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# MAXIMALLY CONCENTRATING OPTICS FOR PHOTOVOLTAIC SOLAR ENERGY CONVERSION

TECHNICAL PROGRESS REPORT
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## Abstract

The use of a two-stage concentrator with a fresnel lens primary and a non-imaging dielectric totally internally reflecting secondary, has unique advantages for photovoltaic concentration. Our previous research showed that this concentrator design can increase the angular acceptance to more than seven times that of a singe-stage fresnel lens concentrator. In other words, this new design has a much larger acceptance angle than the conventional lens-cell concentrating system. In the continuation of this research, an optimally designed prototype "Mod C" (our previous prototypes were called Mod A and Mod B) which employs a 13.6-cm diameter flat fresnel lens as the primary focusing device, a dielectric compound hyperbolic concentrator (DCHC) as secondary and a 1-cm diameter high-concentration cell for electricity conversion has been built, tested and analyzed. Measurements under sunlight of Mod C show that it has an angular acceptance of $\pm 3.6$ degrees, which is dramatically better than the $\pm 0.5$ degree achievable without a secondary concentrator. This performance agrees well with theoretical ray-tracing predictions. The secondary shows an optical efficiency of $(91 \pm 2)\%$ at normal incidence. Combining with the primary fresnel lens which has an optical efficiency of$(82 \pm 2)\%$, the two-stage system yields a total optical efficiency of $(71 \pm 2)\%$. We expect the secondary optical efficiency can be increased to (94-95)% by making the secondary with a less absorptive material (low-iron glass), improving the finish of the side wall, improving the match at the cell-secondary interface and anti-reflection coating the front surface. The measurements of the system electrical performance yielded a net electrical efficiency of 11.9%. No problems associated with non-uniform cell illumination were found, as evidenced by the excellent fill factor of $(79 \pm 2)\%$ measured under concentration. The secondary geometrical properties and the optimal two-stage design procedures for various primary- cell combinations were systematical studied. A general design principle has been developed.

After the indicated improvements in optical efficiency, an electrical efficiency approaching 14% is expected for the module.

# I. Introduction

## A. Background

Beginning with the early work in the 70's, a family of non-imaging optical concentrators has been used in various ways for solar energy collection. From the start, the motivation for applying this technology to solar energy conversion has been the feature that this new class of concentrators can achieve or approach the maximum theoretical limits of concentration. This property made stationary solar concentrators and very high concentrating solar collectors possible in both thermal and photovoltaic applications. Alternatively, by increasing the angular field of view for a give concentration, the costs associated with precise tracking and alignment of solar energy concentrators can be significantly reduced.

This report describes the research efforts to develop such a concentrating system for solar photovoltaic applications carried out at the University of Chicago from July 1, 1985 through February 15, 1986. This is a continuation of the research work under Grant No. DE-FG02-84CH10201 supported by the SOLERAS program.

The goal of the project is to develop a solar concentrator which will have potential applications in effective solar energy photovoltaic conversion by incorporating a non-imaging concentrator as a secondary element optimally matched to a primary fresnel lens and cell. Because of its improved optical design, tracking and alignment tolerances can be greatly reduced. This advantage offers an attractive path in the effort to mitigate the high cost of conventional photovoltaic power.

As stated in our previous report, for a given concentration cell and fresnel lens, an optimal dielectric concentrator can be designed based on non-imaging optics. By using a fresnel lens as a primary focusing device and a dielectric compound hyperbolic concentrator (DCHC) as the secondary, a two stage concentrator is formed which has a concentration ratio close to the maximum theoretical limit.. Earlier research has already shown the technical feasibility of this approach. The dielectric concentrator as a secondary device, increases the effective cell area by a large factor, typically 10-15 depending on the given fresnel lens and cell. This property can either be used in very high concentration system with relatively high tracking tolerances, for example,approaching 1000:1 in the ideal limit with

±2 or intermediate concentration levels,e.g. 100:1 approaching(in the limit) ±8 tolerances.

A brief summary of what was accomplished during the first year's work is the following:

1) Two pre-prototypes for 1/4 inch dia. cells (Mod A and Mod B) were designed, built, tested and analyzed, and comparisions between these two were made.

2) Technical feasibility was demonstrated both theoretically and experimentally .

3) Detailed measurements of the optical and electrical properties were obtained.

For the second year we proposed to continue our research in the following areas:

1) Design a new Mod C with optimized parameters for a larger 1 cm dia. cell.

2) Build, test and analyze Mod C.

3) Design, assemble, and test a pre-prototype module.

4) Advanced conceptual design studies.

To accomplish our goal, an optimal secondary, Mod C ,larger than Mod A and Mod B was designed, built, tested and analyzed.

**B. Summary of accomplishments**

An optimal DCHC secondary dielectric element (Mod C) was designed and built to match the given 14-cm lens and 1-cm cell. For testing purposes, an electronic module which can measure the output current and voltage of the system simultaneously was designed and built. In association with this I-V device, a series of computer testing programs which run on the HP data acquisition system were written. With all this, a series of systematic measurements of optical and electrical performance was obtained for the cell alone, for the conventional lens-cell system (for comparison purposes) and for the full two-stage system.

The results indicate that both the optical and electrical properties of Mod C are within the expectations which were outlined in last year's proposal. Through comparison with the lens--cell system, the advantages of the two-stage with Mod C are clearly seen. However some problems associated with the thermal properties of the acrylic secondary appeared

which were not encountered with Mod A and Mod B. Solutions to those problems were proposed and studied. Further investigation of these possible solutions will be continued. A series of advanced computer ray-tracing programs for basic design problems and for simulation of the optical performance for various kinds of two-stage systems was written and some very general design principles have been developed. The results of this systematical study of the two-stage concentrator offer a variety of design options for photovoltaic concentration.

## II. Optimization of secondary design parameters

### A. General Principles

The relationship between concentration and field of view of an optical system depends on the optical design, but there exists a fundamental limit set by physical conservation principles which no design can exceed. Specifically the concentration ratio C and acceptance angle Ø of any optical system must satisfy the following relations:

(1) $C \sin(Ø/2.) < n$ (in a translationally symmetric system)

(2) $C \sin^2(Ø/2.) < n^2$ (in a rotationally symmetric system)
(where n is the index of refraction of the material.)

As seen from the above formula, for a given acceptance, there is a maximum concentration ratio or for a given concentration ratio, there exists a maximum acceptance angle. Most optical concentration system( e.g. lenses ,parabolic mirrors) fall far below this limit.

Considerable research has been done in the field of designing optical systems which can meet or closely approach these limits. A large family of nonimaging optical systems (in contrast to imaging forming devices, e.g. lenses,mirrors) has been found and these systems have been used in several areas. Especially in the area of solar energy collection, collectors employing these "ideal" or nearly ideal concentrators have been designed, tested and manufactured.

In applying similar concepts to solar photovoltaic conversion, we proposed a research project to systematical study the effects of employing a non-imaging concentrator in combination with a conventional cell-lens system thereby forming a two--stage. For our two--stage system, the

non-imaging secondary device is a dielectric compound hyperbolic concentrator or DCHC. The design of DCHC is based on the totally internal reflecting(TIR) properties of dielectric material. There are general two independent methods to design a DCHC secondary, technically known as the phase space conservation method and the maximum concentration method. In the phase space conservation method,we require that all the incoming extreme rays (rays entering at the maximum acceptance angle) leave the exit aperture at the same output angle while satisfying the TIR condition inside the DCHC (as illustrated in Fig.II.1). The DCHCs generated in this way have been used in fiber optics, because of the critical angle requirement for fiber transmission. In the maximum concentration method, the only requirement is that the extreme rays are transmitted while the TIR condition is satisfied (as illustrated in Fig.II.2). The difference between these two methods is that the latter one yields a higher concentration ratio than the former,holding everything else the same. In photovoltaic applications, since we are primarily concerned with total energy throughput, the maximum concentration method was used throughout our research. For any given exit aperture, index of refraction, acceptance angle and front surface curvature, theX-Y profile of the corresponding DCHC can be generated by a new computer design program which we have developed.

**B. MOD C parameters**

For our two-stage design, we use a 13.6-cm diameter flat fresnel lens as our primary which has a focal length of 21.5 cm. A 1-cm diameter concentration cell is used for electrical conversion. The secondary is mounted to the cell mechanically and the lens cell separation is such that the focal plane of the lens is the aperture plane of the secondary separating the spherical front portion from the side profile (see Fig.II.3). The cell is bonded to a heat sink for heat dissipation. A thermocouple wire is attached to the back of cell for temperature measurements. The distance between the cell and lens can be adjusted easily.

As noted above there are four design parameters which completely determine a given DCHC solution. These are the exit aperture, index of refraction, acceptance angle and front surface curvature. The exit aperture of the DCHC is solely determined by the size of cell. In this case we chose an exit diameter, 0.98 cm, which is slightly smaller than that of the cell for easy alignment. For a given lens, the required acceptance angle of the DCHC is related to the focal ratio f/D (focal length/lens diameter). As illustrated in the Fig.II.3, the edge ray from the lens should be the extreme ray for the

secondary. For our lens, this requires that the secondary DCHC have a half angle of acceptance of 22 degrees. As measured by Sandia Laboratory (R.Pettitt, private communication), the acrylic dielectric material we used has an index of refraction of 1.47 and an absorption coefficient of 1.9% per cm averaged over the solar spectrum ( see Fig.II.4 and Fig.II.5). The more curved the front surface, the shorter the DCHC will be. Also, a more curved surface reflects more incoming energy but a shorter DCHC absorbs less . Therefore there is a value of the front surface curvature for which the combined effect of reflection and absorption is minimized for a given index of refraction and absorption coefficient. Computer ray-trace studies show that a front arc angle of 65 degrees gives the DCHC minimum loss. A quantitative discussion of these relationships is given below in part IV. Using the information given above, an optimal DCHC was designed for a given lens-cell combination.

Parameters of DCHC secondary for Mod C:

1) Acceptance angle= ±22 degrees
2) Front arc angle= ±65 degrees
3) Exit aperture=.98 cm
4) Entrance aperture=3.66 cm
5) Height = 3.23 cm
6) geometrical Concentration Ratio=13.92

The ideal limit of concentration for given index of refraction and acceptance angle is given by equation (2) which is 15.4. Thus the Mod C DCHC achieves 13.92/15.4 = 90% of ideal concentration.

### C. Testing facilities

All the tests were conducted under actual sun on the roof of the High Energy Physics building on the campus of the University. Data were taken through our HP data acquisition systems and outputs were either plotted directly or printed. On the roof station, we have a platform which can be directed to the sun manually.A normal incidence radiometer (NIP) and a radiometer (PSP) for total radiation measurement are fixed to the platform. The system we want to measure is also fixed to the platform. All the output data are transmitted to the acquisition system downstairs through a cable connection. Because of the fast speed of data acquisition, voltage ,current and radiation information for each point are taken almost simultaneously. It allows us to plot current as normalized in real time to either total or beam radiation. The NIP and PSP instruments both have uncertainties of about 2%. In the following discussion, all of the errors associated with our results are mainly caused by this uncertainty.

## III. Mod C studies

### A. Optical performance

The optical performance of Mod C is characterized by the optical transmission ratios, or optical efficiencies of the secondary alone and the two-stage as a function of incident angles. We refer to these as the angular acceptance functions of the secondary and two-stage respectively. One major concern we have with any two stage design is that losses due to secondary material absorption, front surface reflection etc... which reduce the overall performance be minimized. The best way to investigate such effects is to analyze the angular response functions in detail.

Since we know that the cell short circuit current is proportional to the energy received, all the optical performance tests were based on measurements of short circuit current. The optical efficiency of the secondary at a particular incidence angle Ø is defined as:

$$E(Ø)=(Ist(Ø)-Isd(Ø))/(Ict(Ø)-Icd(Ø))/C$$

where Ist(Ø) stands for the short circuit current of the cell with secondary due to total insolation while Isd(Ø) stands for that portion of the short circuit current contributed by only diffuse radiation when the angle between the symmetry axis of secondary and incoming beam is Ø. Both are normalized by beam insolation. Ict(Ø) and Icd(Ø) refer to the performance of the cell by itself and are also normalized by beam insolation. C is the geometrical concentration ratio which is defined as area ratio of the entrance aperture to the cell area. The normal incidence case is when Ø equals zero. Alternatively one can define efficiency as :

$$E(Ø)=((Ist(Ø)-Isd(Ø))/Ict(Ø)/C$$

In this case Ict(Ø) is normalized by the total insolation rather than just beam while the other symbols remain the same. Physically, these two slightly different definitions ought to give similar answers because for the cell alone, Ict normalized by total insolation is the same as (Ict-Icd) normalized by beam .

The actual measurement was done with two different 1-cm diameter cells, cell#1 and cell#2. Cell #1 has a two-layer anti-reflection coating. One important point to make clear is that the cell surface coating

properties affect the optical efficiency as defined above. Ict is measured when the cell is directly exposed to the radiation and Ist is measured with secondary coupled to the cell. In the former situation, the interface is air(index 1.)-coating-silicon and in the latter case, this is secondary-coating-silicon where the acrylic secondary has an index of refraction close to 1.5. Optically these two different interfaces have different transmittance. Thus the optical efficiency defined above by taking the ratios of short circuit currents measured for different interface structures clearly depends on the cell used to do the measurements. This cell dependence of the optical efficiency is evident in the following discussion.

Fig. III.1 shows the efficiency vs. angle curve measured with cell #1. The optical efficiency at normal incidence is (91+2)% . The ideal response would be a flat plateau out to a fairly sharp cut-off at the design acceptance angle. What is actually observed is considerably more rounded. The factors which affect the angular acceptance function are front surface reflection loss, material absorption loss and acrylic-cell interface losses (or gains). Ray-tracing analysis shows that the front surface loss varies from 3.65% to 5% depending on incident angle. The absorption loss which also depends on the incident angle varies from 7-9 % for our given acrylic physical properties ( index of refraction of 1.47 and absorption coefficient 1.9% per cm). As can seen from the ray-trace results, these two factors alone will result in an optical efficiency for normal incidence about 88% which is slightly smaller than what we actually measured with this cell (See Fig.III.2 for comparision). This can be explained as a secondary-cell interface effect. In this case it turns out to be a gain over the air-cell case.

Cell#1 has two layers of AR surface coating; one layer of $TiO_2$ which has an index of refraction of 2.2 and is 630 A thick, and another layer of $Al_2O_3$ which has an index of refraction of 1.86 and is 860 A thick. The transmittance of the AR coatings depend not only on these parameters, but also on the index of refraction of the silicon cell and the media which the coating directly interfaces with. For a detailed discussion one can refer to Macleod (**Thin Film Optical Filters** , American Elsevier,New York 1969). Here we just give the results. The formula for calculating the transmittance of a two layer coating is the following:

$$T=4 \times Hi \times Hf/(A^2+B^2)$$

where,

$$A=(Hi+Hf)\cos\emptyset 1\cos\emptyset 2-(Hi \times H2/H1+Hf \times H1/H2)\sin\emptyset 1\sin\emptyset 2$$

$$B=(H2+Hf \times Hi/H2)\sin\emptyset 2\cos\emptyset 1+(H1+Hi \times Hf/H1)\cos\emptyset 2\sin\emptyset 1$$

$\emptyset 1=2 \times N1 \times d1\cos i1$ phase difference in layer 1

$\emptyset 2=2 \times N2 \times d2\cos i2$ phase difference in layer 2

$Hr=Nr\cos ir$ for TE waves

$=Nr/\cos ir$ for TM waves

r = i, 1, 2, f stands for the media(acrylic, or air), AR layer 1, AR layer2 and final material ( silicon). ir stands for refraction angles in each material respectively.

We put this information on AR coatings into our computer ray-trace programs. It turns out that the interface effect not only can explain the measured optical efficiency for normal incidence but also part of the rounding in the angular acceptance curve. As one can see from Fig.III.3, the acrylic-cell interface effect is a 4.5 % gain at normal incidence relative to air-cell interface. As the angle gets larger, this gain gradually decreases until finally there is a loss. This explains part of the rounding. This effect was demonstrated experimentally. We measured the cell short circuit current both with and without a thin layer of optical compound on its surface ( optical compound has an index of refraction close to acrylic), and saw a small increase in the short circuit current. As will be discussed later in this report , this interface effect will explain some other phenomena which we encountered.

Another possible explanation for the rounding is a TIR loss caused by secondary profile surface irregularities. Total internal reflection occurs when a ray passes from a high index of refraction material to a lower index material at an incidence angle larger than the critical TIR angle ( which is arcsin(n1/n2), where n1<n2). Small irregularities on the scale of typical solar wavelengths can cause a loss. This irregularity may be small scratches caused by either manufacturing or handling of the acrylic. A reasonable estimate is that each TIR loses about 5% of the energy. Comparison of measurement data with ray-tracing results including the possible TIR losses is shown in Fig.III. 3. Considering all this, we can see that ray-tracing predictions and experiments agree for both optical efficiency and angular cut offs .

The optical efficiency and the shape of the angular cut-offs for the whole system can also be defined in a similar fashion. In this case we have one more degree of freedom, the distance between the cell and secondary top. As we varied the distance we found that the short circuit current varies ±7% about the average even though the lens focal spot is entirely within the secondary entrance aperture. One such measurement curve is shown in Fig.III.4. It reaches a maximum at about 16cm and a minimum at 22.5cm. Our design operating distance is 21.5cm which is the focal length of the primary fresnel lens. We suspected that is phenomena might also be attributable to TIR loss, so we polished the side wall of the secondary and again measured a minimum at 22.5cm but this time, the variation is only about±5% of the average (see Fig.III.5). This effect can be explained by considering the above loss mechanisms, namely front surface reflection loss, material absorption loss, interface loss(or gain) and a possible 5% TIR loss. We also performed the ray-trace simulation based on the same model outlined above. The ray-trace result is shown in Fig.III. 6. We can see the agreement between them is excellent .

The angular acceptance curve for the two-stage system at the design distance was also measured. The measured curve shows a flat short circuit current response up to 3.6 degrees from normal incidence. This is the most significant advantage of the two-stage system over conventional lens-cell concentrators. The optical efficiency is about (71±2)% for the whole system. As measured independently, the flat fresnel lens we used has an optical transmittance of (82±2)%. Taking these factors into account, the ray-trace results for the angular acceptance with front surface reflection loss, material absorption , interface loss(or gain) and TIR loss agrees with measured data very well (see Fig.III.7). We note the ray-trace results indicate that the effective optical efficiency of the secondary in the two-stage system is reduced below its normal incidence value because the distribution of directions on the secondary includes large angles. The value is only about (86±2)% because the net gain from the interface effect is nearly zero. At larger incidence angles on the lens this gain increases to 4.5% which has the effect of making the angular acceptance curve of the two-stage system more "square" than that of the secondary alone.

