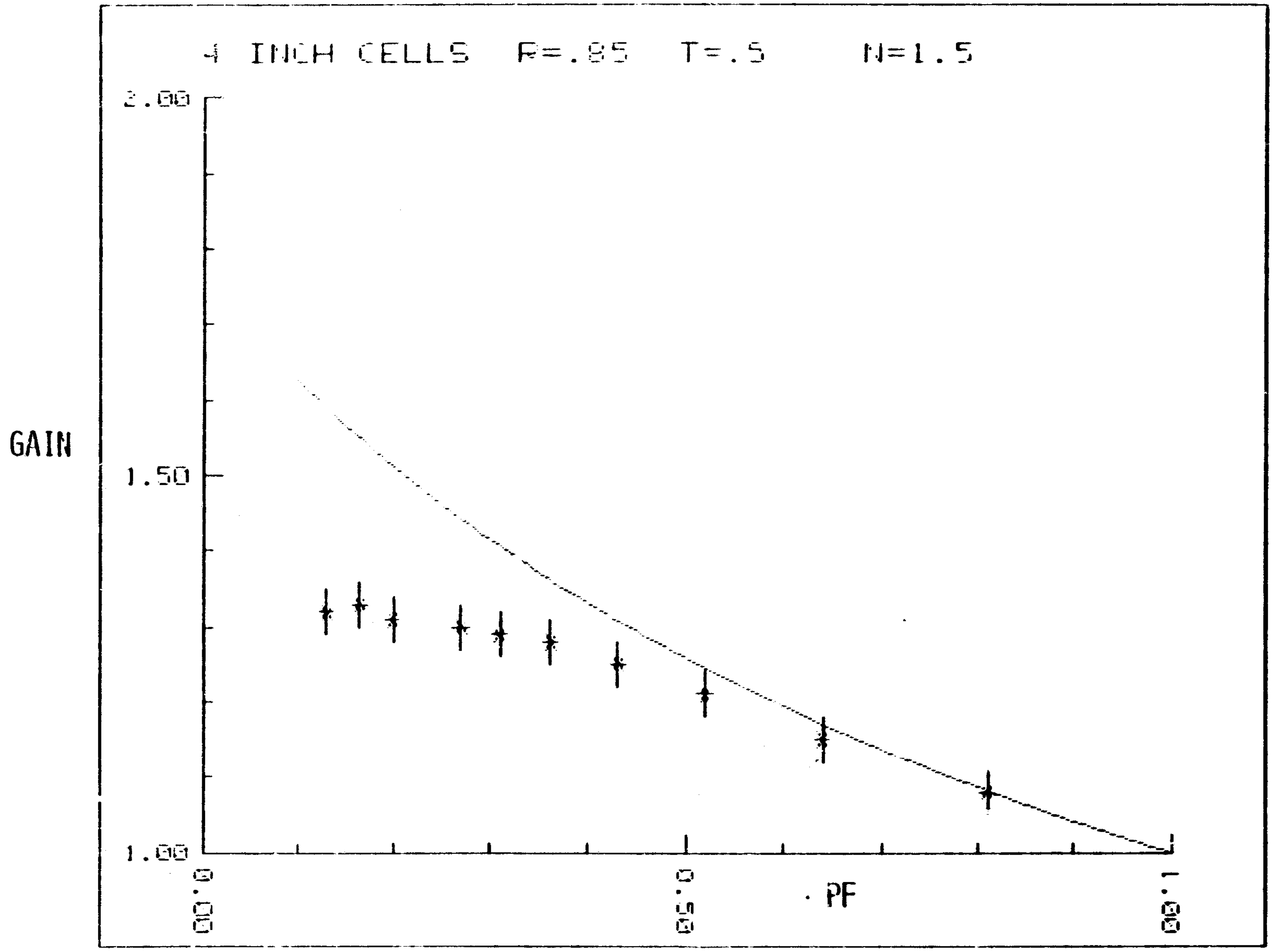
TITLE: CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION (Continued)

PURPOSE: COMPARES MONTE-CARLO AND CLOSED FORM SOLUTION

DEFINITIONS:

DISCUSSION:

CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION



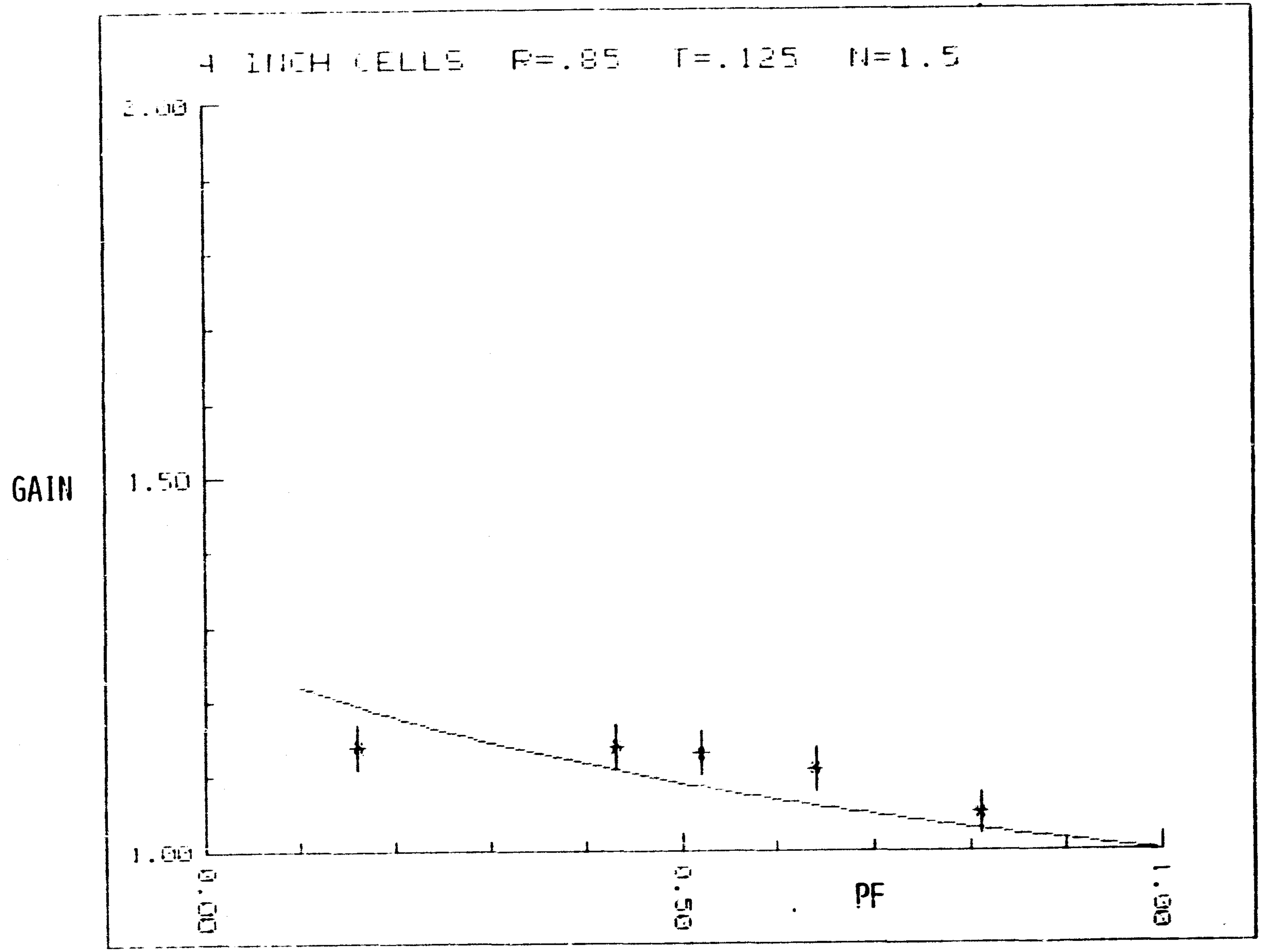
TITLE: CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION (Continued)

PURPOSE: COMPARES MONTE-CARLO AND CLOSED FORM SOLUTION

DEFINITIONS:

DISCUSSION:

CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION



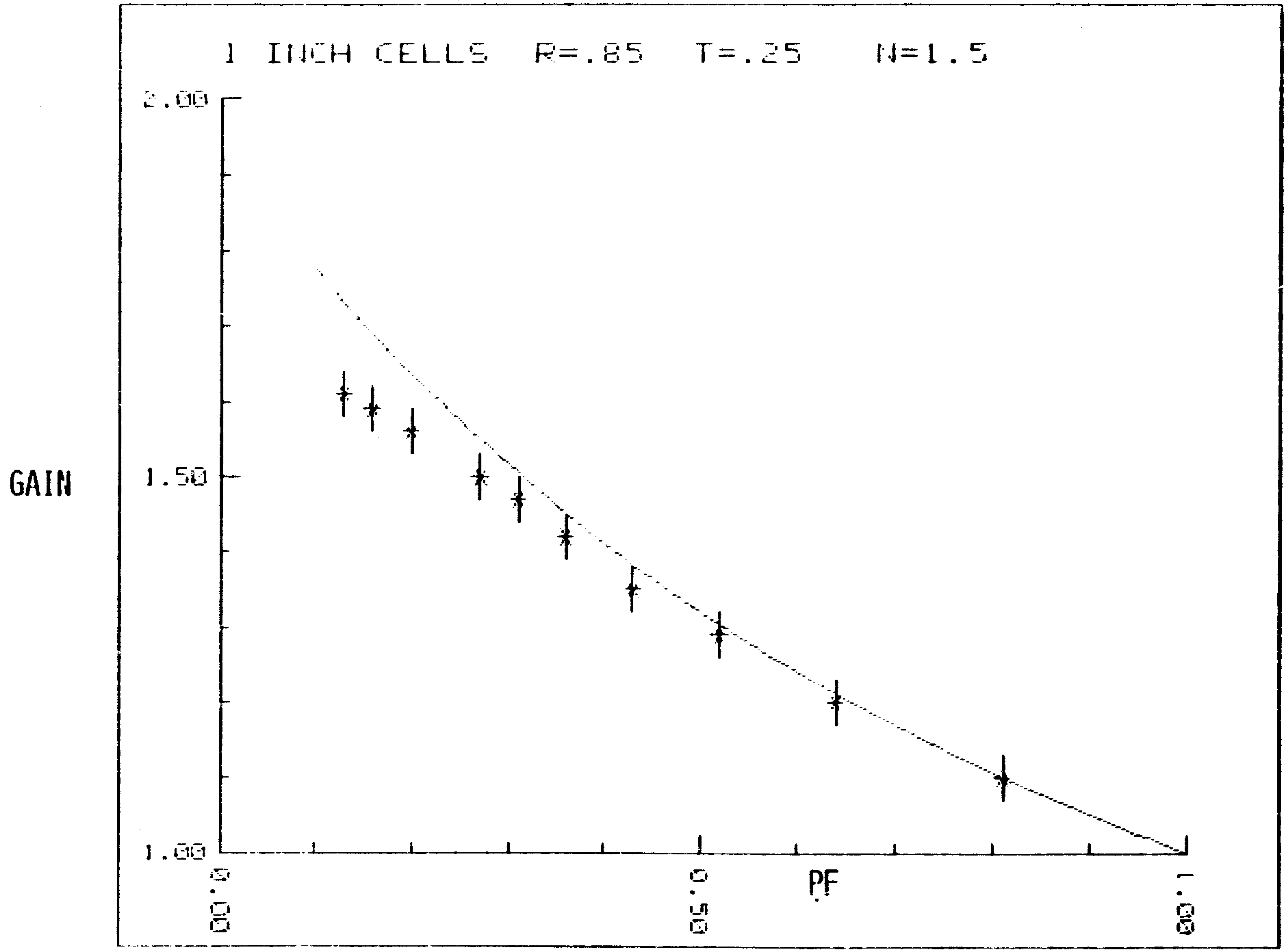
TITLE: CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION (Continued)

PURPOSE: COMPARES MONTE-CARLO AND CLOSED FORM SOLUTION

DEFINITIONS:

DISCUSSION:

CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION



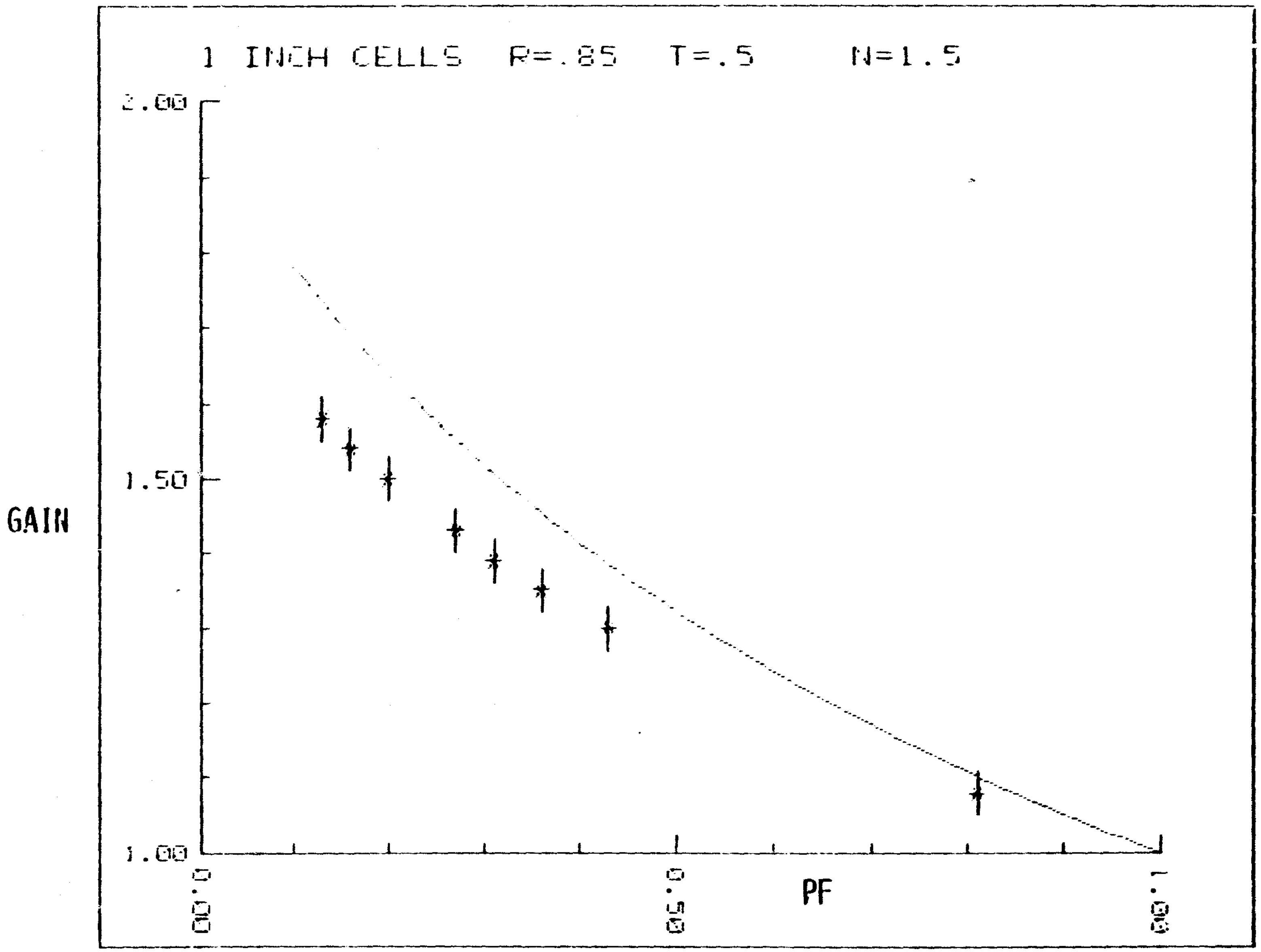
TITLE: CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION (Continued)

PURPOSE: COMPARES MONTE-CARLO AND CLOSED FORM SOLUTION

DEFINITIONS:

DISCUSSION:

CLOSED FORM EQUATION VERSUS COMPUTER CALCULATION



TITLE: BASELINE MODULE DESIGN

PURPOSE: OUTLINES FOLLOWING SECTION

DEFINITIONS:

DISCUSSION:

A.3: BASELINE MODULE DESIGN

- MODULE LAYOUT, CELL SPACING GEOMETRY
- BASELINE PERFORMANCE ESTIMATES
- EXPERIMENTAL CONFIRMATION

TITLE: LIGHT TRAPPING CONCENTRATION FOR PV CONCEPT DESCRIPTION

PURPOSE: TO LIST SELECTED TRADE-OFF PARAMETERS

DEFINITIONS:

DISCUSSION: THE EFFECTIVENESS OF TRAPPING IS CONTROLLED BY THE MATERIALS SELECTED AND THE GEOMETRY OF THE PANEL. TRAPPING WORKS FOR RAYS COMING FROM ALL DIRECTIONS OF THE FORWARD HEMISPHERE. THEREFORE, BOTH DIRECT SUNLIGHT AND DIFFUSELY REFLECTED SUNLIGHT (SKY RADIATION) IS CONCENTRATED.

LIGHT TRAPPING CONCENTRATION FOR PV
CONCEPT DESCRIPTION

- LIGHT TRAPPED BY DIFFUSE BACK REFLECTION FROM THE REGION BETWEEN CELLS CAN CONTRIBUTE TO SYSTEM PERFORMANCE
- SYSTEM TRADE-OFF IS BETWEEN CELL SPACING, COVER THICKNESS AND INDEX OF REFRACTION
- LIGHT TRAPPING WORKS OVER THE ENTIRE HEMISPHERE THUS, PROVIDING CONCENTRATION OF SOLAR DIFFUSE RADIATION AS WELL AS DIRECT