The same kinds of experiments and analysis were also done for cell#2. The only difference between those two cases is the interface structure . Comparisons were also made and the ray-trace and experiments agree well. After performing studies of the optical properties of the secondary

concentrator, both through ray-trace analysis and experiments, we found that the four factors affecting the secondary optical efficiency are front surface reflection( 4%), material absorption(8%), TIR(<5%) and finally interface effects which depend on the cell. For the given AR coated cell, we achieved an optical efficiency of (91±2)% for the secondary alone at normal incidence ( this drops a small fraction for angles close to the acceptance angle).The secondary demonstrates an effective (86±2)% optical efficiency in the combined two-stage system. Knowing the loss mechanisms, we will discuss possible steps to be taken to reduce these losses in part V.

### B. The electrical performance of the two-stage system

The electrical performance tests were done with 1-cm cell#2. For the cell itself we measured an electrical efficiency of 13.7%, fill factor of 72%, open voltage of .62v and a short circuit current of 23.7mA under one sun(see Fig.III.8). Under a high concentration of 185 suns (our nominal condition) we expect ( from data provided by Sandia) an electrical efficiency of 17.30% ,a fill factor of 79%, short circuit current of 4.33 A and open circuit voltage of .73v.. The measured I-V curve at the design lens-cell separation at normal incidence for the two-stage system is shown in Fig.III.9 (All the I-V curves in this report are normalized to one sun). We can see the two-stage system achieves an electrical efficiency of 11.9%, fill factor of 81% ,open circuit voltage of .73v and short circuit current of 28.0A. The consistent fill factor and open circuit voltage indicate that using a secondary concentrator does not cause any nonuniform radiation distribution which may adversely affect cell performance. In fact in comparison to the lens-cell system, the secondary concentrator makes the irradiance on the cell more uniform(see part C of this section ). The reduction of short circuit current is explained in the sense that the lens has an optical efficiency of (82±2)% and the secondary has an optical transmittance of about (86±2)% (see part A of this section). The small reduction in electrical efficiency is mainly caused by the loss in optical efficiency. The most significant advantage of the secondary over the system without secondary is the increase in the angular acceptance to ±3.6 degrees. We also measured the I-V curve at 3 degrees from normal incidence. This also demonstrated good electrical performance (the measured curve is showed in Fig .III.10).

From all these measurements it is clear that the two-stage system has good electrical performance. The advantages of the two-stage system over systems without a secondary are made more evident in the next section.

**C. The Comparisions of two-stage performance with lens-cell system.**

Since the electrical performance depends strongly on the cell used, we will disscuss the cell #1 and cell #2 separately. The measured I-V curves of lens-cell system at different lens-cell separations at normal incidence are shown in Fig.III.11-13 and optical efficiencies as a function of angle are shown in Fig.III.14-15. The measurments were done with the same flat fresnel lens and cell we used for the two-stage. As we can see from these results that the electrical efficiency varies from 10% to 12.4% depending on the lens-cell separation. A short circuit current vs. lens-cell separation at normal incidence was also obtained. One can see from Fig.III.16 that the short circuit current is maximum at a lens-cell distance equal to the lens focal length (this also can be seen in Fig.III.14-15). This is natural because fresnel lenses do not have a sharp image. At the focal length, the cell intercepts the largest fraction of the sun's "image"; that fraction goes down as the lens moves away from this location. On other hand, the cell gives the best performance electrically when the radiation distribution is more uniform. Further away from the focal-distance, the uniformity improves. As our measurements indicates, the cell gives the maximum output at a lens-cell separation equal to 20.00-cm which is 1.5 cm away from the focal distance. Comparing Fig.III.11 at a distance of 20.0cm with Fig.III.13 at a distance of 21.05 cm, we see a drop in short circuit current and an increase in fill factor which is an indication that the cell intercepts less radiation which is more uniformly distributed. Fig.III.12 is an I-V curve at an intermediate distance of 20.75.cm.

The angular acceptance curves for two of these cases are shown in Fig.III.14-15. As one can see they all drop rapidly as the sun's direction deviates from normal incidence. If we define the angle corresponding to 90% of the short circuit current at normal incidence as the half acceptance angle, then they all have a half acceptance angle of approximately 0.5 degrees. Practically, this means that they require a precise alignment and tracking system for effective solar photovoltaic conversion.

The measurements of the two-stage indicate that it has significant advantages in two respects. The first advantage is the insensitivity of the short circuit current dependence to both the incident angle and lens-cell separation. This is evident when we compare the angular acceptance curves at various distances and the short circuit current vs. lens-cell spacing ( referred to as the I-D curve) of the two-stage with the lens-cell

system. The I-D curve of the two-stage is shown in Fig.III.17 and the angular acceptance curves at three different separations are given in Figs.III.18-20. The distance for the two-stage is measured between the lens and secondary aperture plane. The angular acceptance curves of the two stage at distances slightly different from the design distance show a small decrease in acceptance angle as expected.

These advantages of the two-stage concentrator are, of course, a consequence of the fact that introducing a secondary has increased the effective cell area by a factor equal to the secondary geometrical concentration ratio. One can think of the two-stage as a lens-cell system with a much larger cell ( in this case 13 times larger ). Thus the two-stage can be operated over a range of distances or a range of angles much wider than with the cell alone.

Another advantage of the two-stage system is that the energy distribution on the cell surface is more uniform. This is an expected effect for nonimaging concentrators and is verified by computer simulations. The effect can be seen from measured I-V curves at different lens-cell separations of the two-stage done at normal incidence (see Fig.III.21-25). These curves shows a fill factor of (78.4-81.4)% only weakly dependent on the lens-cell separation and an open circuit voltage of .72v. By contrast, I-V curves for the lens-cell system alone show a big variation in fill factor from 59.9% to 78.4% and a lower open circuit voltage of .68v. Note in particular that the I-V curve of the two-stage at +3 degrees ( half acceptance angle =3.6) and at the design distance also shows a fill factor of 80%. This indicates that the two-stage can be operated at distances different from the focal distance or at angles different from normal incidence without loss of electrical; performance due to non-uniformity of the radiation distribution on the cell surface.

From these points it follows that the two-stage system offers a degree of flexibility that conventional lens-cell systems do not. We operated the two-stage at a design distance where we obtained maximum angle tolerance (or acceptance). At this distance, our prototype Mod C shows an electrical efficiency of 11.5% and an acceptance angle of ±3.6 degrees. By contrast, lens-cell system shows a maximum electrical efficiency of 12.4% and an acceptance angle of 0.5 degree for the same cell and fresnel lens. The two-stage system can also been operated at a smaller distance than designed, the electrical efficiency will be slightly higher (consistent with the slight increase in short circuit current seen in the I-D curve) and the

acceptance angle will be slightly smaller. Similar comparisions for the cell*1 were also made.
The possible disadvantage of the two-stage is the added complexity and cost resulting from introducing a secondary concentrator. A study of the economical feasibilities of the two-stage system has been proposed for the next phase of research.

## IV. General two-stage design principles

As we mentioned in the secondary design parameters in part II of this report, there are two different methods to generate the DCHC profiles, one known as the phase conservation method and another as the integration method (or maximum concentration method). The second one gives a higher concentration ratio while holding other parameters the same. Since in photovoltaic application one emphasizes the concentration ratio, the second method is used and all the following analysis is based on this method. There are four independent parameters one has to specify for a DCHC concentrator.The set of four parameters for this specific application are exit aperture, index of refraction, acceptance angle and front surface arc angle. The situation is so complicated that an analytical solution is not feasible. A program in Fortran was written and for a given set of these four parameters, this program gives the X-Y coordinates of the secondary profile which has the maximum concentration ratio. The following results are based on numerical output from this program.

In fact, for a given lens primary there is only one parameter choice e.g., the front surface arc angle. Because the exit aperture is determined by the size of the cell, index of refraction is determined by the dielectric material property and one will see later that acceptance angle is determined essentially by the f/D ratio of the primary lens. In practice, for a given primary lens and cell the optimization procedure of secondary design is to choose the correct front surface arc angle for maximum system performance. In our discussion we use the front surface arc angle as the free-variable.

We define the profile height as DCHC height and the distance from the spherical top to bottom of the concentrator as total height.The computer output indicates that there is a inverse relationship between front surface arc angle and DCHC height. This also holds for the total height. The

quantitative relations are plotted in Fig.IV.1. The entrance aperture varies only slightly with the arc angle.

As emphasized in the previous part, the optical losses of the secondary are front surface reflection loss, absorption loss, TIR loss and cell-secondary interface loss. Qualitatively, the material absorption is proportional to the height of the concentrator and the front surface reflection loss increases with arc angle. The criteria of the best arc angle is that at this angle the combining loss of those two effects for the given material is minimum. This depends on the specific properties of the material. For Mod C, the absorption, reflection and total loss as a functions of arc angle at normal incidence are plotted in Fig.IV.2 The total loss is minimum when the arc angle is about 65 degrees.

The acceptance angle of the secondary should be chosen such that the ray coming from the one side of the lens to the opposite side of the secondary is just within the acceptance(see Fig.II.3). The analytical expression for the half acceptance angle is

$$\emptyset = \tan^{-1}((L+E)/2H)$$

where L is the lens aperture, E is the secondary entrance aperture and H is the focal length of lens. As one expects, the secondary entrance aperture varies with the acceptance angle. We can define the ratio of concentration to the theoretical maximum limit for given acceptance as idealness; a plot of idealness vs. acceptance angle is showed in Fig.IV.3. From this graph we see that entrance aperture decreases with the acceptance angle while holding the exit aperture fixed. So the determination of Ø is to solve a transcendental equation which can be done numerically. The solution for various focal lengths for a 13.6cm diameter lens is plotted in Fig.IV.4. As seen from the graph, for our primary lens which has a focal length of 21.5cm, the acceptance angle is about 22 degrees. The same kind solution can be done for different lens cell combinations.

The procedures discussed above provide an optimally match to a given cell and lens . This was used to design Mod C and will be used to design the forthcoming module (see part V).

## V. Module design and outlook

Based on the previous discussions and the MOD C studies we have made, a module with four operating units will be designed and tested in the remaining months of this research period. Although the optical and electrical performances of the two-stage with acrylic secondary are encouraging, a significant problem still needs to be resolved. Even though our primary thermal measurments indicate that the secondary only reaches a temperature of 25 degrees above ambient (just by passive cooling), high flux hot spots from the lens cause softening of the secondary in continuing operation because of the low melting temperature of acrylic. Two possible solutions have been carefully examined. In one solution, we would use glass instead of acrylic for the secondary. Technically since glass has a smaller absorption than acrylic, this solution is somewhat preferred. Another solution is to make just the top spherical portion of glass because that is where the lens focuses while the rest remains acrylic. We call this the two-component solution. The top lens part is easily available and the bottom part can be manufactured in the same way as Mod C. Measurements of the two-component secondary indicate a good optical efficiency of (90±2)%. These solutions need more study before we select which to use for our module. As for the other components, we will use 1-cm dia. concentration cells and a 13.6 cm flat fresnel lens as our primary. The holding assembly will be designed for low material (light weight). A conceptual design diagram is showed in Fig.V.1. Either the all-glass or two-component secondary will be optimally designed for our given lens and cell properties using the procedures outlined in previous part. The TIR loss will be kept low by ensuring a smooth side wall of the secondary. Choosing a material with low absorption coefficient will improve the optical efficiency. The interface structure will be studied in detail. Both front surface reflection loss and interface loss can be reduced by applying multilayer coatings. A module with four two-stage photovoltaic concentrators will be tested and their overall performance evaluated.

## VI. Status Summary

As shown in this report, a new optimally designed preprototype Mod C secondary photovoltaic concentrator has been built, tested and analyzed in much more detail than previous Mod A and Mod B versions (see our previous report). Progress has been made in understanding both the

theoretically optimal design and practical manufacturing and assembly of the two-stage system. The perfo mances of Mod C agrees well with our expectations. Compared with the lens-cell systems, the two stage has certain significantly advantages. The testing results are encouraging. There exists an improved understanding of two-stage performance both theoretically (ray-trace) and experimentally. We have identified the factors which contribute to optical losses in the secondary. This potentially allows us to reduce these losses in future module design. General design principles have been worked out. A series of ray-tracing programs for advanced conceptual designs as well as for experiment analysis have been prepared. A systematic testing procedure has been developed which will facilitate future testing. Finally a module based on this work will be built and studied.

END

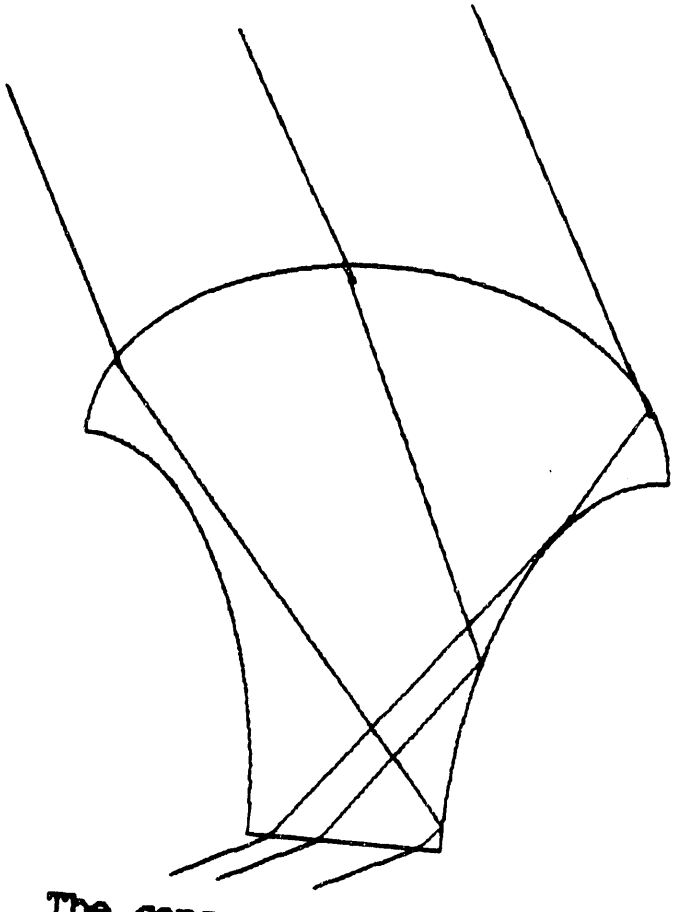


Fig.II.1 The conservation method of generating DCHC secondary.All rays come out at same angle

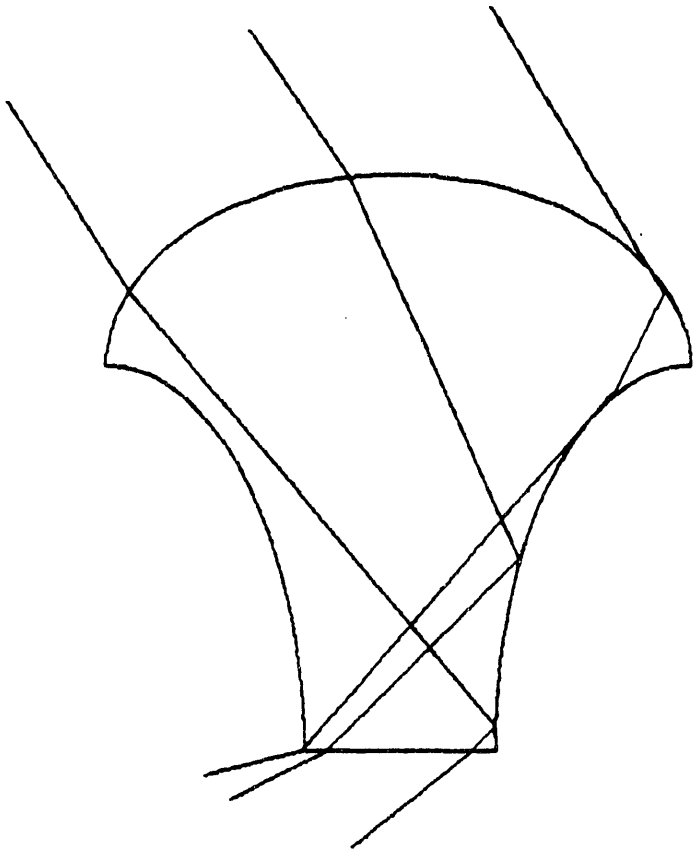
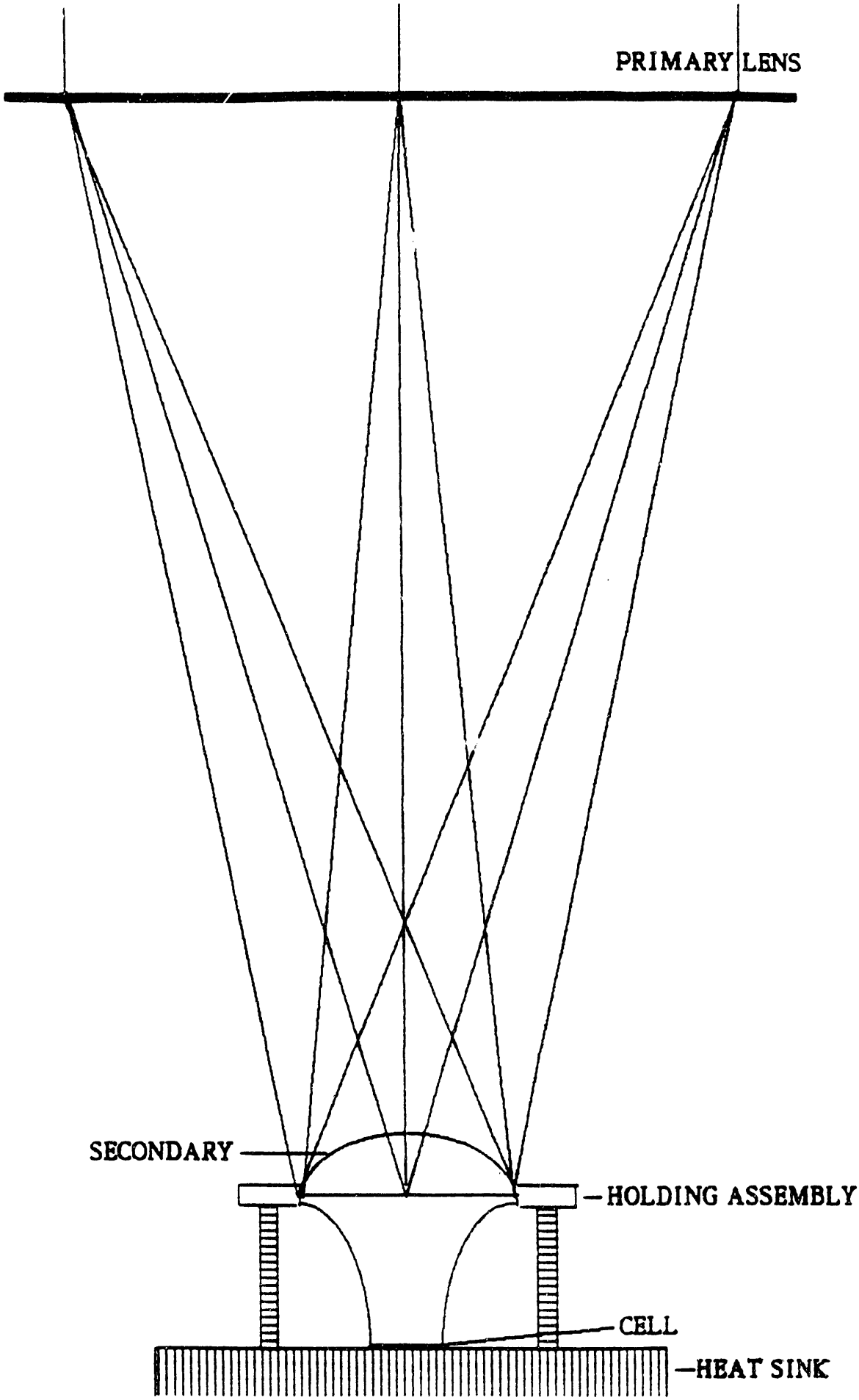


Fig.II.2. Maximum concentration method of generating DCHC secondary.Out coming rays barely satisfy TIR to give maximum concentration.