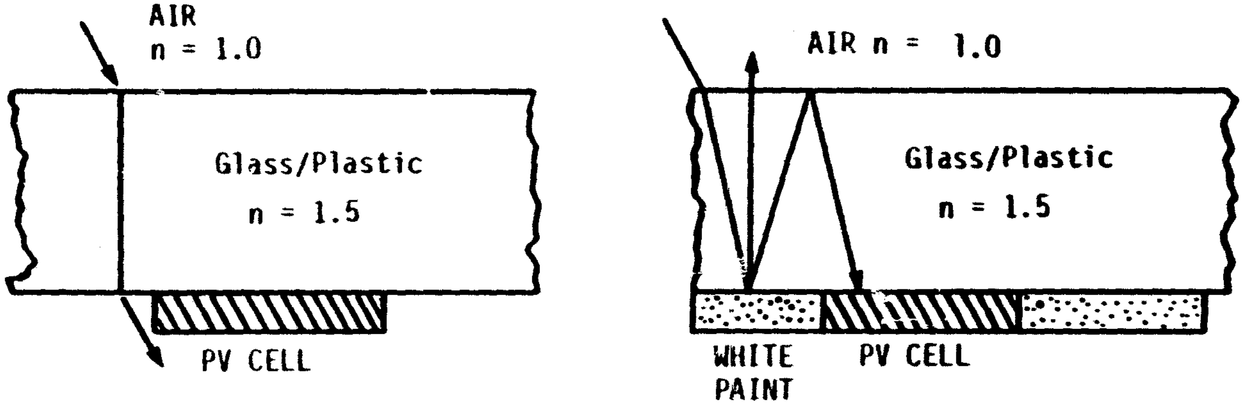
TITLE: MODULE LAYOUT, CELL SPACING GEOMETRY

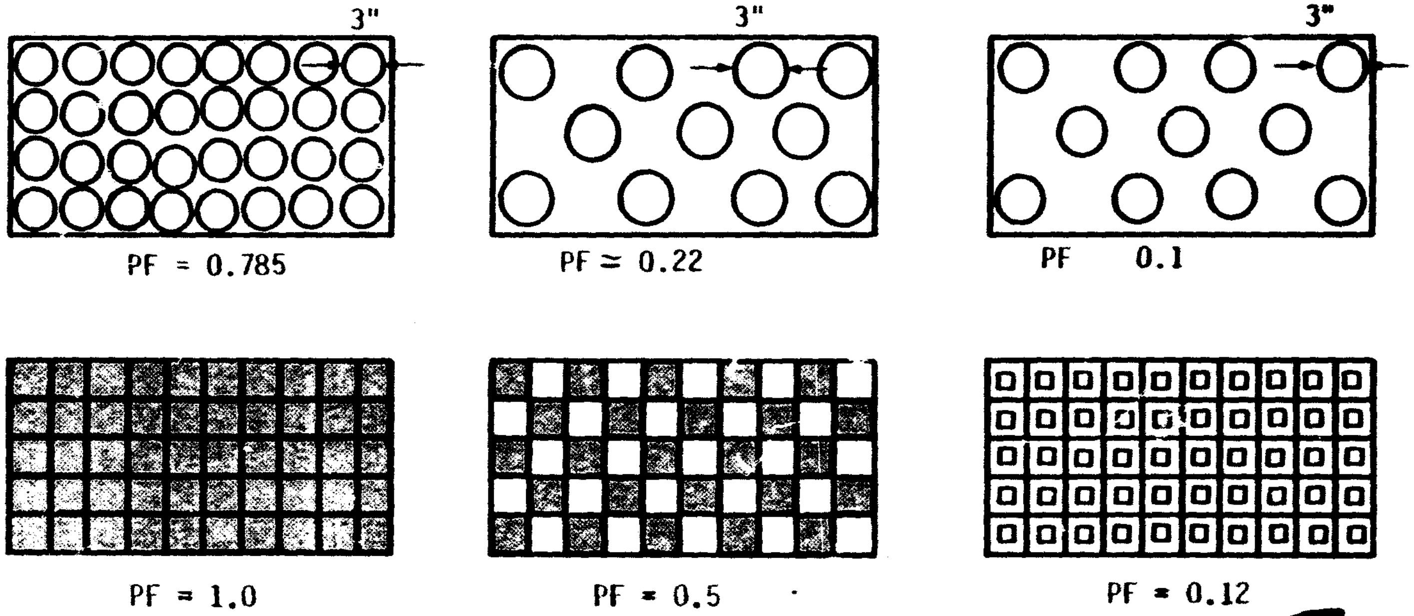
PURPOSE: SHOWS POTENTIAL VARIATION IN CELL SHAPES AND SPACING GEOMETRY IN PRACTICAL PHOTOVOLTAIC MODULES

DEFINITIONS: P.F. = PACKING FACTOR - THE RATIO OF CELL AREA TO ARRAY AREA

DISCUSSION: THE PACKING FACTORS OF PRACTICAL PHOTOVOLTAIC MODULES CAN VARY AS SHOWN FROM (NEAR) 1.0 TO 0.1, WHEN LIGHT TRAPPING IS USED. THE OPTIMUM PACKING FRACTION WILL DEPEND ON A NUMBER OF VARIABLES INCLUDING THE COSTS OF CELLS, ENCAPSULATING MATERIALS, MOUNTS AND REAL ESTATE. THIS IS TREATED IN MORE DETAIL LATER IN SECTION A.6.

MODULE LAYOUT, CELL SPACING GEOMETRY





TITLE: DEFINITION OF LAYERS IN BASELINE MODULE CROSS SECTION

PURPOSE: TO PRESENT THE STRUCTURE OF A TYPICAL MODULE

DEFINITIONS:

DISCUSSION: STARTING AT THE FRONT SURFACE OF THE MODULE THIS CHART INDICATES THE LAYERS, PERFERRED MATERIALS AND THE THICKNESS OF THESE MATERIALS. BOTH THE SUPERSTRATE AND SUBSTRATE ARE CONSIDERED.

DEFINITION OF LAYERS IN BASELINE MODULE CROSS SECTION*

OPTICALLY IMPORTANT MODULE LAYERS FROM SUN SIDE DOWN	PREFERRED MATERIAL CHOICES AND NOMINAL THICKNESS	
	LAMINATION	CASTING
SUPERSTRATE DESIGN:		
TOP COVER	LOW IRON, TEMPERED SODA-LIME GLASS, 125 MIL MINIMUM	SAME
POTTANT	ETHYLENE VINYL ACETATE (EVA) OR ETHYLENE METHLYACRYLATE (EMA), 5 MIL MINIMUM	POLY-N-BUTYL ACRYLATE, OR ALIPHATIC POLYETHER URETHANE, OR GE SILICONE 534-044, 5 MIL MINIMUM
SPACER	NON-WOVEN GLASS MAT TO ACHIEVE MINIMUM POTTANT THICKNESS - CRANEGLAS	MAY NOT BE REQUIRED
SUBSTRATE DESIGN:		
TOP COVER	BIAXIALLY ORIENTED POLYMETHYLMETH - ACRYLATE (PMMA) OR TEDLAR, 3 MIL	SAME
POTTANT	NONE REQUIRED ON SUN SIDE	SAME
FOR EITHER MODULE:		
CELLS	FOUR INCH ROUND OR FOUR BY ONE INCH RECTANGULAR, PACKING FACTOR 0.6 TO 0.85	SAME

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*SOURCE: JPL LETTER TO SAI OCTOBER 1, 1980.

TITLE: VARIATION IN MODULE THICKNESS

PURPOSE: TO PRESENT SOME OF THE PARAMETERS THAT ARE USED TO DETERMINED THE THICKNESS OF A MODULE

DEFINITIONS:

DISCUSSION: THE THICKNESS OF A STANDARD PV MODULE IS USUALLY A FUNCTION OF MODULE SIZE, MATERIALS USED, ENVIRONMENTAL LOADS AND THE DESIGN OF THE STRUCTURE FOR MODULE SUPPORT. LIGHT TRAPPING MODIFICATIONS CAN BE APPLIED TO MOST OF THESE MODULES WITHOUT MATERIALLY ALTERING THEIR THICKNESSES. HOWEVER, WHEN LIGHT TRAPPING IS DESIGNED INTO A MODULE FROM THE OUTSET THE THICKNESSES OF THE LAYERS THAT MAKE UP THE MODULE ARE PARAMETERS THAT CAN BE USED ALONG WITH OTHER PARAMETERS INCLUDING MATERIALS, LABOR AND REAL ESTATE COSTS TO OPTIMIZE COST/WATT-HOUR.

VARIATION IN MODULE THICKNESS

- THE THICKNESS OF A PHOTOVOLTAIC MODULE IS A FUNCTION OF MODULE SIZE, MATERIALS USED, WIND AND ENVIRONMENTAL LOADS ON THE MODULE AND THE ARRAY STRUCTURE.

- IN MODULES WHERE THE ENCAPSULATING MATERIALS PROVIDE MOST OF THE MODULE STRENGTH, SUPERSTRATE LAYER THICKNESSES MAY INCREASE OPTICAL PERFORMANCE AND STRENGTH.

- IN LIGHT TRAPPING PV MODULES, THE IMPORTANT DESIGN PARAMETERS ARE:
    - MATERIAL INDEX AND TRANSMISSION
    - LENGTH OF TRANSMISSION PATHS
    - NUMBER OF REFLECTIONS, ENERGY ABSORBED
    - TRAPPING LAYER MATERIAL HEAT CAPACITANCE

- MATERIAL(S), THICKNESS OF TRAPPING LAYER(S), CELL SIZE AND PF CAN BE CONTROLLED TO MAXIMIZE GAIN, OR TO MINIMIZE MODULE COST PER WATT.

- THESE PARAMETERS AND COSTS CAN BE TRADED OFF AGAINST LAND, STRUCTURE, AND OPERATION AND MAINTENANCE COSTS TO MINIMIZE SYSTEM COST PER WATT.

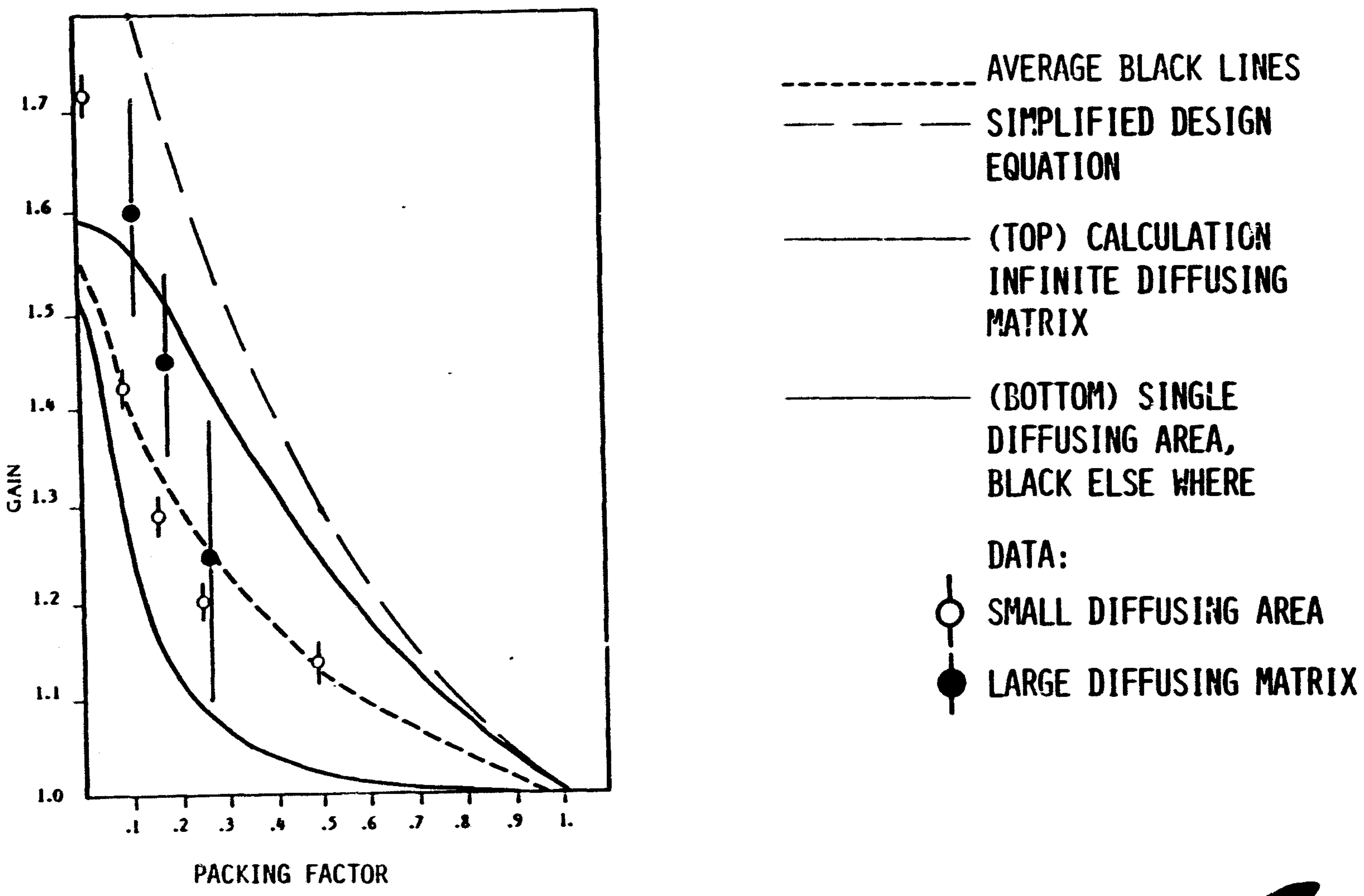
TITLE: EXPERIMENTAL CONFIRMATION

PURPOSE: TO SHOW THE COMPARISON OF CALCULATIONS WITH MEASURED DATA

DEFINITIONS:

DISCUSSION: A SMALL EXPERIMENT PHOTOVOLTAIC MODULE WAS CONSTRUCTED AND TESTED. FIRST ALL MINI-CELLS WERE SET UP WITH A REFLECTING WALL AT THE LAYER EDGE TO SIMULATE AN INFINITE MATRIX (BLACK DOTS), THE MEASURED GAINS AGREED SATISFACTORIALLY WITH THE CALCULATED GAINS. SECONDLY ALL BUT ONE CELL WAS COVERED BY A MASK CUT TO THE EXACT SIZE OF THE CELL - THEN A SERIES OF MASKS EACH SLIGHTLY LARGER THAN THE ONE BEFORE WERE USED. THIS CORRESPONDED TO A MIXTURE OF THE INFINITE CASE, AND THE SINGLE DIFFUSING AREA WITH BLACK SURFACE ELSEWHERE (BOTTOM LINE). THE DATA (OPEN CURVES) AGAIN AGREED FAIRLY WELL WITH THIS MEAN. THE SIMPLIFIED DESIGN EQUATIONS DO NOT AGREE PARTICULARLY WELL WITH THIS CASE.

EXPERIMENTAL CONFIRMATION



TITLE: DESIGN RULES

PURPOSE: OUTLINES MATERIAL IN SECTION 4.A

DEFINITIONS:

DISCUSSION:

A.4: DESIGN RULES

- VARIATION IN MODULE THICKNESS/MATERIAL INDEX OF REFRACTION
- TRAPPING GAIN AS A FUNCTION OF PACKING FACTOR AND LAYER THICKNESS

TITLE: GRAPHS OF DESIGN EQUATIONS FOR VARIOUS MODULE PARAMETERS

PURPOSE: TO ALLOW THE DESIGN ENGINEER TO ESTIMATE LIGHT TRAPPING GAINS SIMPLY FROM GRAPHS.

DEFINITIONS: GRAPH TITLE - 4 INCH DIAMETER CELLS, WITH R = 0.85 DIFFUSING LAYERS, SHOWN FOR VARIOUS INDICES N = 1.5 TO 2.8

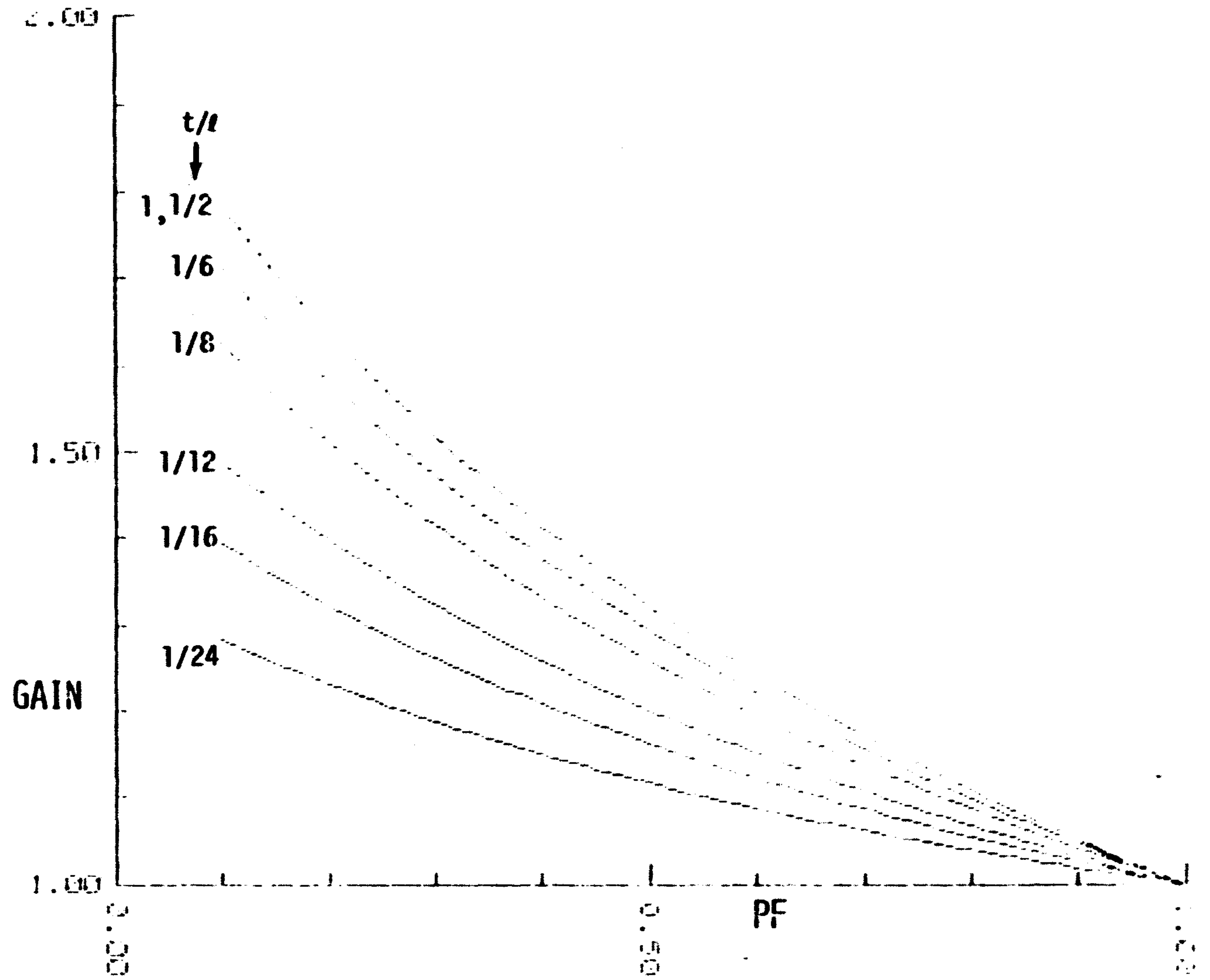
AXES Y - GAIN
X - PACKING FACTOR

CURVES GAINS FOR t/ℓ RATIOS INDICATED
t = LAYER THICKNESS
ℓ = CELL SIZE (DIAMETER)

DISCUSSION: ALTHOUGH THE CURVES ARE GENERALIZED FOR 4 INCH DIAMETER CELLS, THEY ARE VALID FOR ANY CELL SIZE FOR WHICH t/ℓ HAS BEEN ACCURATELY SPECIFIED.