Fig.11.3 TWO-STAGE DESIGN



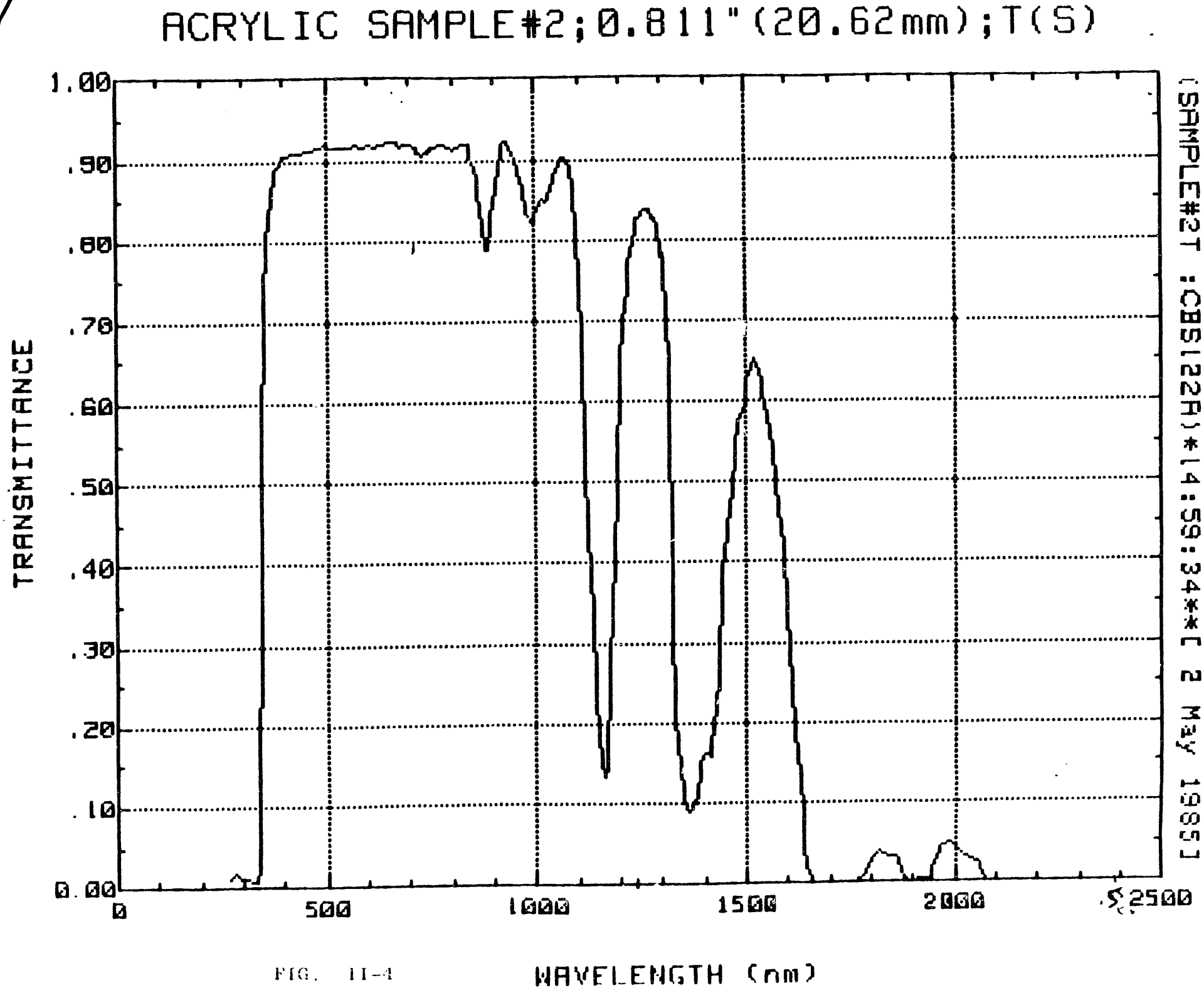

ACRYLIC SAMPLE#2;0.811"(20.62mm);T(S)
TRANSMITTANCE
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0.00
0
500
1000
1500
2000
2500
WAVELENGTH (nm)
[SAMPLE#2T :CB5122A)*14:59:34**[ 2 May 1985]