GRAPHS OF DESIGN EQUATIONS FOR VARIOUS MODULE PARAMETERS (INDEX OF ENCAPSULANT, THICKNESS AND PACKING FACTOR)

4 INCH CELLS R=.85 N=1.5



TITLE: GRAPHS OF DESIGN EQUATIONS FOR VARIOUS MODULE PARAMETERS (Continued)

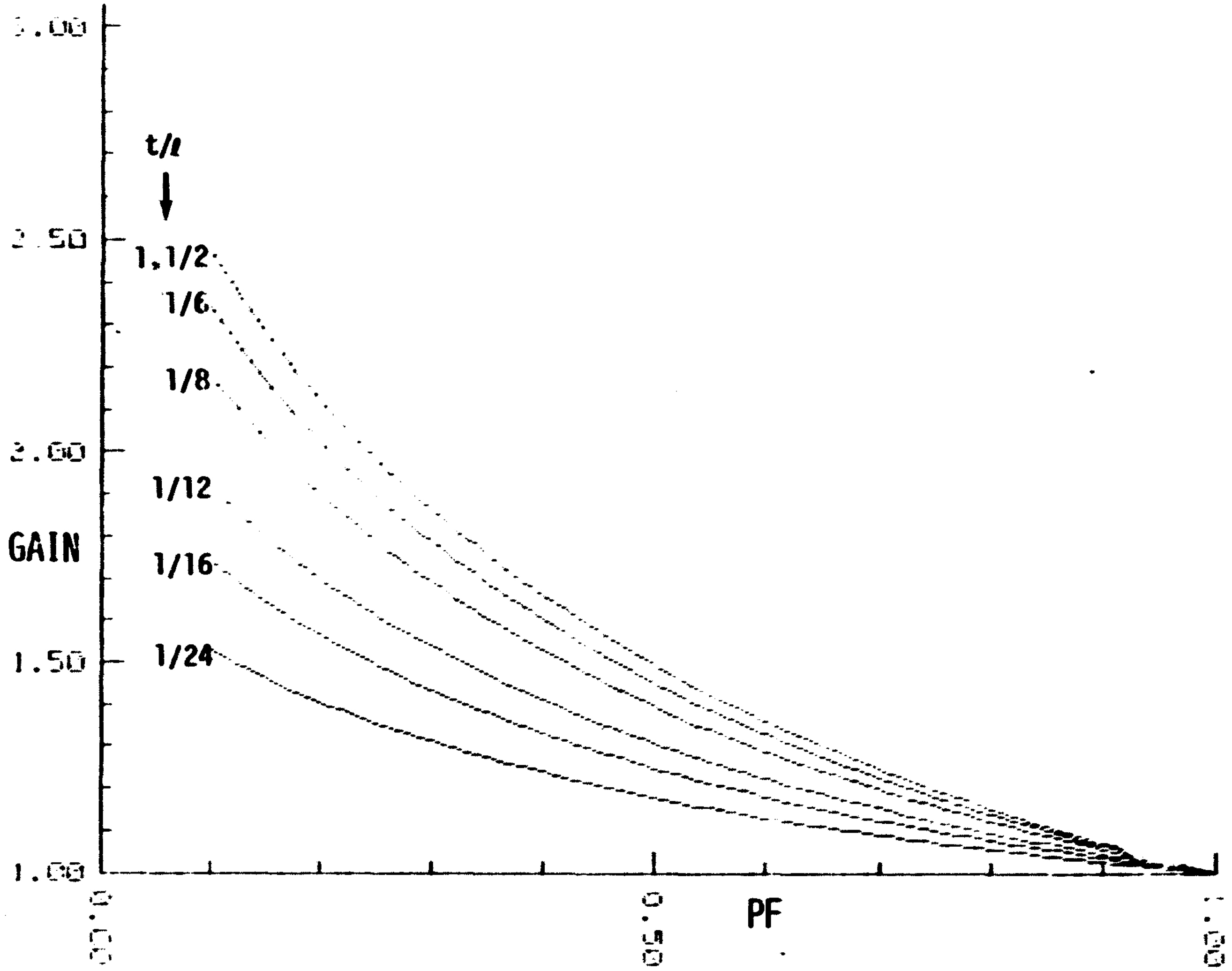
PURPOSE:

DEFINITIONS:

DISCUSSION:

GRAPHS OF DESIGN EQUATIONS FOR VARIOUS MODULE PARAMETERS (INDEX OF ENCAPSULANT, THICKNESS AND PACKING FACTOR)

4 INCH CELLS P=.85 N=2



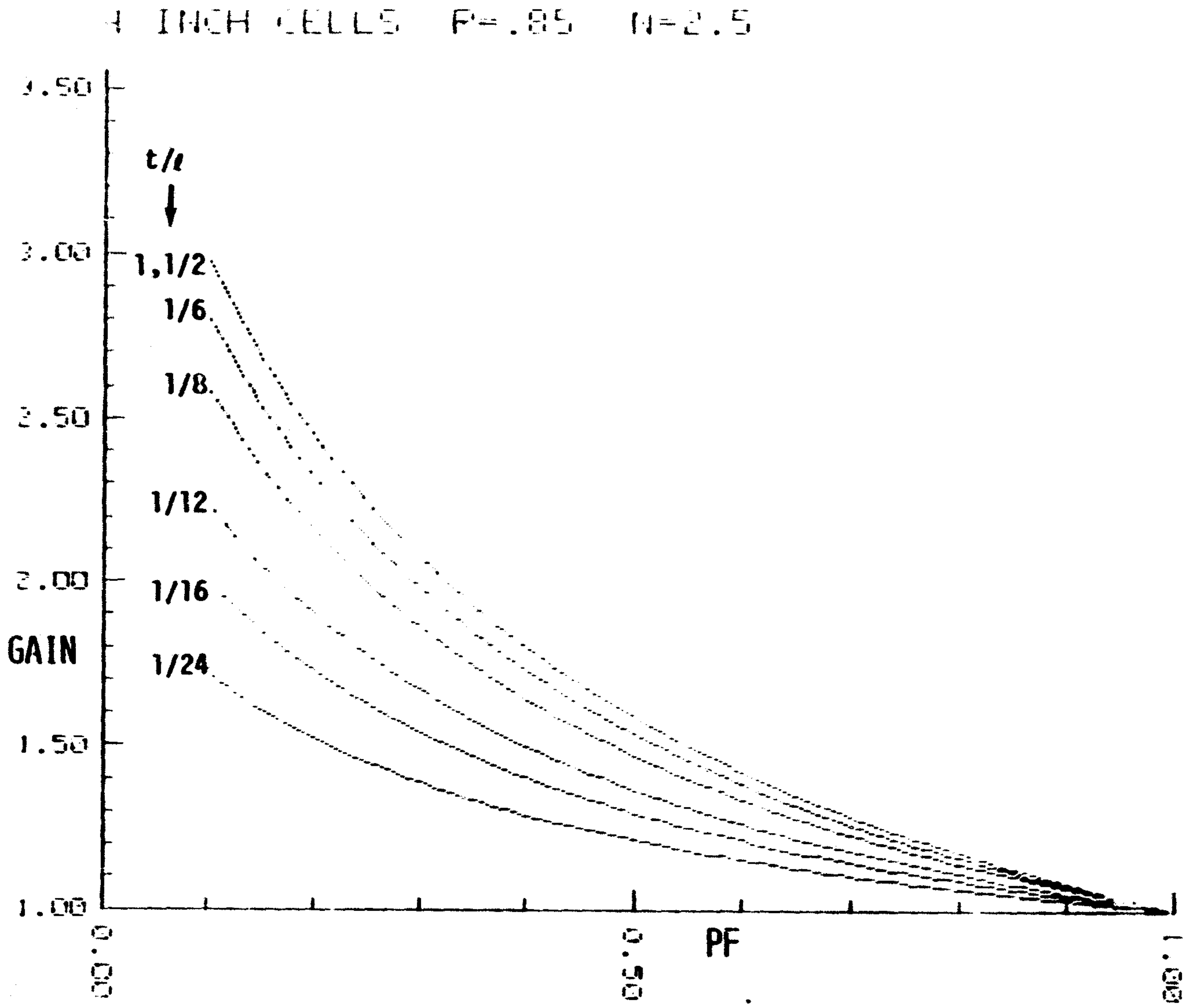
TITLE: GRAPHS OF DESIGN EQUATIONS FOR VARIOUS MODULE PARAMETERS (Continued)

PURPOSE:

DEFINITIONS:

DISCUSSION:

GRAPHS OF DESIGN EQUATIONS FOR VARIOUS MODULE PARAMETERS (INDEX OF ENCAPSULANT, THICKNESS AND PACKING FACTOR)



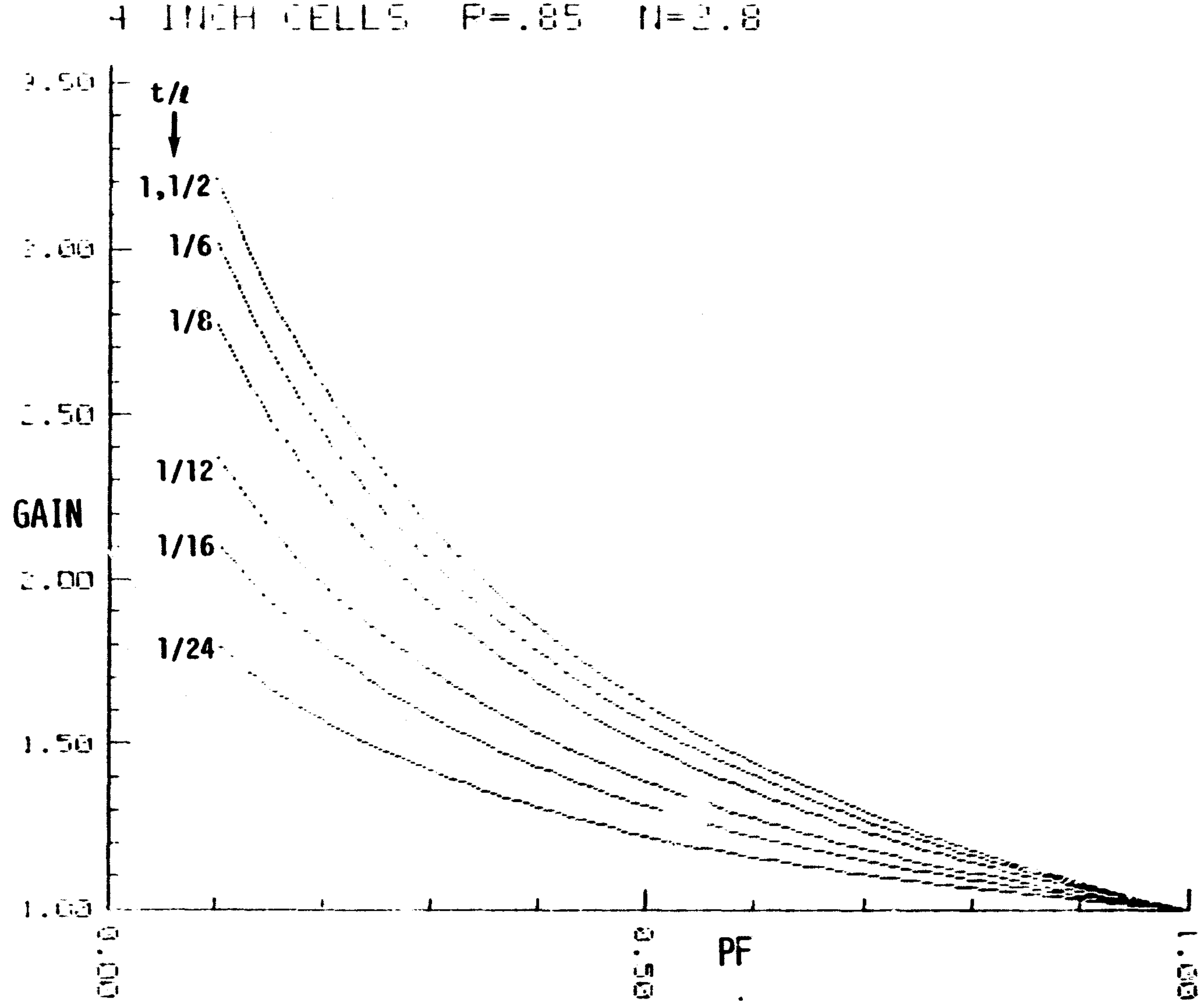
TITLE: GRAPHS OF DESIGN EQUATIONS FOR VARIOUS MODULE PARAMETERS (Continued)

PURPOSE:

DEFINITIONS:

DISCUSSION:

GRAPHS OF DESIGN EQUATIONS FOR VARIOUS MODULE PARAMETERS (INDEX OF ENCAPSULANT, THICKNESS AND PACKING FACTOR)



TITLE: TYPICAL GAINS FOR SOLAR MODULES USING SIMPLIFIED DESIGN EQUATIONS

PURPOSE: TO SHOW PRACTICAL EXAMPLES OF USE OF THE EQUATIONS

DEFINITIONS:

DISCUSSION: DATA IN THE PHYSICAL CONFIGURATION OF THE BLOCK III MODULES WERE OBTAINED FROM JPL, AND THE AS CONFIGURED GAINS CALCULATED FOR R = 0.85. SOME MODULES WILL ACTUALLY HAVE THESE GAINS IF A WHITE DIFFUSING LAYER IS USED, OTHERS WILL NOT ACHIEVE THE FULL AMOUNT IF THE REFLECTANCE (R) OF THE DIFFUSING SURFACE APPLIED IS LESS THAN THAT ASSUMED. ALSO SHOWN IS THE IMPROVED GAIN WITH A TOTAL OF 1/2 INCH THICKNESS UTILIZED. NO COMMERCIAL MODULES ARE MADE CURRENTLY WITH THIS COVER THICKNESS.

TYPICAL GAINS FOR *SOLAR MODULES USING SIMPLIFIED DESIGN EQUATIONS

SUPPLIER	*AS CONFIGURED	WITH τ = 1/2"
A	1.08	1.17
B	1.10	1.20
C	1.12	1.24
D	1.06	1.13
E	1.13	1.26

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*THESE VALUES WERE CALCULATED FROM DATA TAKEN FROM JPL BLOCK III PROCUREMENT MODULES.

TITLE: MODULE DESIGN

PURPOSE: OUTLINES MATERIAL PRESENTED IN SECTION A.5

DEFINITIONS: INTER-CELL - REFERS TO TRAPPING FROM SPACES BETWEEN THE CELLS

INTRA-CELL - REFERS TO TRAPPING FROM SPACES ON THE CELL - SPECIFICALLY THE SPACES ON THE CELL OCCUPIED BY THE ELECTRIC GRIDS.

DISCUSSION:

A.5: MODULE DESIGN

- MODIFICATIONS FOR LIGHT TRAPPING
- MAXIMIZING GAIN IN A DENSELY PACKED MODULE
- MULTIPLE LAYERS
- INTER-CELL/INTRA-CELL TRAPPING

TITLE: MAXIMIZING GAIN IN A DENSELY PACKED MODULE

PURPOSE: PRESENT APPROACHES USED TO MAXIMIZE LIGHT TRAPPING GAIN

DEFINITIONS:

DISCUSSION: THIS CHART LISTS THOSE THINGS THAT CAN BE DONE TO MAXIMIZE GAIN IN A DENSELY PACKED, LIGHT TRAPPING MODULE. THE MOST COST EFFECTIVE DESIGN WILL RESULT FROM THE ANALYTICAL CONSIDERATION OF MANY PARAMETERS INCLUDING GAIN, AND MAY NOT (USUALLY DOESN'T) COINCIDE WITH MAXIMUM GAIN.

MAXIMIZING GAIN IN A DENSELY PACKED MODULE

THESE STEPS WILL PRODUCE AN OPTICALLY EFFICIENT PV MODULE:

- AR COATING
- ADD DIFFUSE REFLECTOR
- OPTIMIZE SUPERSTRATE THICKNESS BASED ON CELL SIZE
- UTILIZE TWO OR MORE TRAPPING LAYERS
- USE DIFFUSING LAYER ON CELL GRIDS
- ADD REFLECTORS TO SUPER- AND SUB-STRATE EDGES
- OPTIMIZE LOAD

TITLE: MODIFICATIONS FOR LIGHT TRAPPING

PURPOSE: PRESENTS THE DESIGN OPTIONS

DEFINITIONS:

DISCUSSION: THE MAJOR REGIMES OFFERING PROMISE ARE INTER-CELL, INTRA-CELL, SINGLE LAYER AND MULTI-LAYER. AS SOLAR CELL TECHNOLOGY PROGRESSES, SQUARE CELLS ARE BEING SUBSTITUTED FOR ROUND CELLS AND THE INTER-CELL SPACES ARE BECOMING LESS AND LESS. THE INTRA-CELL AREA OBSCURED BY ELECTRICAL GRIDS OFFERS POTENTIAL FOR PERFORMANCE IMPROVEMENT.

MODIFICATIONS FOR LIGHT TRAPPING

Design Options to be Considered

MATRIX OF STUDY CASES	PANEL PERFORMANCE IMPROVEMENT DUE TO TRAPPING FROM	
COMPLEXITY OF TRAPPING LAYER	INTER-CELL REGION	INTRA-CELL REGION
Single Layer	(BASELINE CASE)	
• Existing Design	Use Commercial Module Design	Use Commercial Cell Design
• Optimal Design	Design is a Function of Time as Cell Costs Decline with Time	Optimize Cell Grid Layout
Multiple Layers		
• Existing Design	Use Commercial Module Design	Use Commercial Cell Design
• Optimal Design	Design is a function of Time as Cell Costs Decline with Time	Optimize Cell Grid Layout

TITLE: INTER-CELL/INTRA-CELL TRAPPING

PURPOSE: DEFINE INTER- AND INTRA-CELL TRAPPING

DEFINITIONS:

DISCUSSION:

INTER-CELL/INTRA-CELL TRAPPING

- INTER-CELL TRAPPING TRAPS LIGHT BY DIFFUSE BACK REFLECTION FROM THE REGIONS BETWEEN CELLS
- INTRA-CELL TRAPPING USES A DIFFUSING LAYER ON THE CELL GRID ITSELF TO RECOVER A LARGE PART OF GRID BLOCKAGE LOSSES
- IN BOTH CASES LIGHT TRAPPING WORKS OVER THE ENTIRE HEMISPHERE THUS PROVIDING CONCENTRATION OF THE SKY DIFFUSED COMPONENT OF SOLAR RADIATION

TITLE: SYSTEM CONCEPTS THAT EXPLOIT LIGHT TRAPPING

PURPOSE: OUTLINES SECTION A.6

DEFINITIONS:

DISCUSSION:

A.6: SYSTEM CONCEPTS THAT EXPLOIT LIGHT TRAPPING

- GROWTH SYSTEM
- WALL INTEGRATED SYSTEMS

TITLE: GROWTH SYSTEM

PURPOSE: INTRODUCE THE GROWTH SYSTEM MADE POSSIBLE BY LIGHT TRAPPING TECHNOLOGY

DEFINITIONS:

DISCUSSION:

GROWTH SYSTEM

- DESIGNING A PHOTOVOLTAIC SYSTEM TO ALLOW FOR THE OPTIMUM PACKING FACTOR WITH TODAY'S PRICES, CAN ALSO ALLOW A MORE EFFECTIVE SYSTEM WHEN THE DOE COST GOALS ARE MET OR EXCEEDED, SINCE THE INFLATION SENSITIVE MATERIAL AND LABOR ITEMS ARE PRODUCED EARLY.