FIG. II-4

# U OF CHICAGO ACRYLIC SAMPLES : REAL INDX

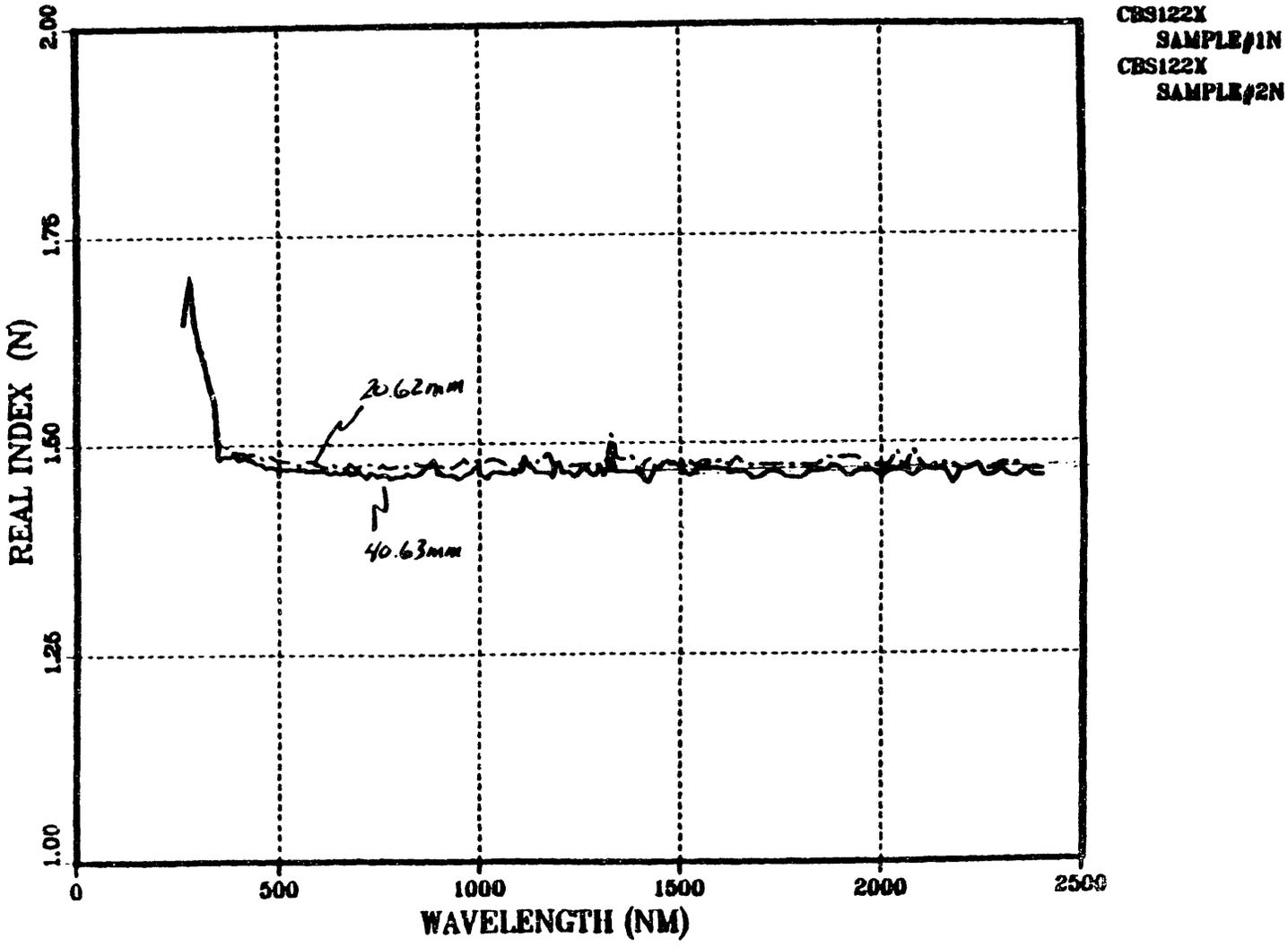



FIG. II-5

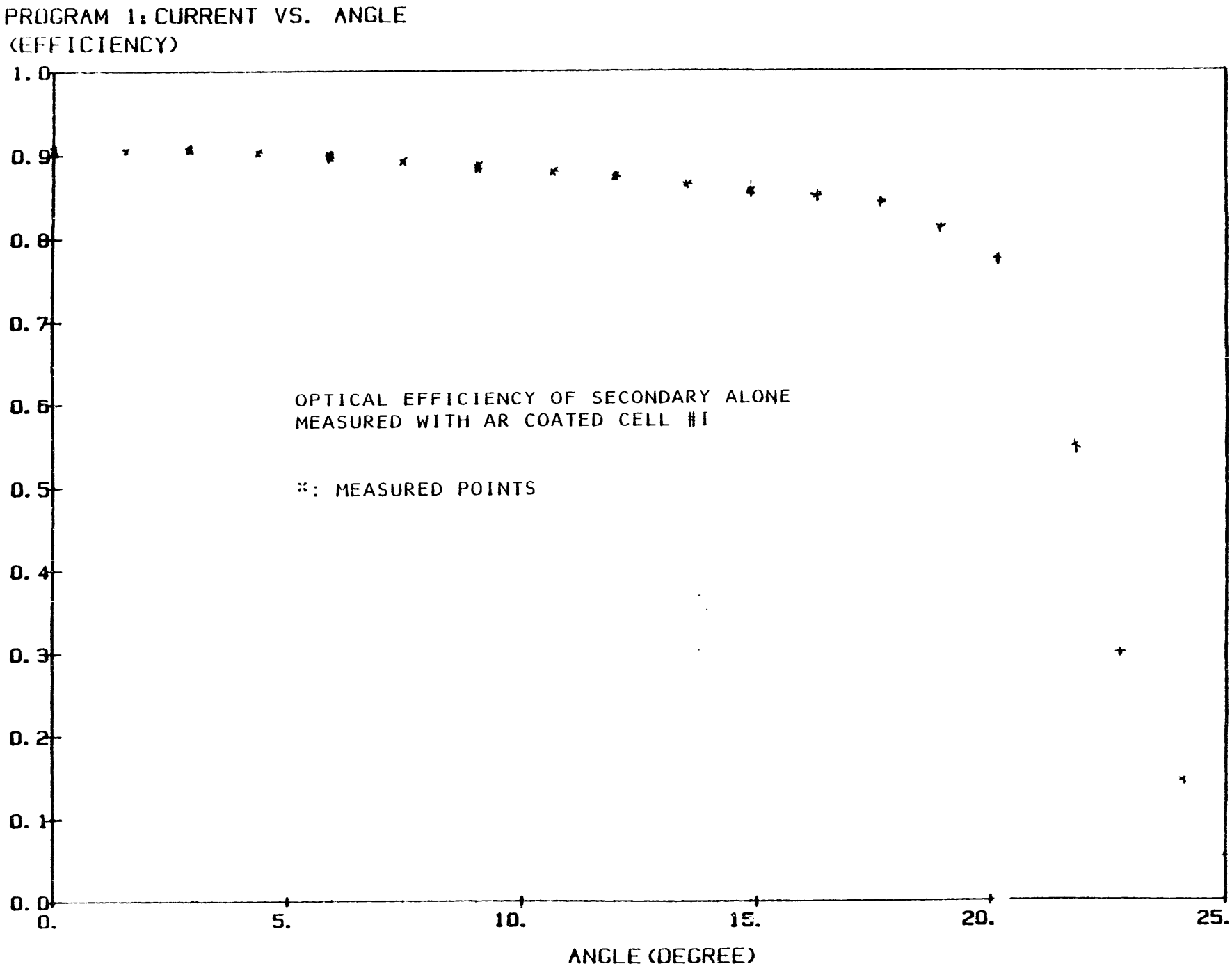



FIG.III.1 ANGULAR ACCEPTANCE CURVE FOR DCHC ALONE

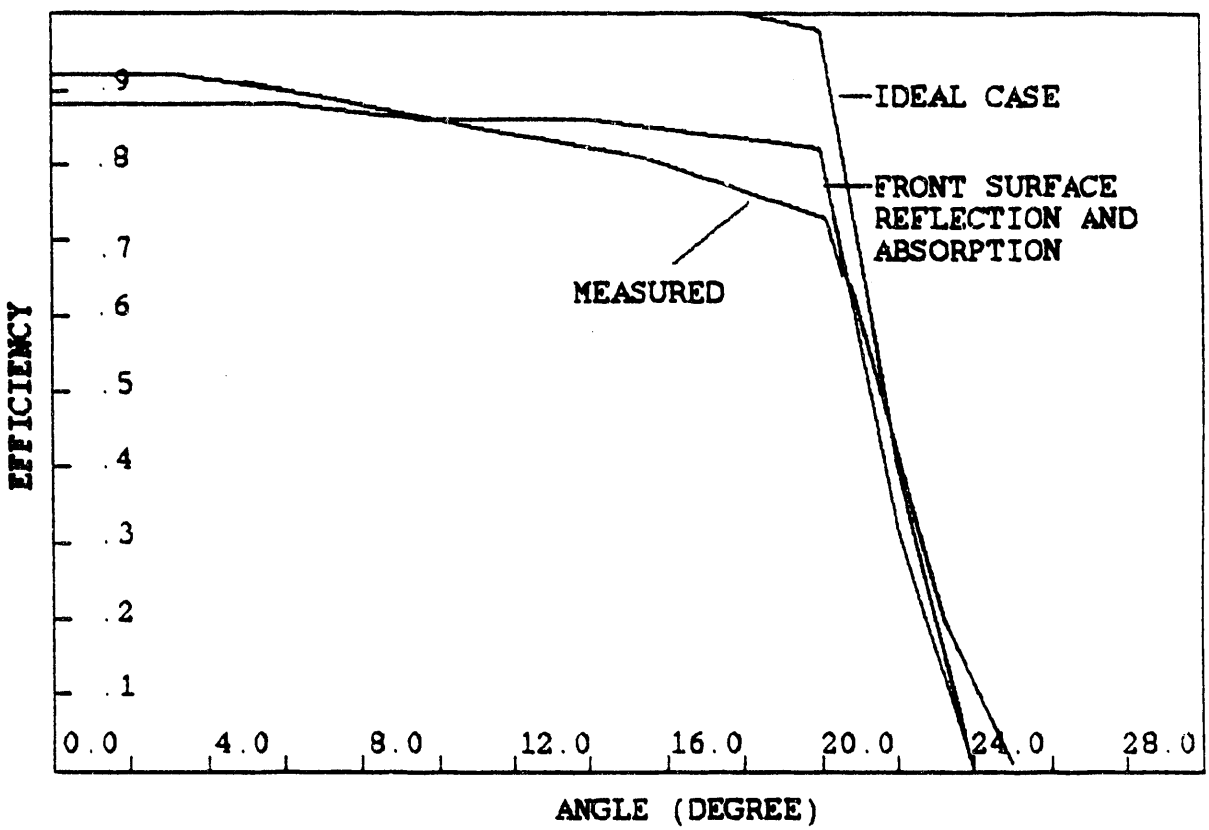



**FIG.III.2 ANGULAR ACCEPTANCE FOR DCHC RAY-TRACE AND MEASUREMENT COMPARISONS**

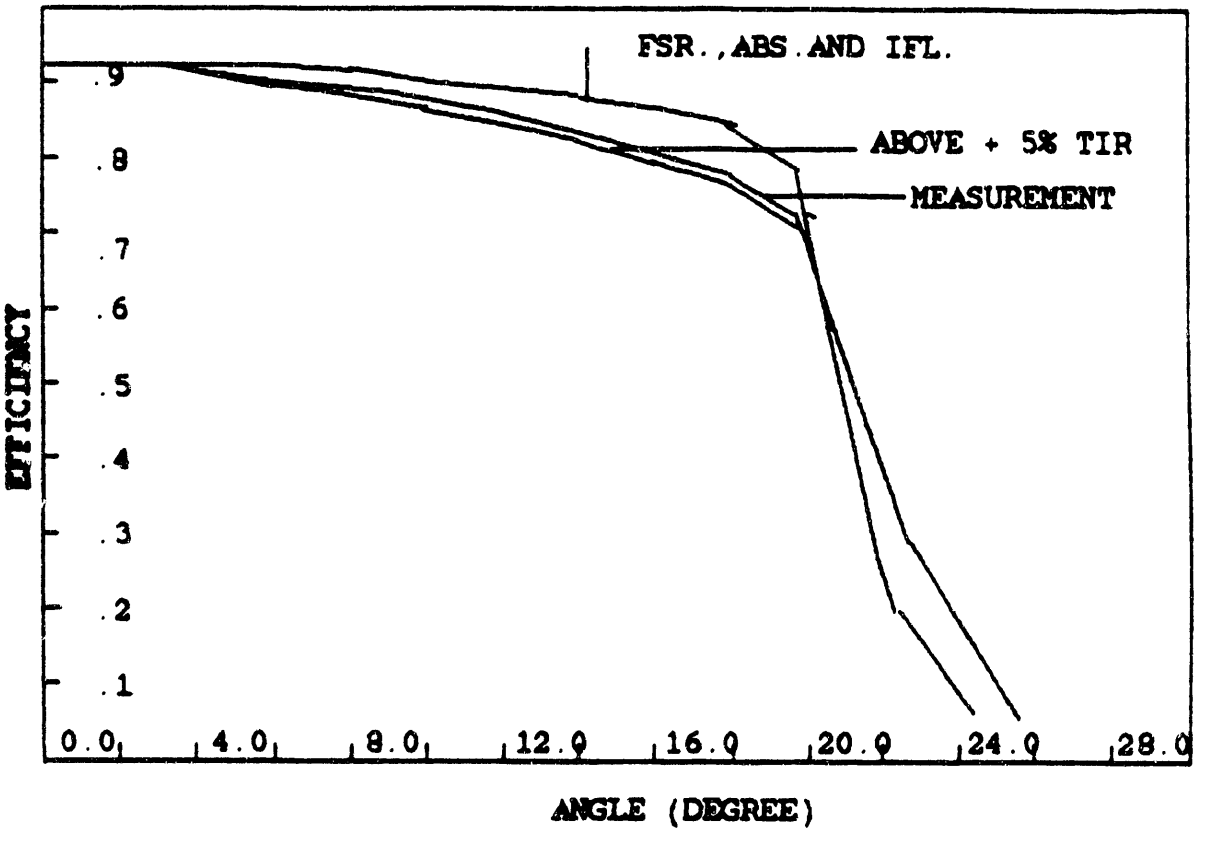



FIG.III.3 ANGULAR ACCEPTANCE FOR DCHC
RAY-TRACE AND MEASUREMENT COMPARISONS

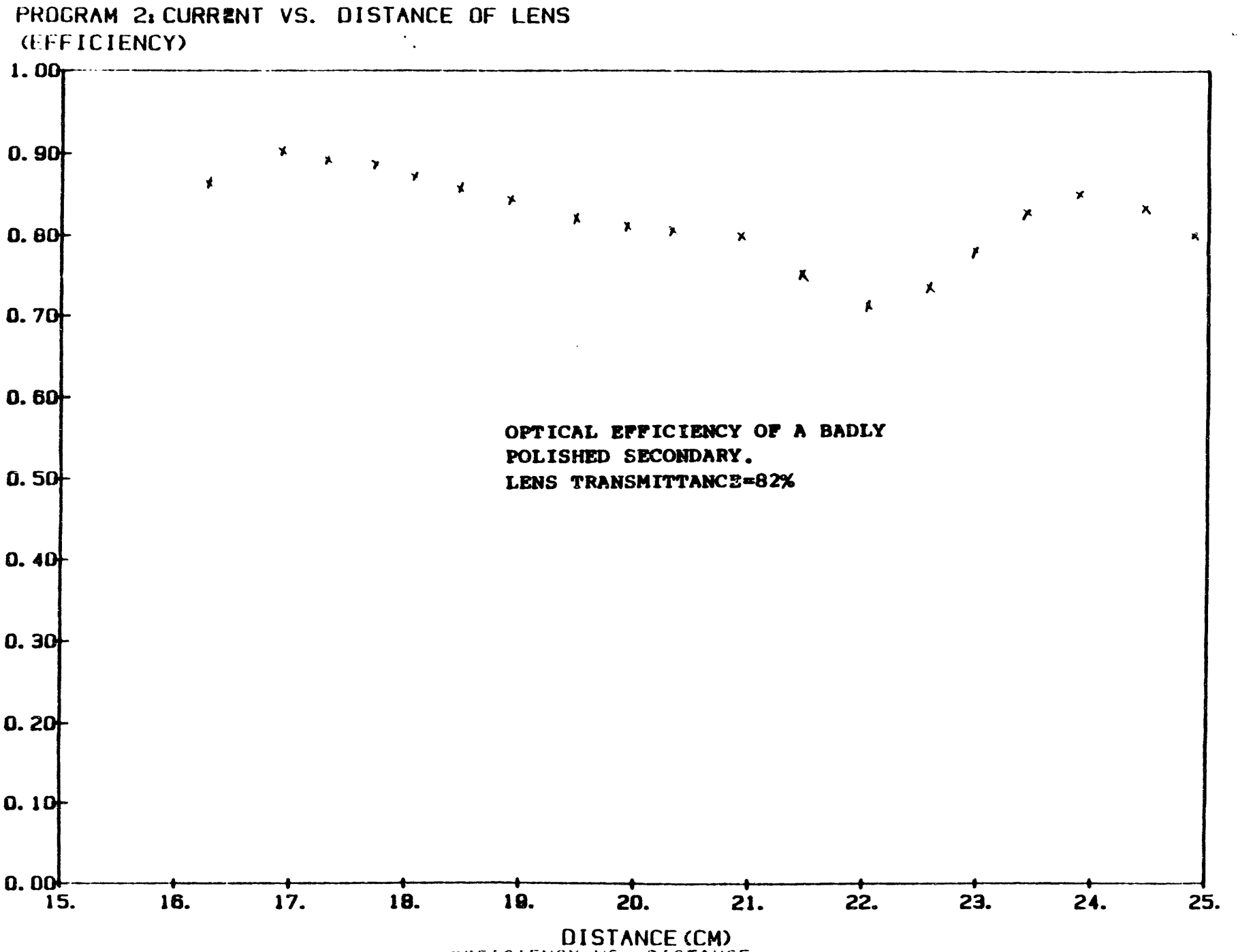



FIG.III.4 EFFICIENCY VS. DISTANCE