TITLE: GROWTH SYSTEM ECONOMIC MODEL

PURPOSE: PRESENTS EQUATIONS FOR CALCULATING SYSTEM COSTS

DEFINITIONS:

A_s = AREA OF SOLAR CELLS REQUIRED TO PRODUCE A GIVEN POWER OUTPUT
P_{out} = POWER OUTPUT
n = SOLAR CELL EFFICIENCY
I = INSOLATION
G = GAIN (PRODUCED BY LIGHT TRAPPING)
A_T = TOTAL ARRAY AREA REQUIRED
P.F. = PACKING FACTOR REQUIRED TO PRODUCE THE G DEFINED ABOVE
C_T = TOTAL COST OF A SYSTEM PROVIDING A GIVEN POWER OUTPUT P_{out}
C_s = COST PER UNIT AREA OF SOLAR CELLS
C_c = COST PER UNIT AREA OF TRAPPING LAYER
C_f = COST PER UNIT AREA OF STRUCTURE
C_L = COST PER UNIT AREA OF LAND (OR OTHER MOUNTING SPACE)

DISCUSSION: IN A GIVEN MODULE DESIGN, GAIN VERSUS PACKING FACTOR CAN BE ESTABLISHED. THIS RELATIONSHIP CAN THEN BE USED WITH THE EQUATIONS GIVEN HERE TO EVALUATE COST VERSUS PACKING FACTOR FOR A PHOTOVOLTAIC SYSTEM WITH A GIVEN POWER OUT.

GROWTH SYSTEM

ECONOMIC MODEL

REQUIRED AREA OF SOLAR CELLS $A_S = \frac{P_{OUT}}{\eta\ I\ G}$

REQUIRED TOTAL AREA $A_T = \frac{A_S}{P.F.}$

TOTAL COST = $C_T = A_S\ C_S + A_T\ [C_C + C_F + C_L]$

COST/M^2 OF: SOLAR CELLS TRAPPING LAYER STRUCTURE LAND

$$C_T = \frac{P_{OUT}}{\eta\ IG} [C_S + \frac{1}{P.F.} (C_C + C_F + C_L)]$$

TITLE: EXAMPLE: 1980 PRICES, THREE ENCAPSULANT THICKNESSES

PURPOSE: TO SHOW POWER/COST OPTIMIZATION USING ENCAPSULANT THICKNESSES AND PACKING FACTOR.

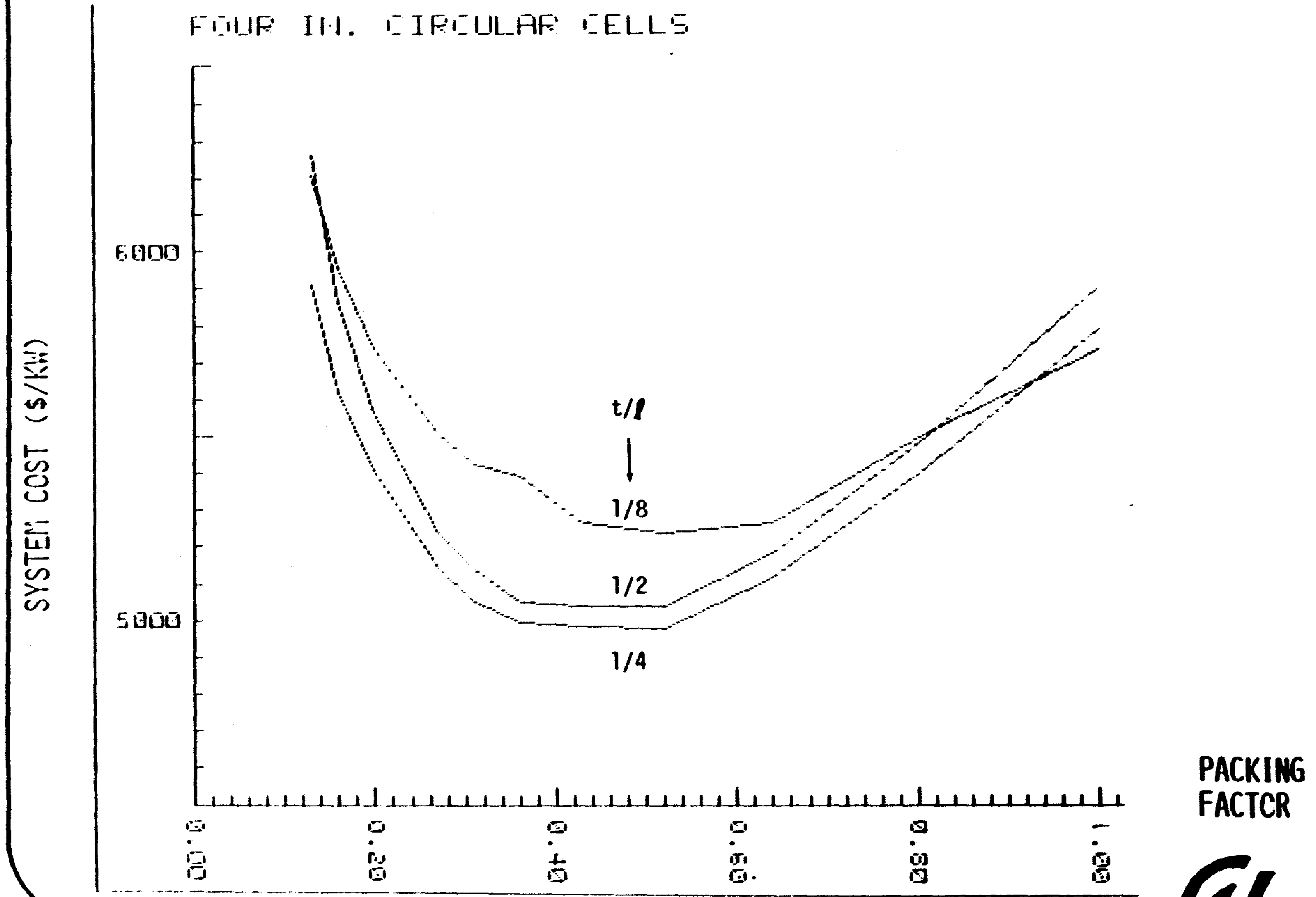
DEFINITIONS:

t = ENCAPSULANT THICHNESS

ℓ = CELL DIAMETER

DISCUSSION: MODUEL COSTS IN \$/kW ARE DISPLAYED VERSUS PACKING FACTOR FOR THREE CASES OF t/ℓ RATIO. THE COST BENEFIT EQUATIONS COST THE INCREASED MATERIALS AND LABOR FOR THE THICKER MODULES. A COST OPTIMUM WITH 1980 CELL PRICES OCCURS AT ABOUT PF = 0.5 AND IS ABOUT 10% LESS COSTLY THAN A PF = 0.8 MODULE.

EXAMPLE: 1980 CELL PRICES, THREE ENCAPSULANT THICKNESS



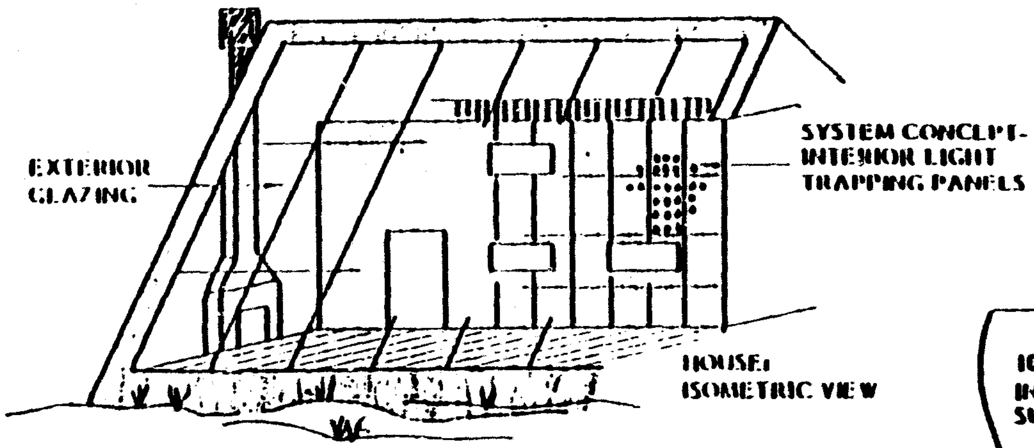
TITLE: WALL INTEGRATED SYSTEM

PURPOSE: TO SHOW HOW A LIGHT TRAPPING PV SYSTEM CAN BE INTEGRATED INTO A RESIDENCE.