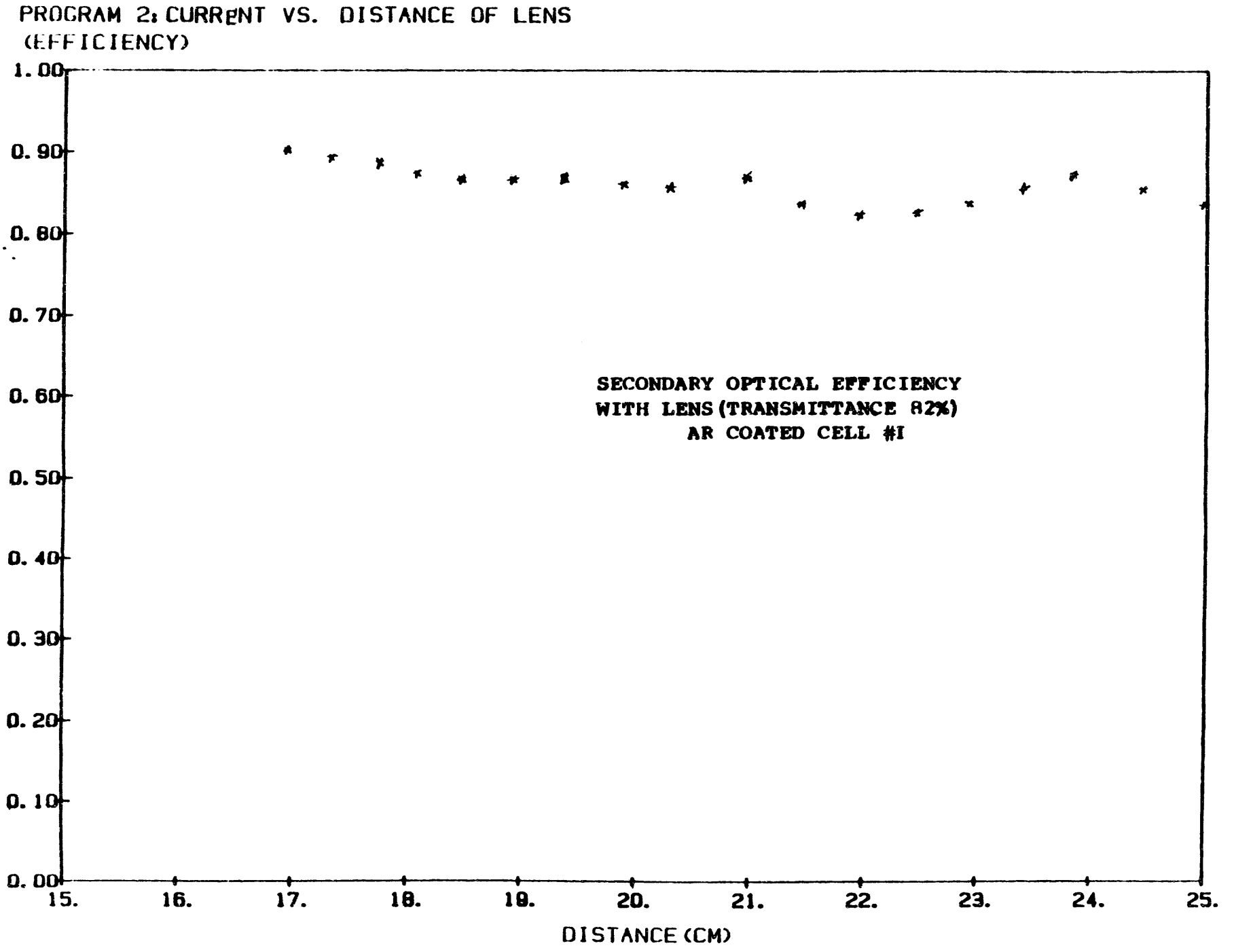



FIG.III.5 EFFICIENCY VS. DISTANCE

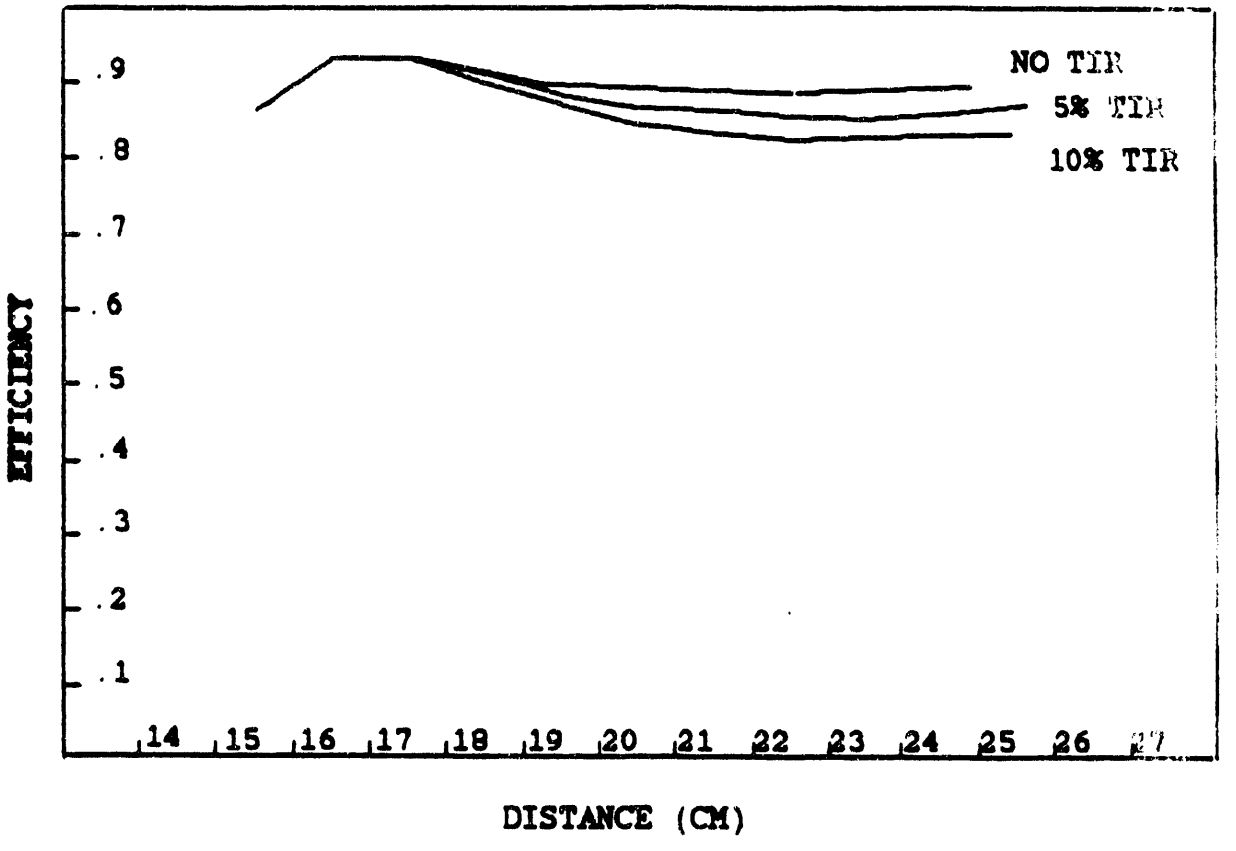



**FIG .III.6 EFFECIENCY VS. DISTANCE CURVE**

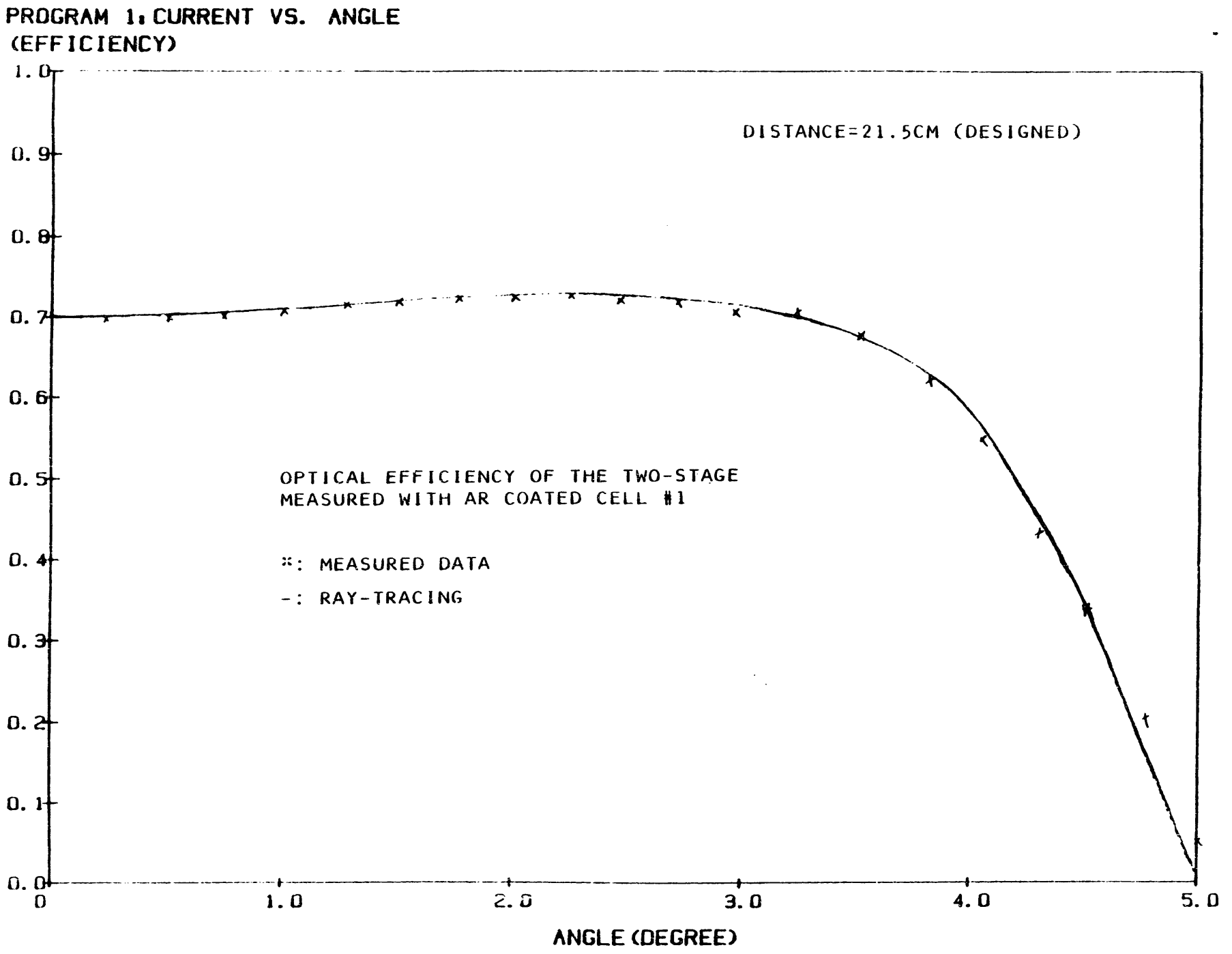



FIG.III.7 ANGULAR ACCEPTANCE

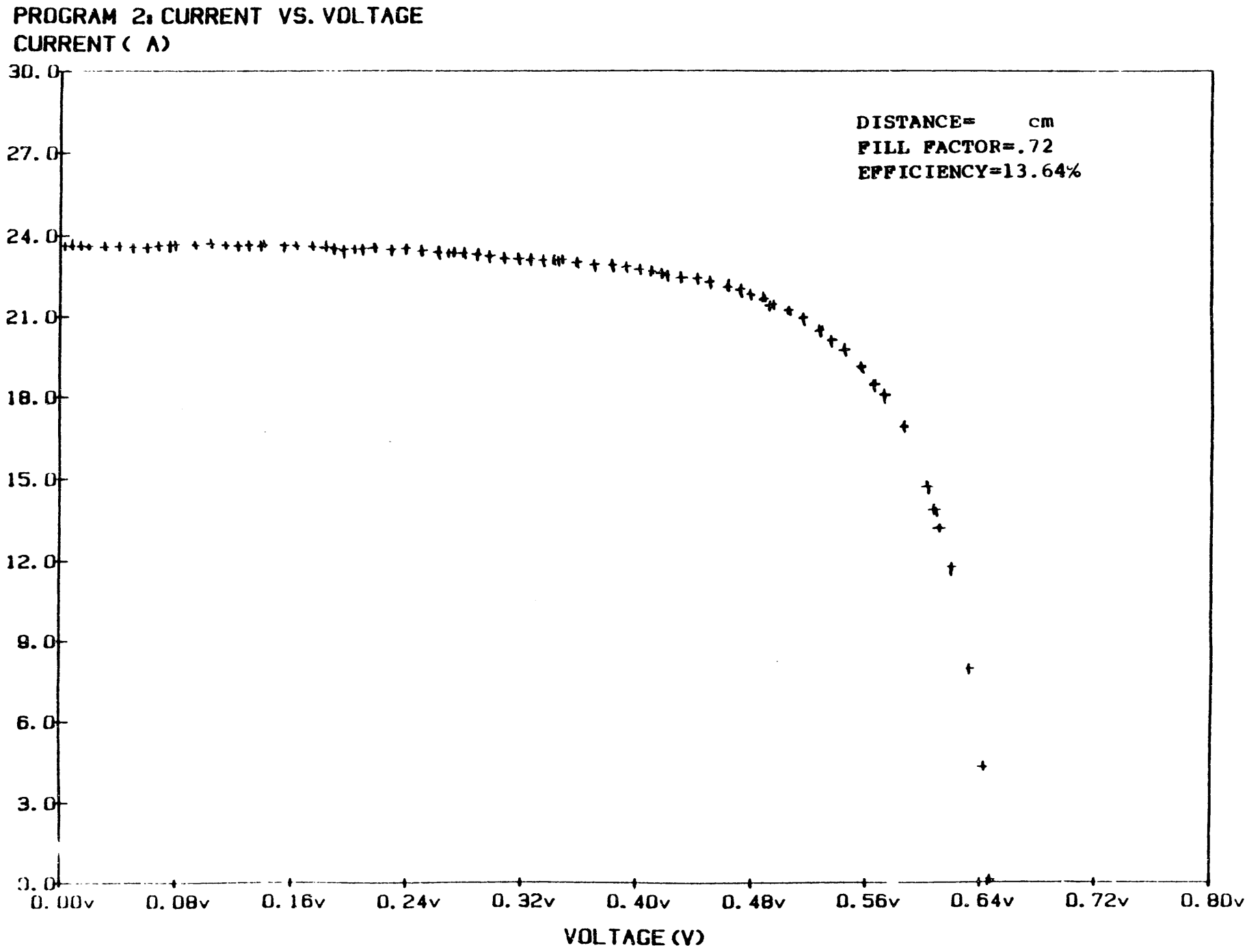



FIG.III.8 I-V CURVE OF CELL#2 ALONE

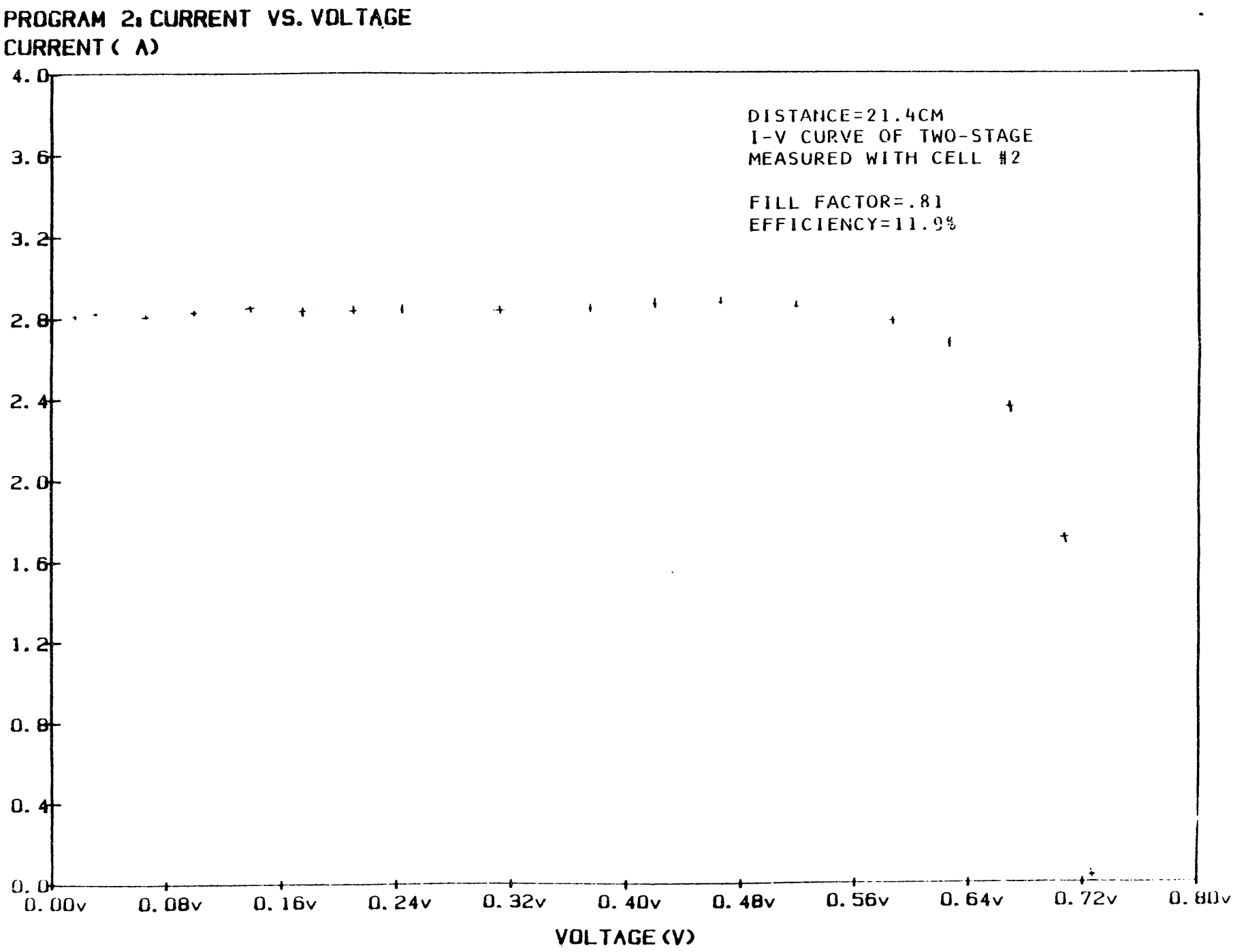



FIG.III.9 I-V CURVE OF TWO STAGE AT DESIGN DISTANCE

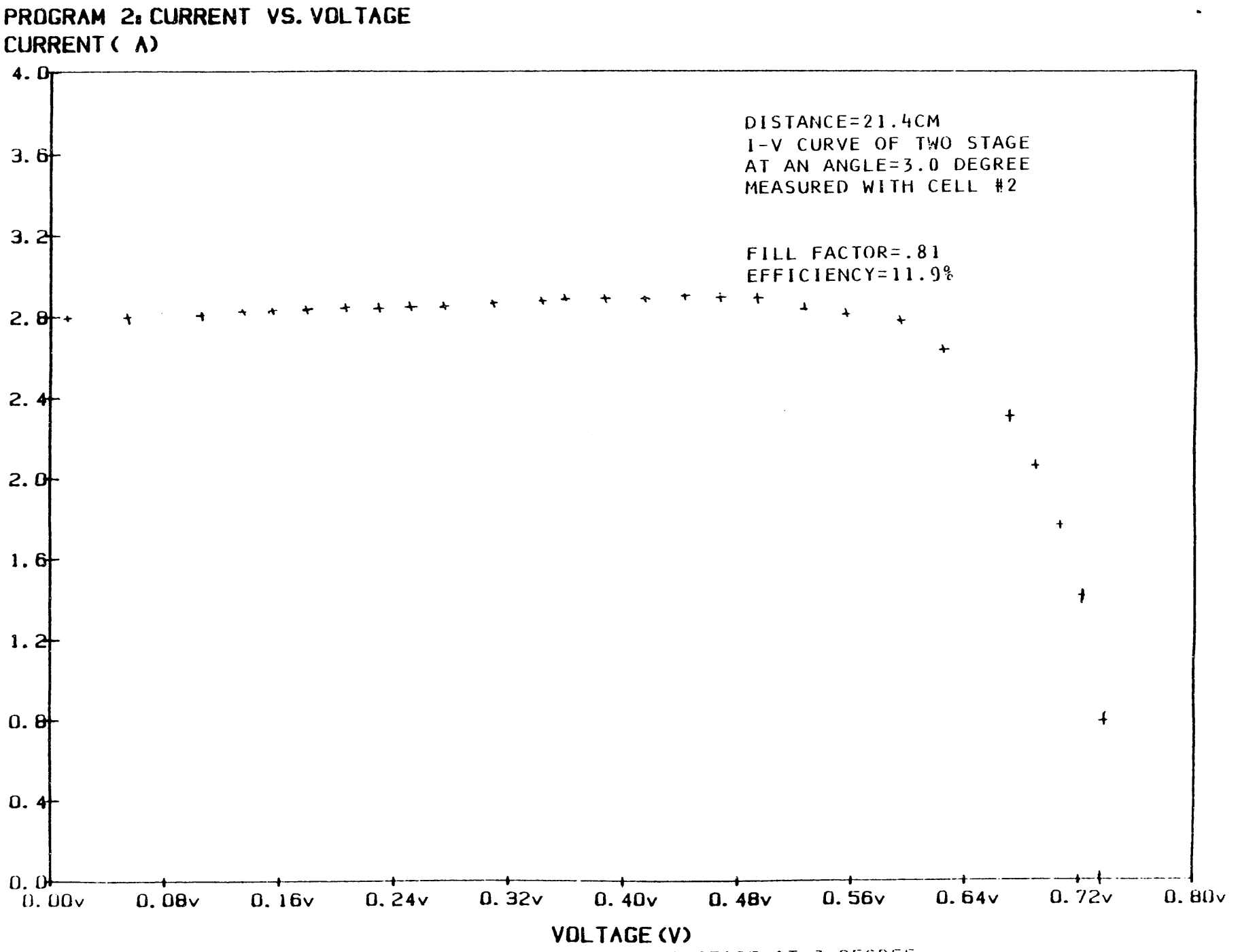



FIG.III.10 I-V CURVE OF TWO-STAGE AT 3 DEGREE

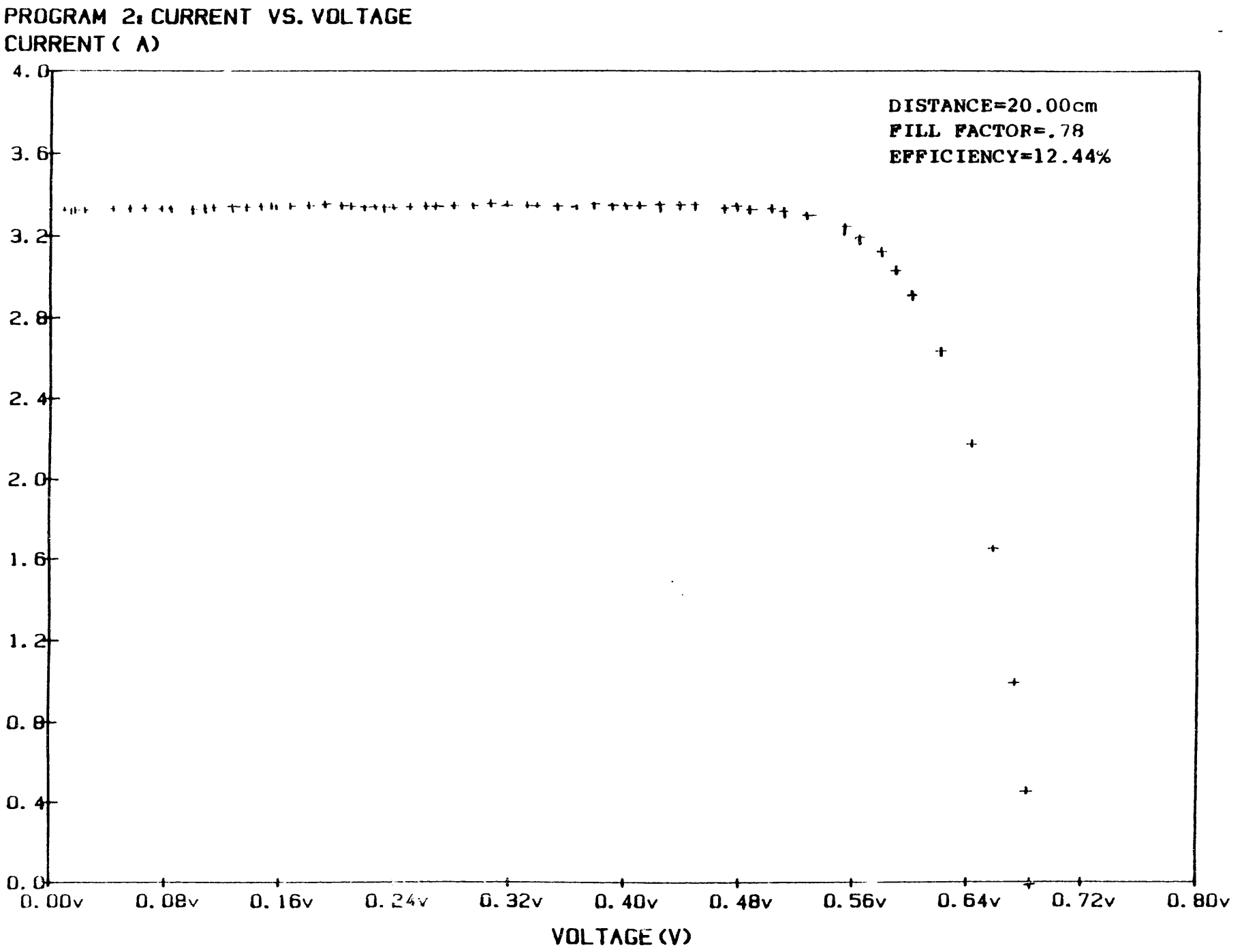



FIG.III.11 I-V CURVE OF LENS-CELL #2

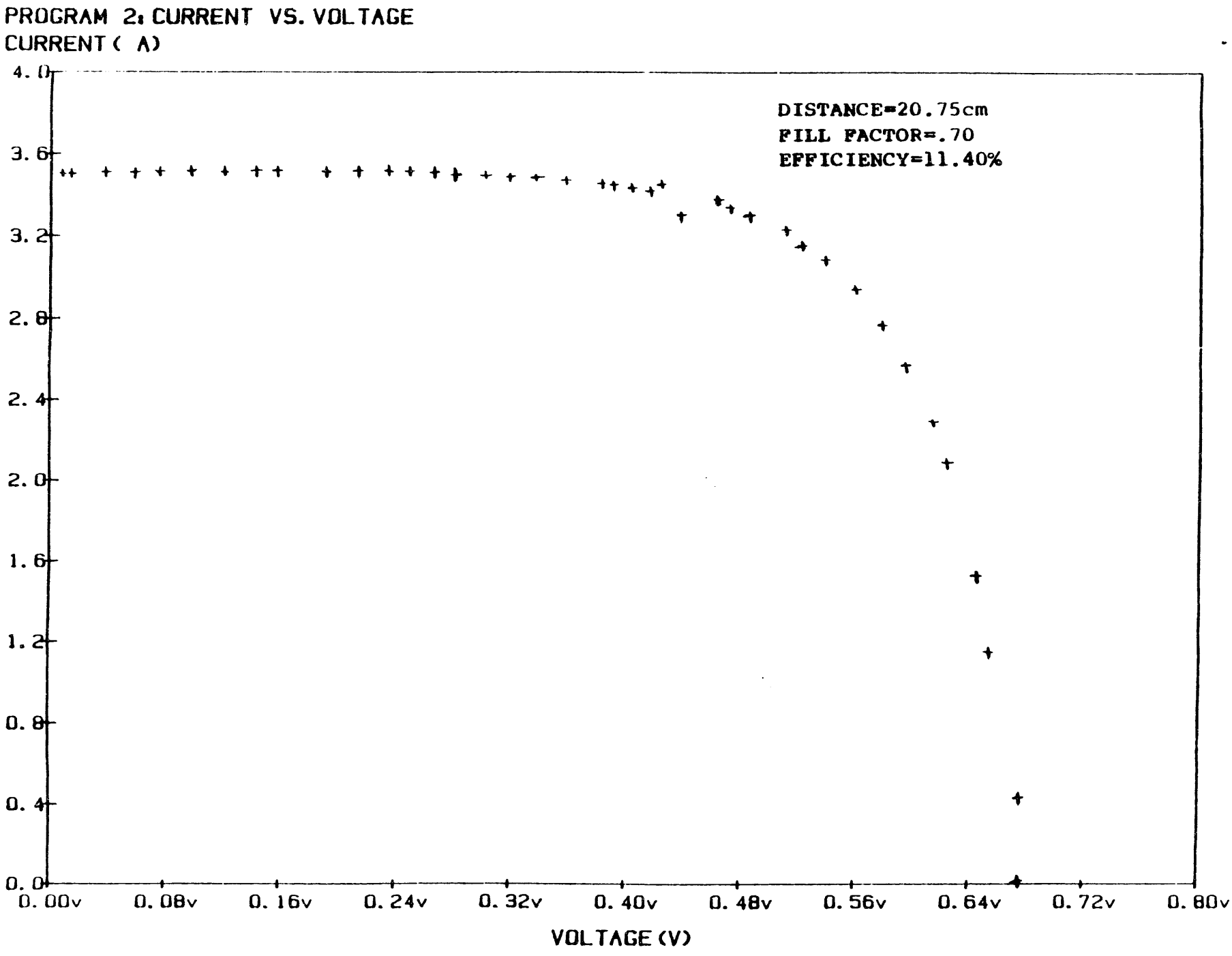



FIG.III.12 I-V CURVE OF LENS-CELL #2

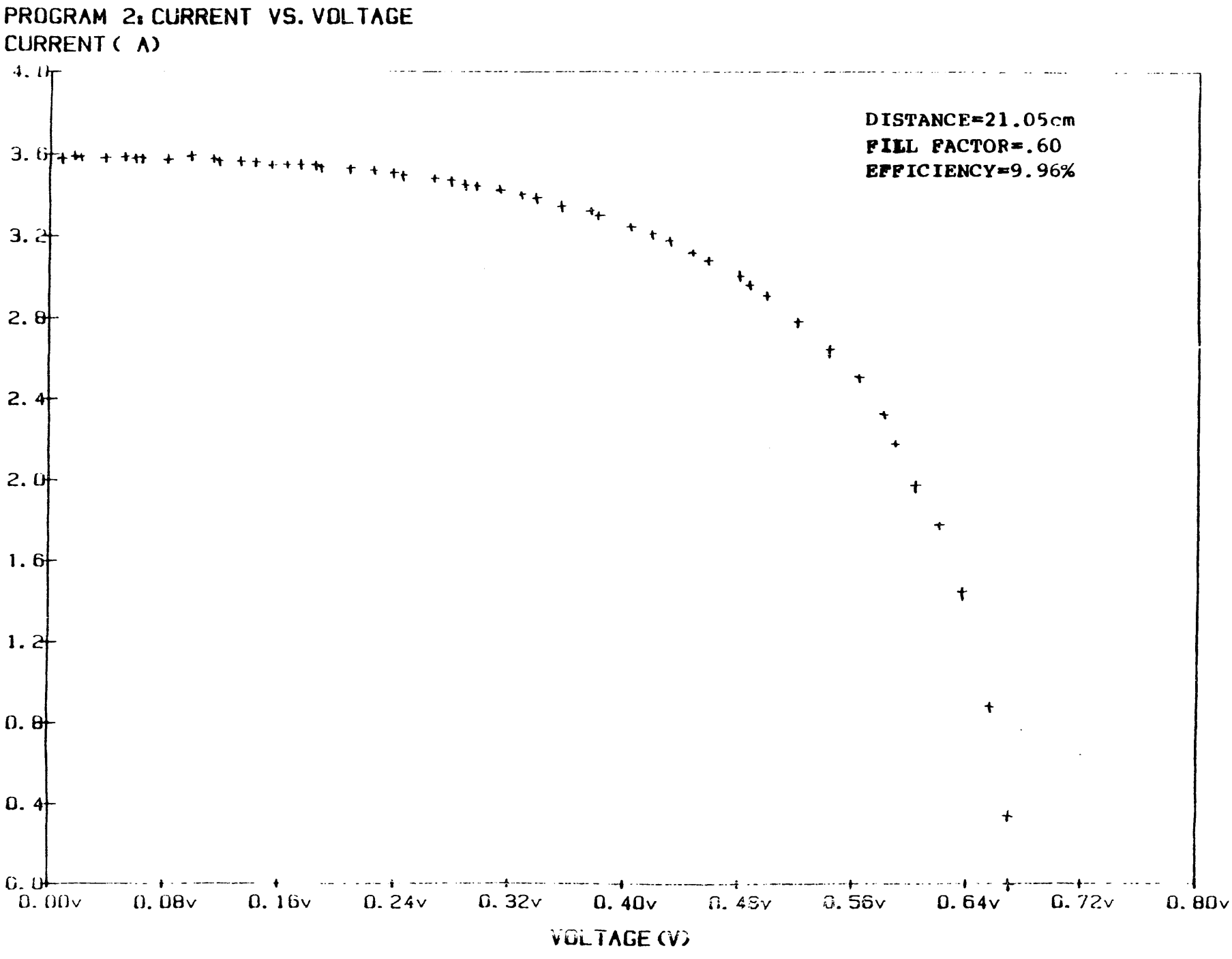



FIG.III.13 I-V CURVE OF LENS-CELL #2

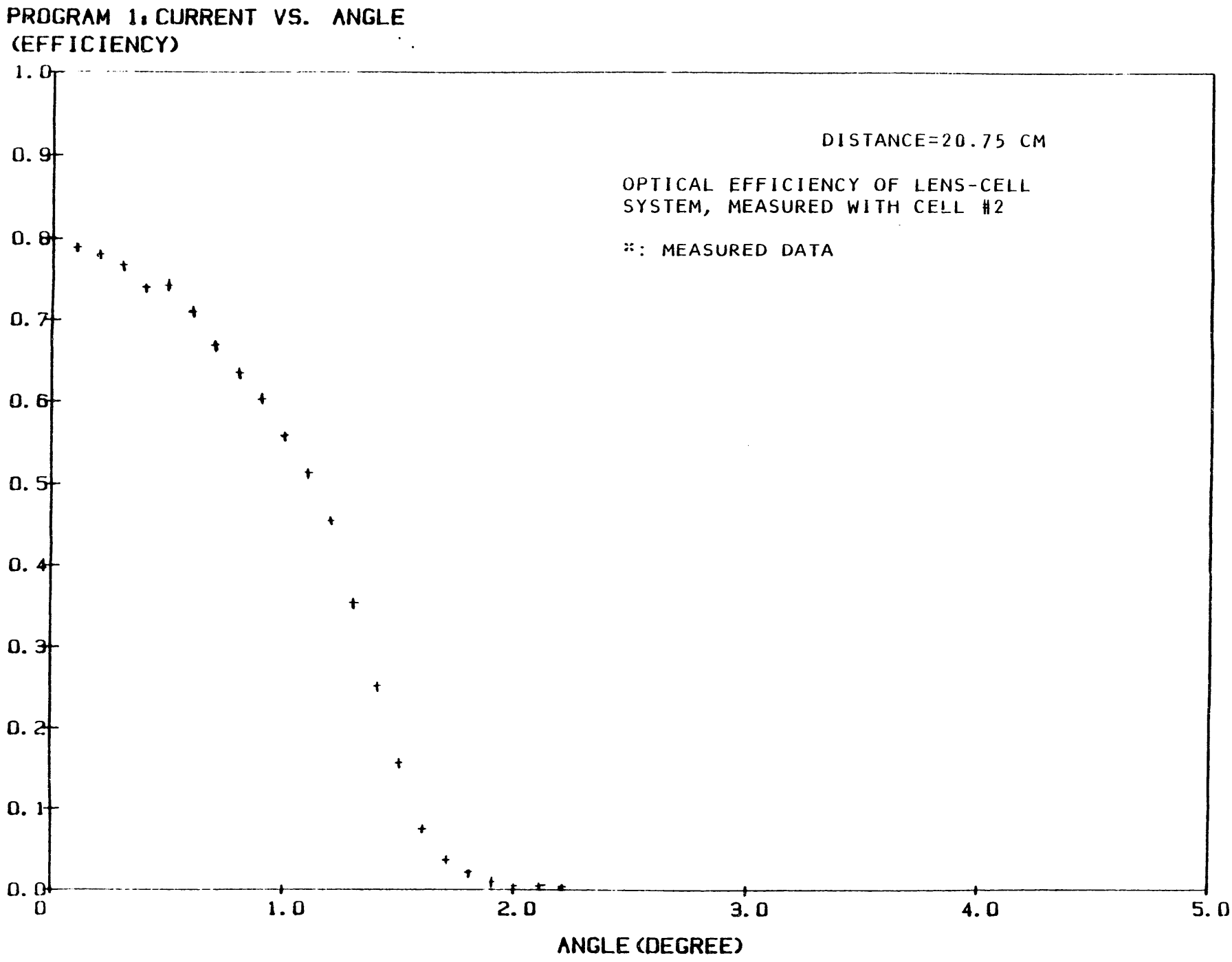



FIG.III.14 ANGULAR ACCCEPTANCE OF LENS-CELL #2

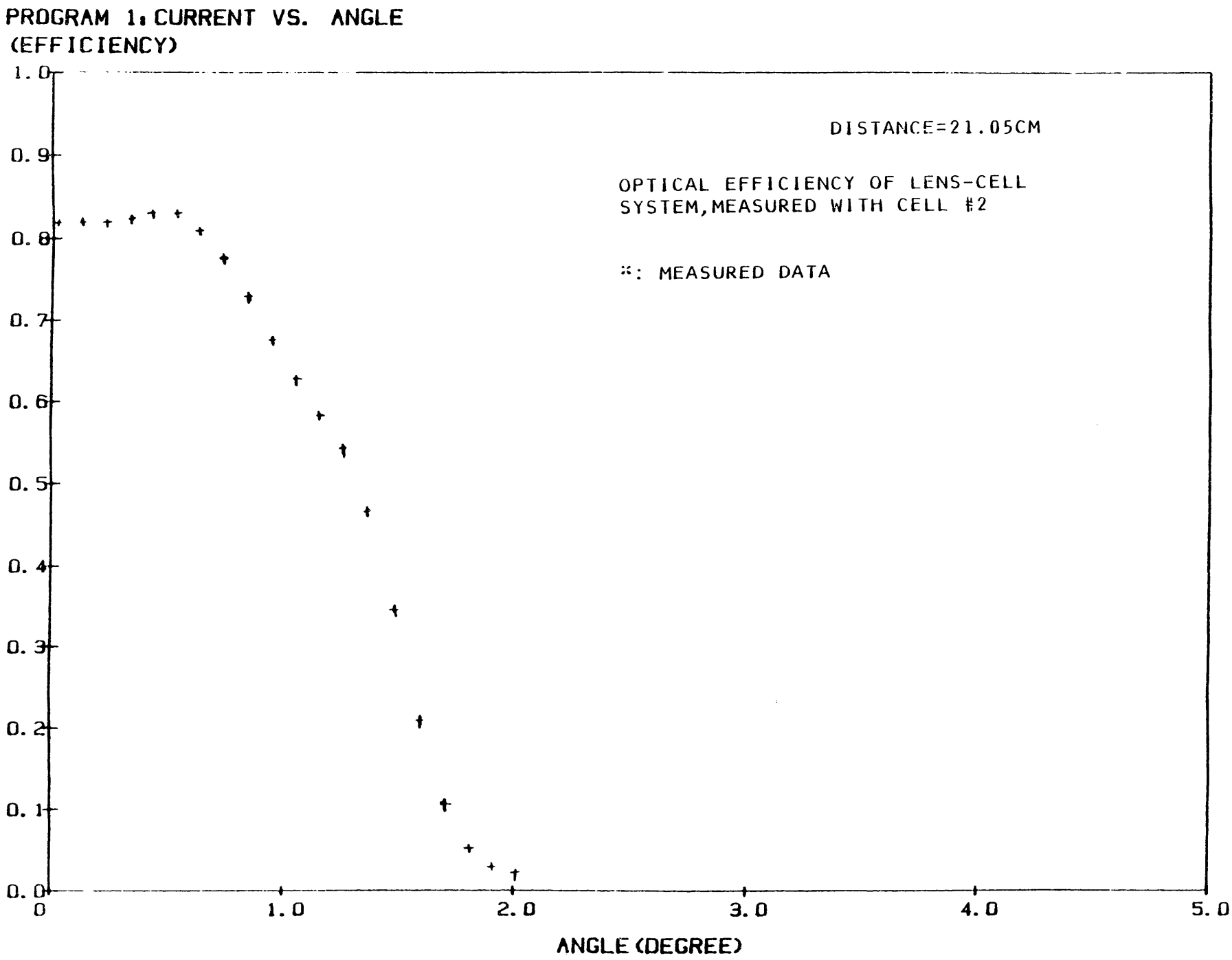



FIG.III.15 ANGULAR ACCEPTANCE OF LENS-CELL #2

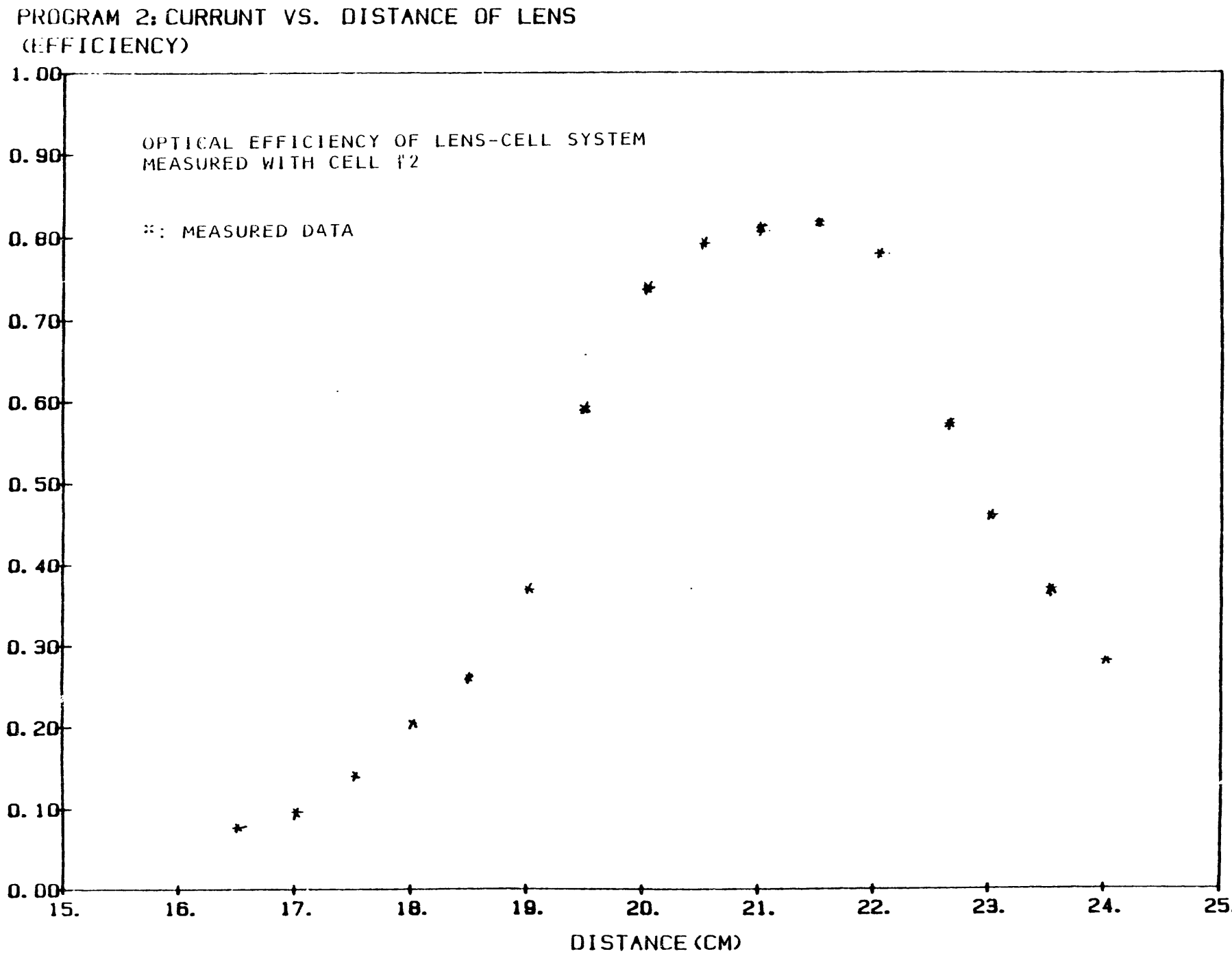



FIG.III.16 I-D CURVE OF LENS-CELL #2

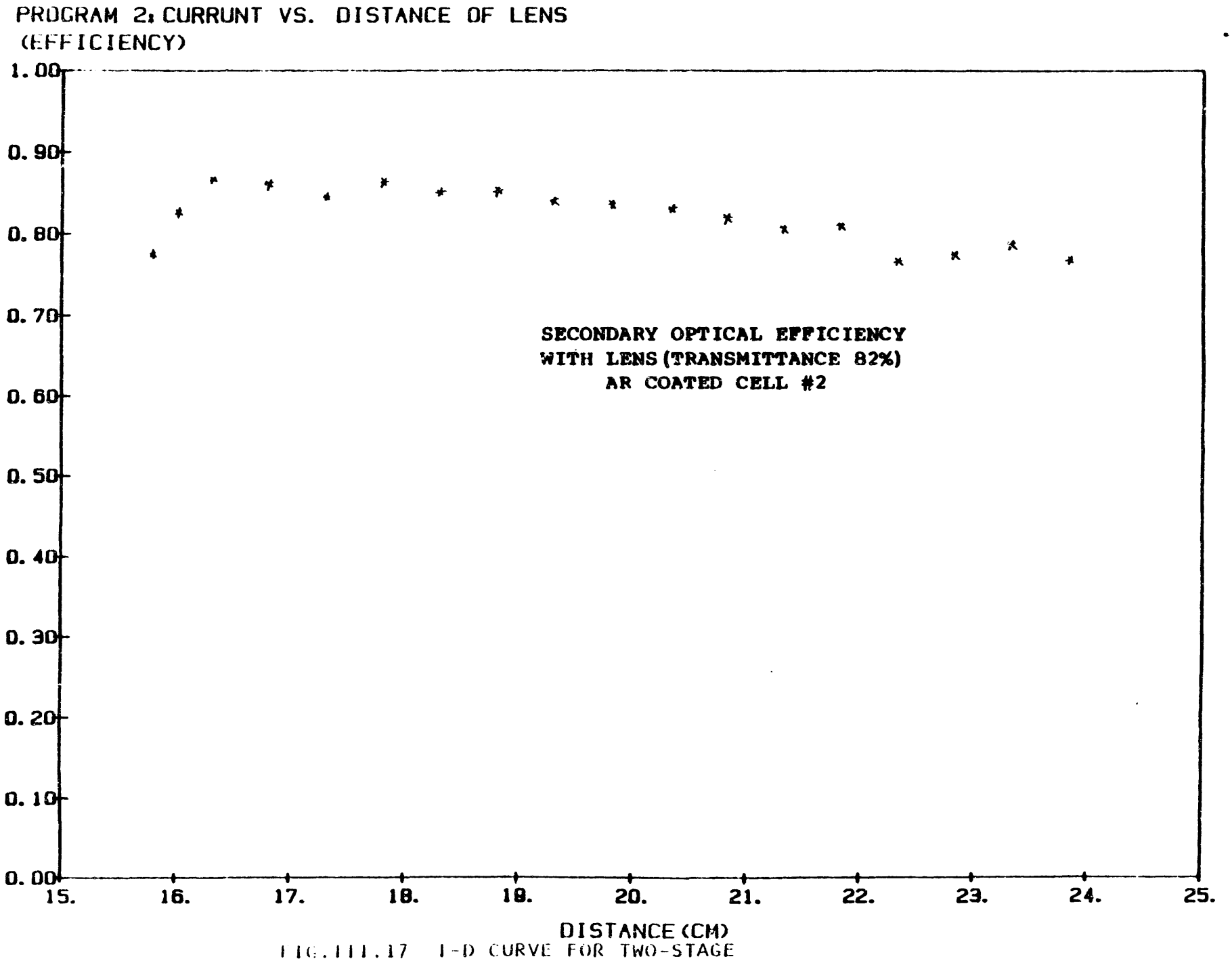