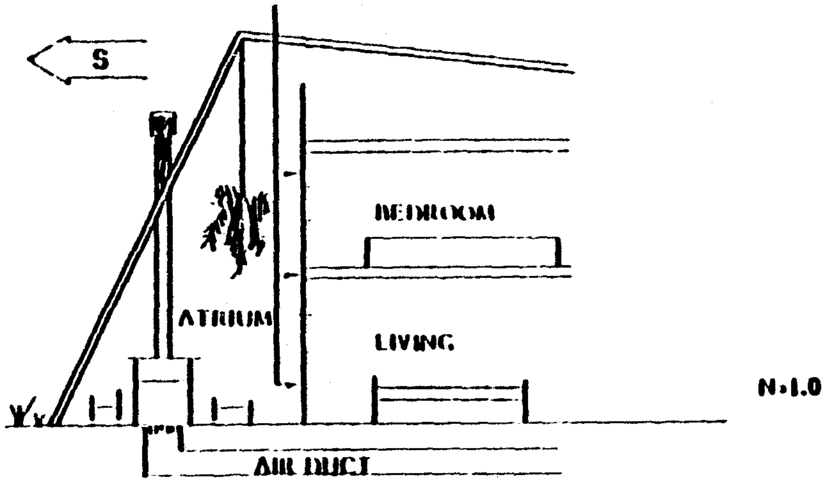
DEFINITIONS: ATRIUM

DISCUSSION: THE LIGHT TRAPPING PANELS ARE INTEGRATED INTO AN INTERIOR WALL OF A SUNLIGHTED ROOM. THE PANEL CAN SERVE AS A DECORATIVE PARTITION, AND PROVIDE ELECTRICITY. ENERGY NOT CONVERTED TO ELECTRICITY IS ABSORBED AND USED TO HEAT THE INTERIOR. HOW THE INCIDENT SUNLIGHT IS USED IS SHOWN AT THE RIGHT OF THE CHART.

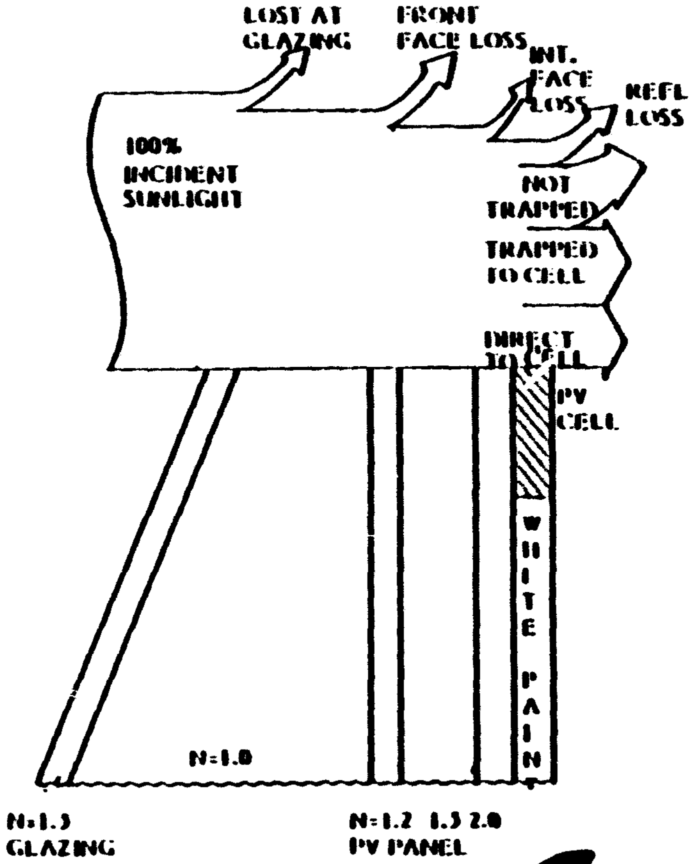
WALL INTEGRATED SYSTEM



DOUBLE SHELL PASSIVE HOME DESIGN
S FACING INTERIOR WALLS USE LIGHT TRAPPING PV PANELS



HOUSE: CROSS-SECTION



TITLE: FUTURE PROSPECT

PURPOSE: OUTLINE OF SECTION A.7

DEFINITIONS:

DISCUSSION:

A.7: FUTURE PROSPECT

- GOALS OF COST/BENEFIT STUDY
- INFORMATION NEEDED

TITLE: GOALS OF COST/BENEFIT STUDY

PURPOSE: PRESENTS FOLLOW UP STUDY PLAN

DEFINITIONS:

DISCUSSION:

GOALS OF COST/BENEFIT STUDY

AS A FOLLOW-UP TO THE DESIGN GUIDE A COST/BENEFIT STUDY WAS PLANNED

- USES SIMPLIFIED DESIGN EQUATION FOR PV MODULE PERFORMANCE
- SIMPLIFIED COSTING EQUATIONS TO RELATE COST OF CELLS, ENCAPSULANT, ARRAY STRUCTURES AND LAND AT A CONSTANT POWER LEVEL, WERE DEVELOPED
- THE GOAL IS TO DETERMINE THE OPTIMUM COST/BENEFIT POINT FOR OPTICAL DESIGN OF PHOTOVOLTAIC PANELS.

TITLE: INFORMATION REQUIRED

PURPOSE: TO LIST FOLLOW-ON STUDY DATA REQUIREMENTS

DEFINITIONS:

DISCUSSION:

INFORMATION REQUIRED

IN ORDER TO PERFORM THE COST/BENEFIT STUDY THE FOLLOWING DATA IS REQUIRED:

- MODULE

  OPTICAL MATERIALS, INDEX, ABSORPTION,
  VOLUMETRIC COST OF MATERIALS, COST
  OF LABOR FOR MANUFACTURER

  COST OF CELLS, AND EFFICIENCY

- ARRAY

  AREA RELATED COST OF ARRAY STRUCTURE,
  COST OF LAND

PROCEDURE IS TO TRADE-OFF PACKING FACTOR, AND/OR MODULE THICKNESS VERSUS COST FOR THE SAME LEVEL OF DELIVERED ELECTRICAL POWER.

TITLE: A.8 CONCLUSIONS

PURPOSE: LISTS CONCLUSIONS RESULTING FROM DESIGN GUIDE DEVELOPMENT

DEFINITIONS:

DISCUSSION:

A.8: CONCLUSIONS

- OPTICAL DESIGNS OF PV PANELS USING LIGHT TRAPPING INTRODUCE A HOST OF NEW PARAMETERS THAT MUST BE CONSIDERED IN PV MODULE DESIGN AND NEW RESEARCH AND DEVELOPMENT AVENUES THAT PROMISE TO PROVIDE EARLY DIVIDENDS.

- LIGHT TRAPPING CAN BE USED TO:
  - IMPROVE EFFICIENCY IN STANDARD PV MODULES
  - OPTIMIZE PV MODULE DESIGNS BASED ON COST USING CURRENT AND PROJECTED MATERIAL, LABOR, MONEY AND REAL ESTATE
  - IMPROVE THE EFFICIENCY OF SOLAR SYSTEMS ARCHITECTURALLY INTEGRATED INTO BUILDINGS TO PROVIDE PV ELECTRIC POWER GENERATION, SPACE HEATING AND DIFFUSE LIGHTING.

- LIGHT TRAPPING PV MODULES USING TRAPPING LAYERS MADE OF CURRENTLY AVAILABLE MATERIALS IS ALREADY A VIABLE PROPOSITION. THE DEVELOPMENT OF HIGHER INDEX MATERIALS CAN IMPROVE THIS SITUATION EVEN AS CELL COSTS DECLINE.

TITLE: DESIGN METHOD

PURPOSE: EXPLAINS HOW DESIGN GUIDE IS USED.

DEFINITIONS:

DISCUSSION:

DESIGN METHOD

- FAMILIARIZATION WITH CONCEPTS - EXAMPLES
- OBTAIN DATA ON MATERIALS: OPTICAL PROPERTIES AND COSTS TO AUGMENT DATA ON MODULE
- USE DESIGN NOMOGRAPHS OR SIMPLFIED DESIGN EQUATION TO OBTAIN GAIN AS A FUNCTION OF PACKING FACTOR AND THICKNESS OF ENCAPSULANT ABOVE CELL
- USE COSTING NOMOGRAPH OR SIMPLIFIED COSTING EQUATIONS TO DETERMINE GAIN FOR VARIOUS PACKING FACTOR AND THICKNESS VALUES, FIND A COST MINIMUM
- ESTIMATE COST SAVINGS OBTAINED AT MINIMUM AND COMPARE WITH STANDARD DESIGN
- REPEAT WITH OTHER MATERIAL CHOICES

TITLE: RECOMMENDED APPLICATIONS

PURPOSE: TO LIST THOSE CONDITIONS UNDER WHICH LIGHT TRAPPING SHOULD BE CONSIDERED.

DEFINITIONS:

DISCUSSION: THIS CHART REVIEWS WHEN LIGHT TRAPPING SHOULD BE APPLIED. FOR EXAMPLE, WHEN ROUND CELLS ARE USED 21.5% OF THE ARRAY AREA AT THE MINIMUM IS AVAILABLE FOR TRAPPING. AMONG THE SEVERAL OTHER REASONS SHOWN ON THIS CHART FOR USING LIGHT TRAPPING IN PHOTOVOLTAIC ARRAYS, THE QUANTITY AND COST OF SILICON USED IS REDUCED. THIS IS DOUBLY IMPORTANT OVER THE NEXT FEW YEARS WHEN THE SUPPLY OF PROCESSED SILICON IS EXPECTED TO BE IN SHORT SUPPLY, AND THE COST HIGH.

RECOMMENDED APPLICATIONS

BASED ON THIS STUDY IT IS RECOMMENDED THAT DESIGNERS CONSIDER LIGHT TRAPPING DESIGNS IN SITUATIONS WHERE

- ROUND CELLS (FULL OR PARTIAL) ARE TO BE UTILIZED
- SILICON IS COSTLY AND/OR IN SHORT SUPPLY
- CELLS ARE ROOF AND/OR WALL INTEGRATED (RESIDENTIAL)
- MODULE THICKNESS IS IMPORTANT - (HAIL AREAS IS AN EXAMPLE)
- RAPID POWER REQUIREMENT GROWTH IS ANTICIPATED AT SITE
- THIN OR SHARP SHADOWS FALL ON ARRAY
- ARRAY AREA COSTS ARE LOW