FIG.III.17 I-D CURVE FOR TWO-STAGE

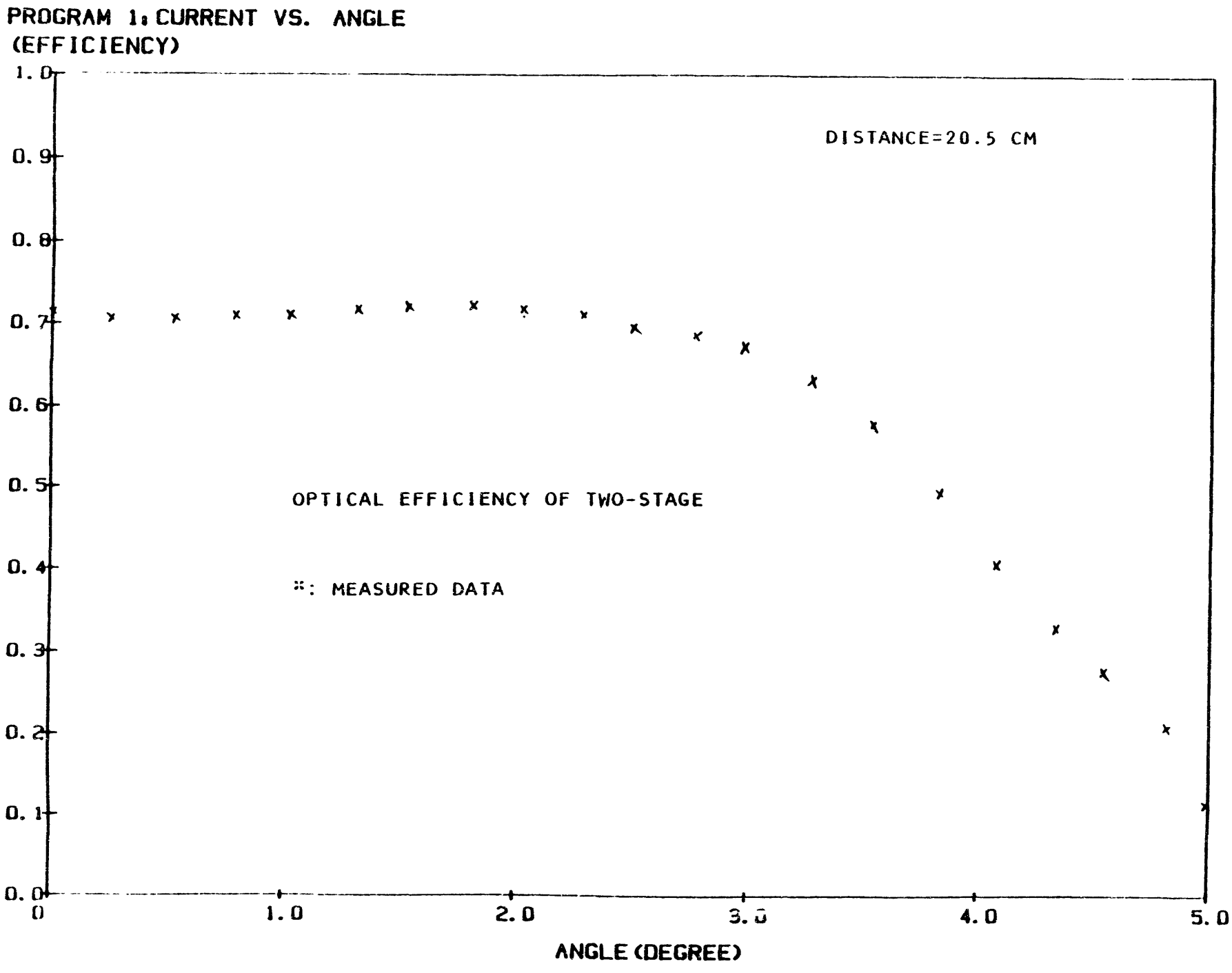



FIG.III.18 ANGULAR ACCEPTANCE CURVE OF TWO STAGE

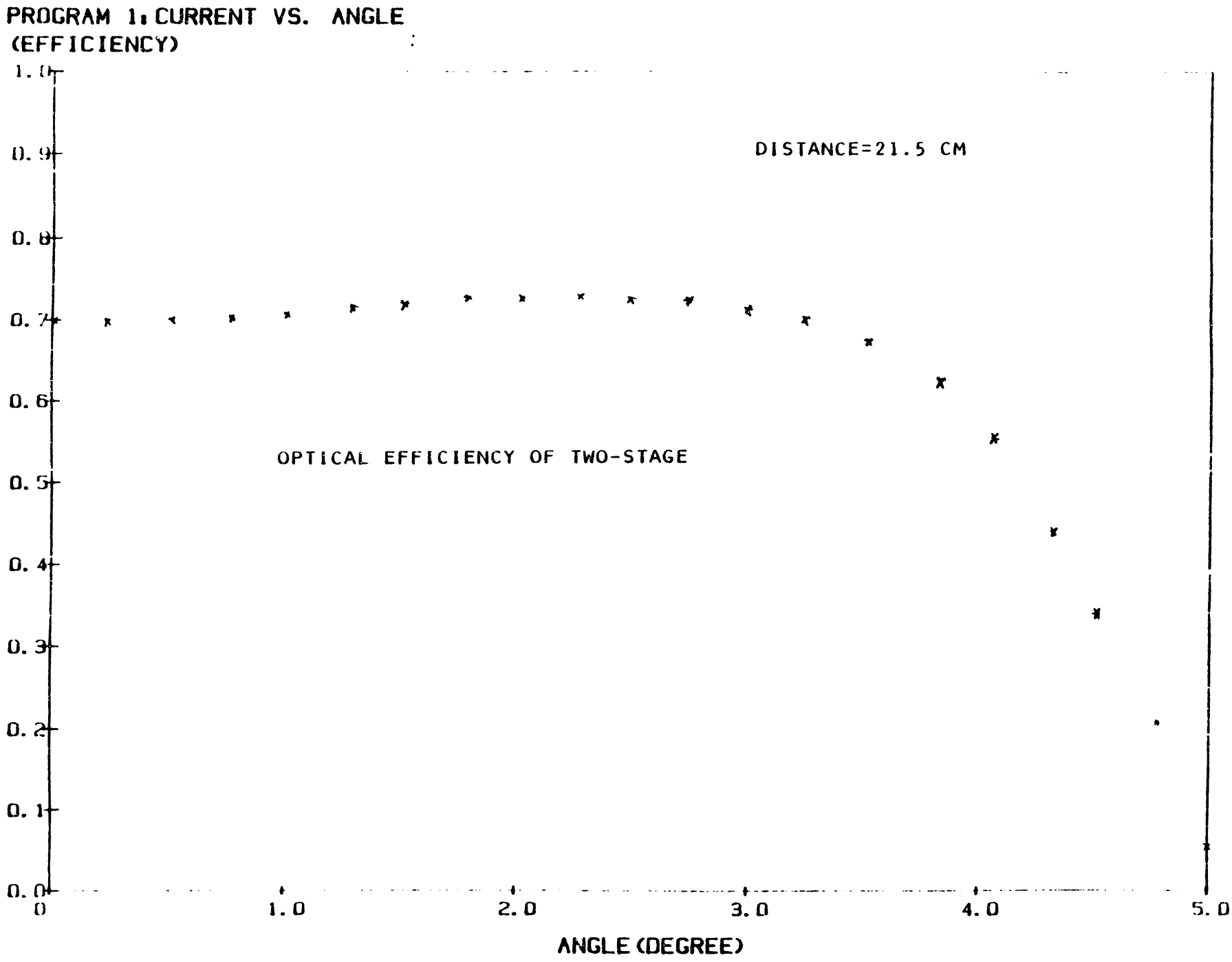



FIG.III.19 ANGULAR ACCEPTANCE CURVE OF TWO-STAGE

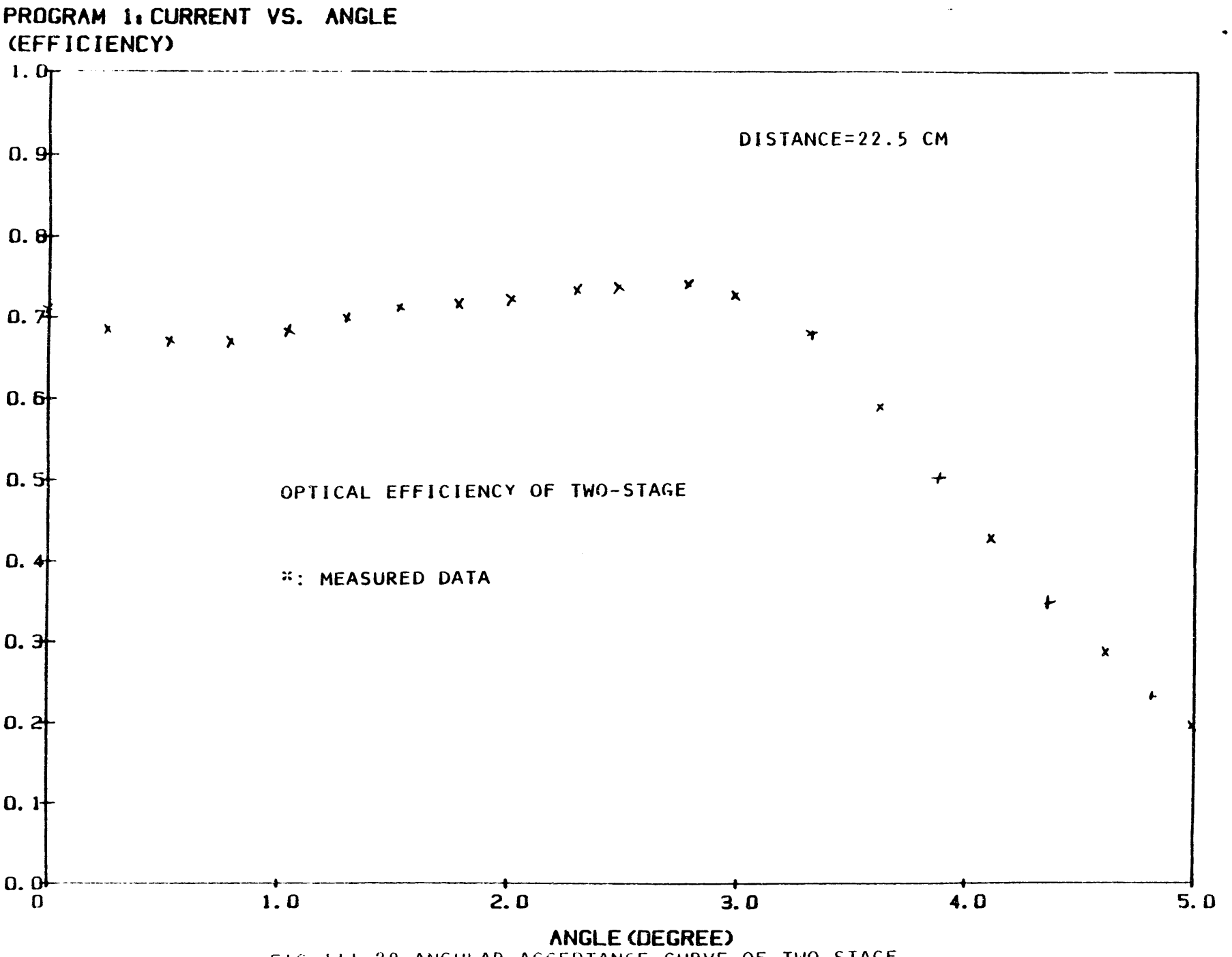



FIG.III.20 ANGULAR ACCEPTANCE CURVE OF TWO-STAGE

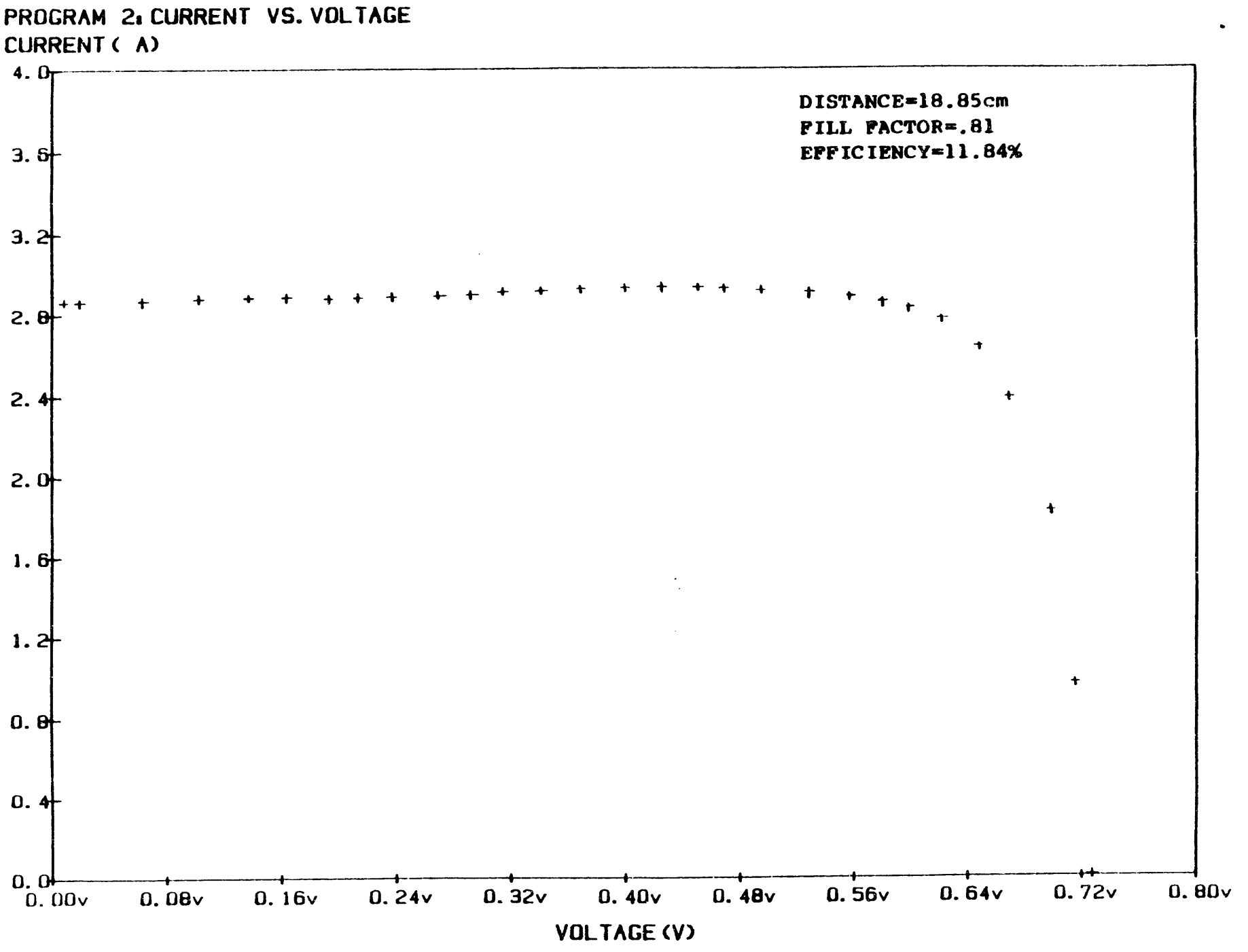



FIG.III.21 I-V CURVE OF TWO STAGE

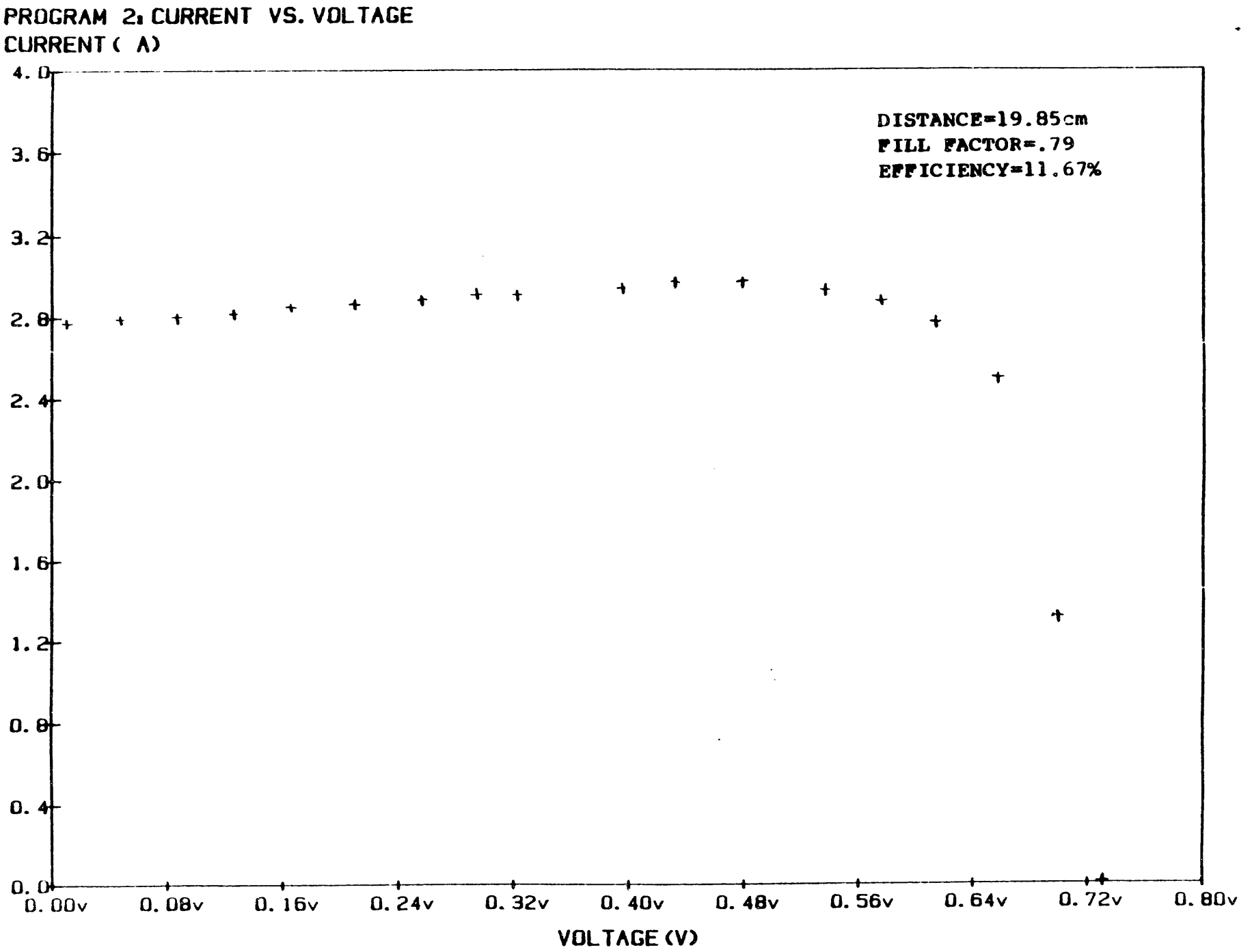



FIG.III.22 I-V CURVE OF TWO-STAGE

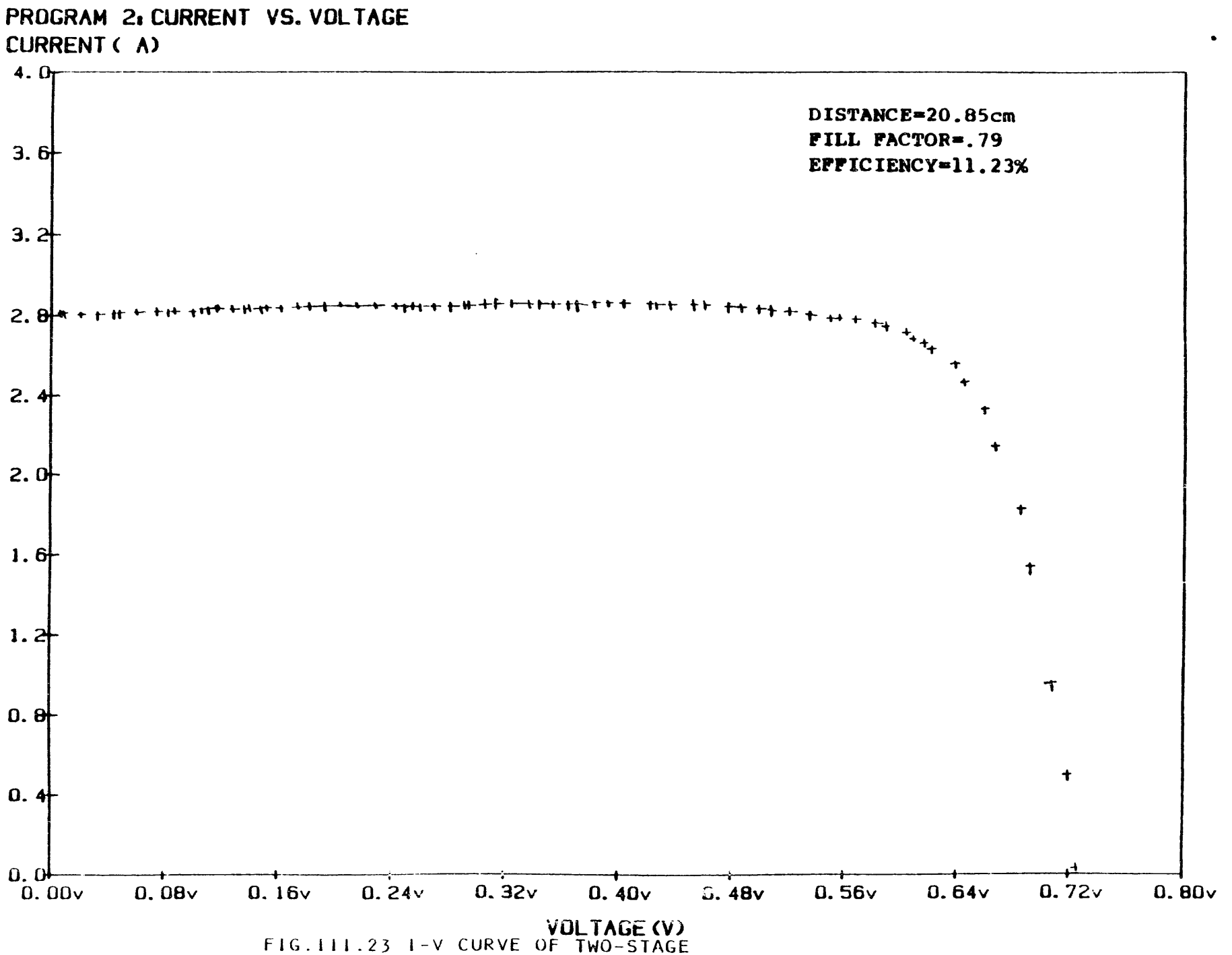



FIG.III.23 I-V CURVE OF TWO-STAGE

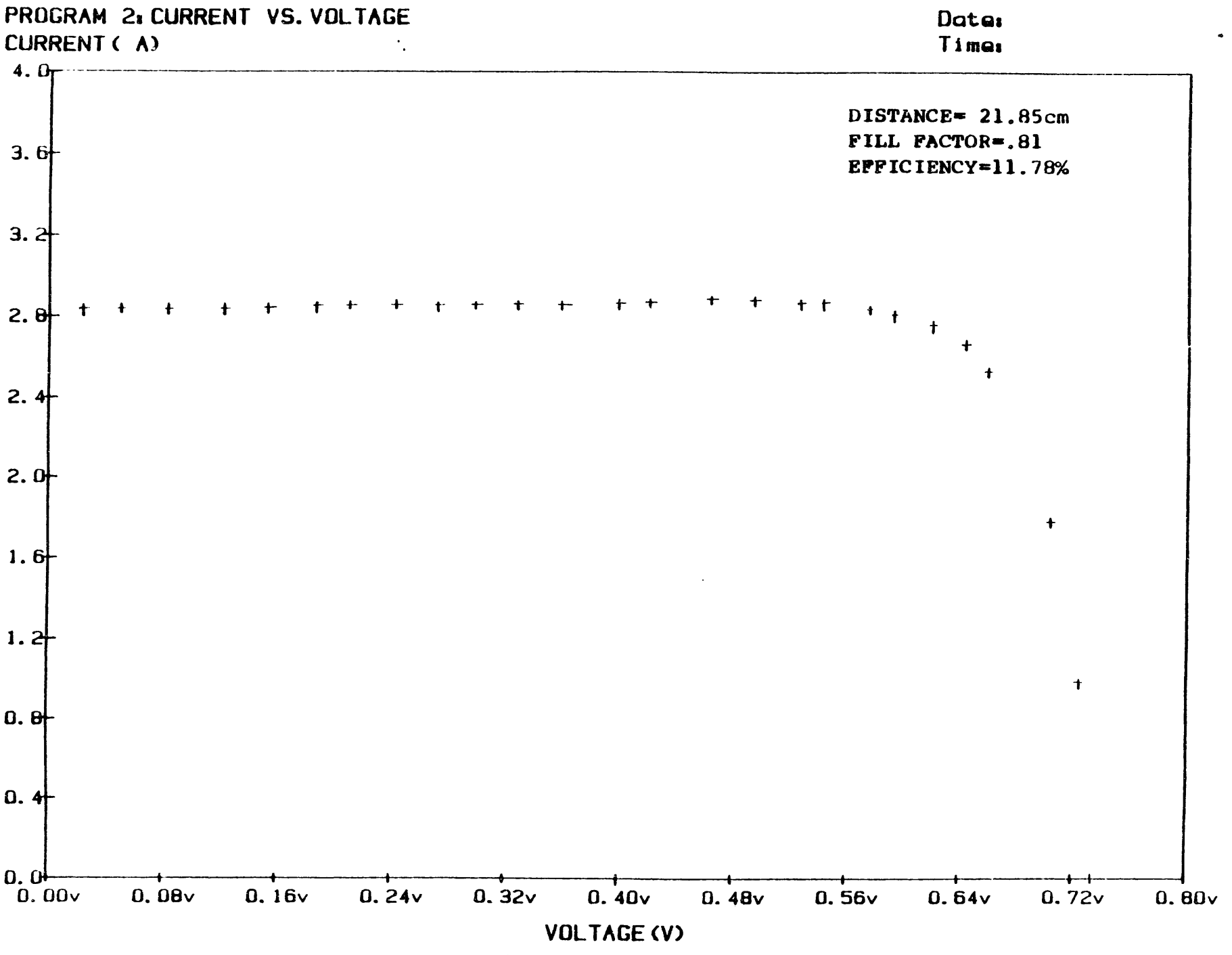



FIG.III.24 I-V CURVE OF TWO-STAGE

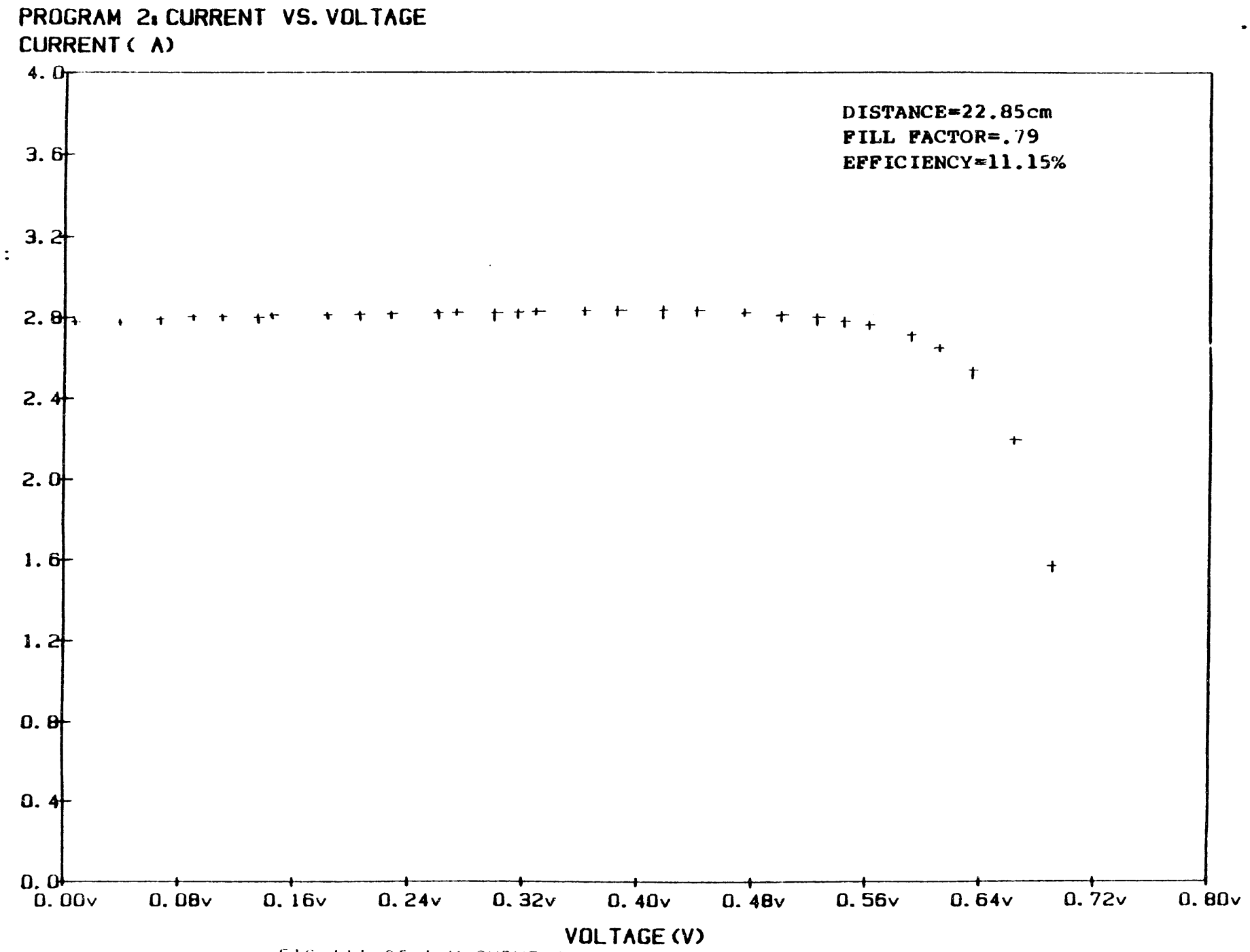



FIG.III.25 I-V CURVE OF TWO STAGE

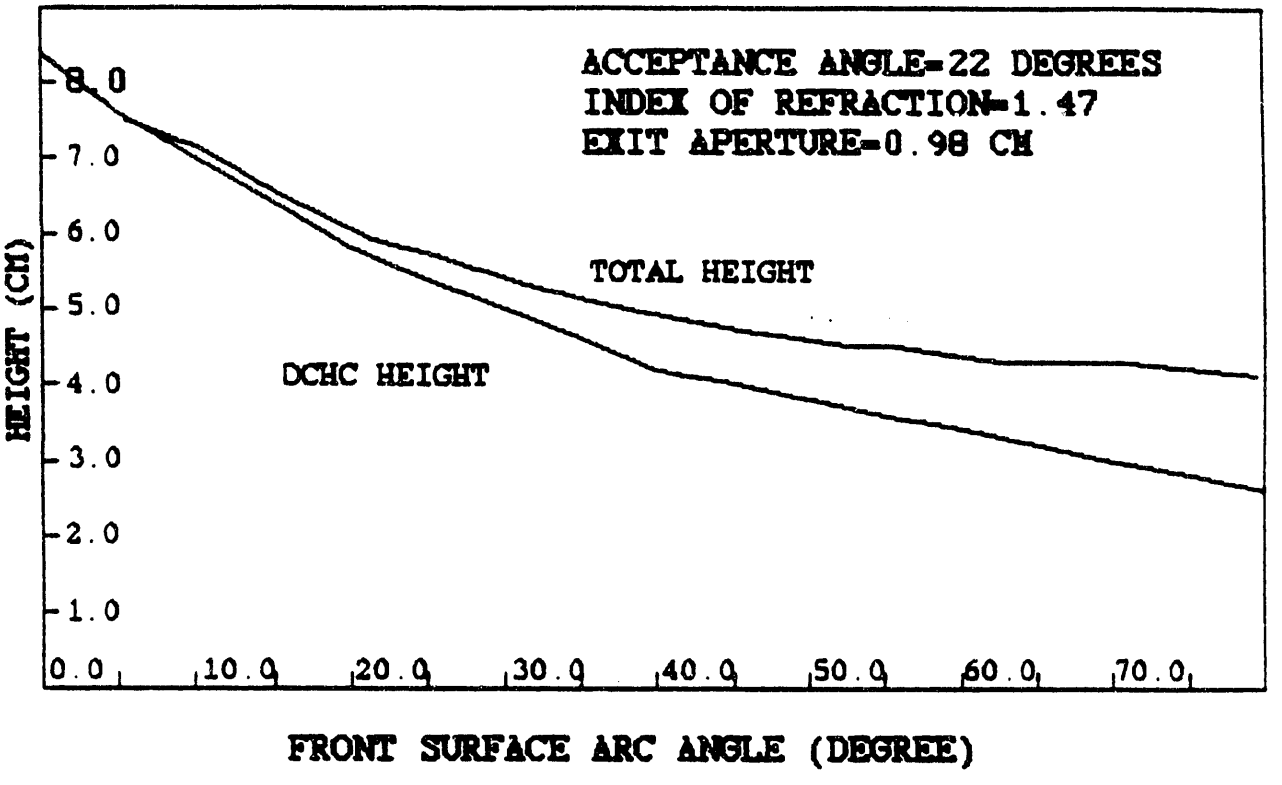



FIG. IV.1 **THE RELATIONSHIP BETWEEN LENS ARC ANGLE AND HEIGHT OF THE DIELECTRIC CONCENTRATOR DCHC**

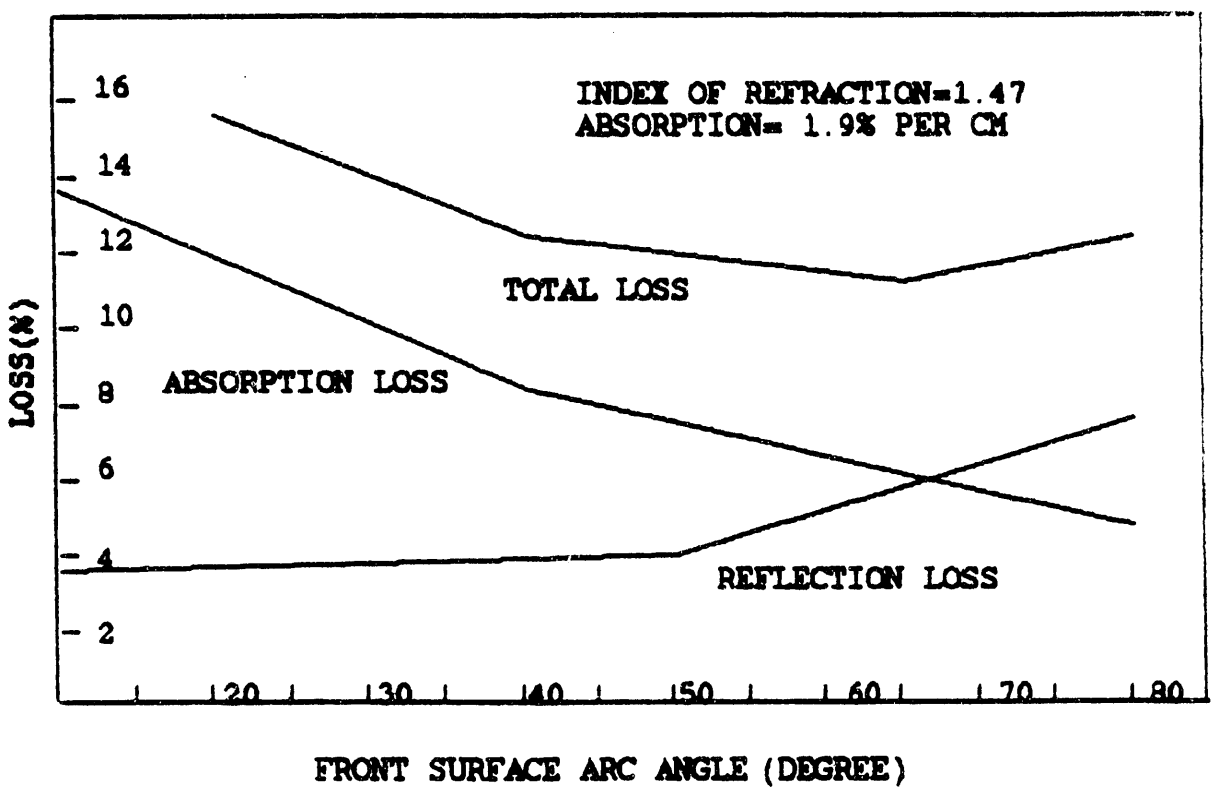



FIG. IV.2 **LOSSES VS. ARC ANGLE**

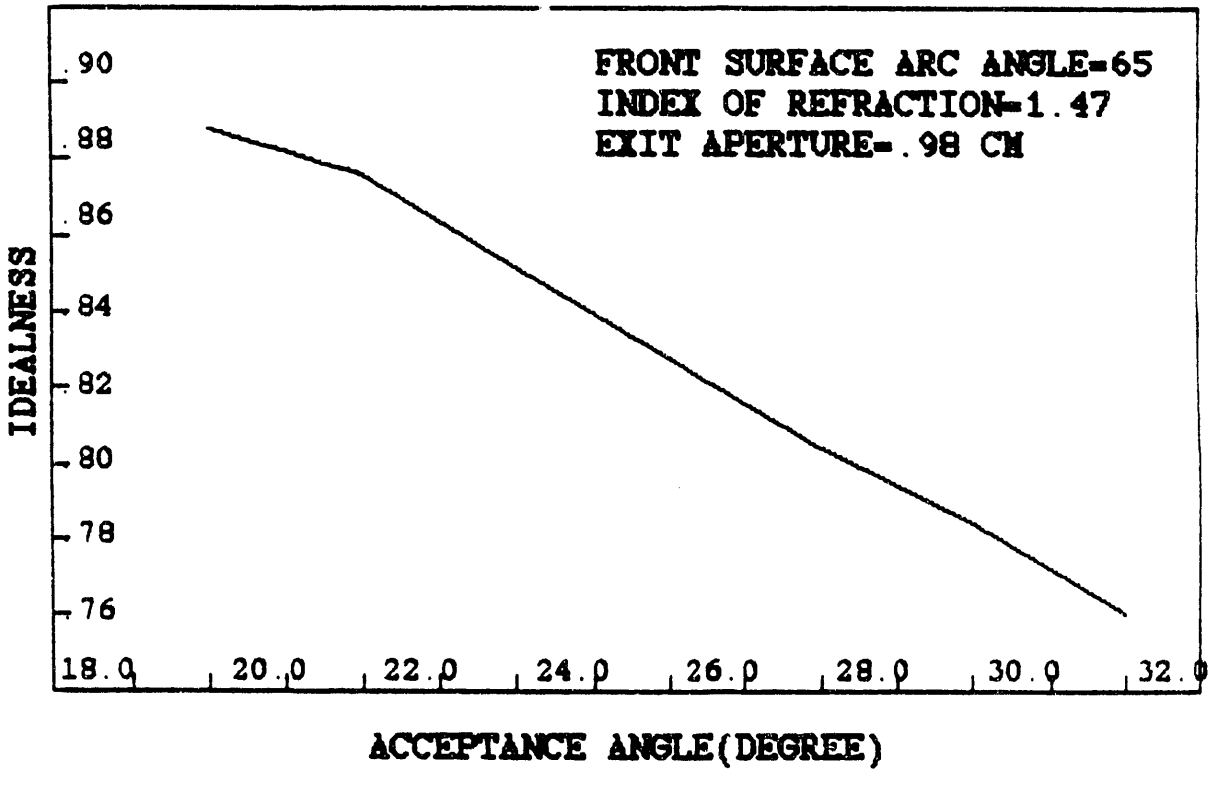



FIG. IV.3 **IDEALNESS VS. ACCEPTANCE ANGLE**

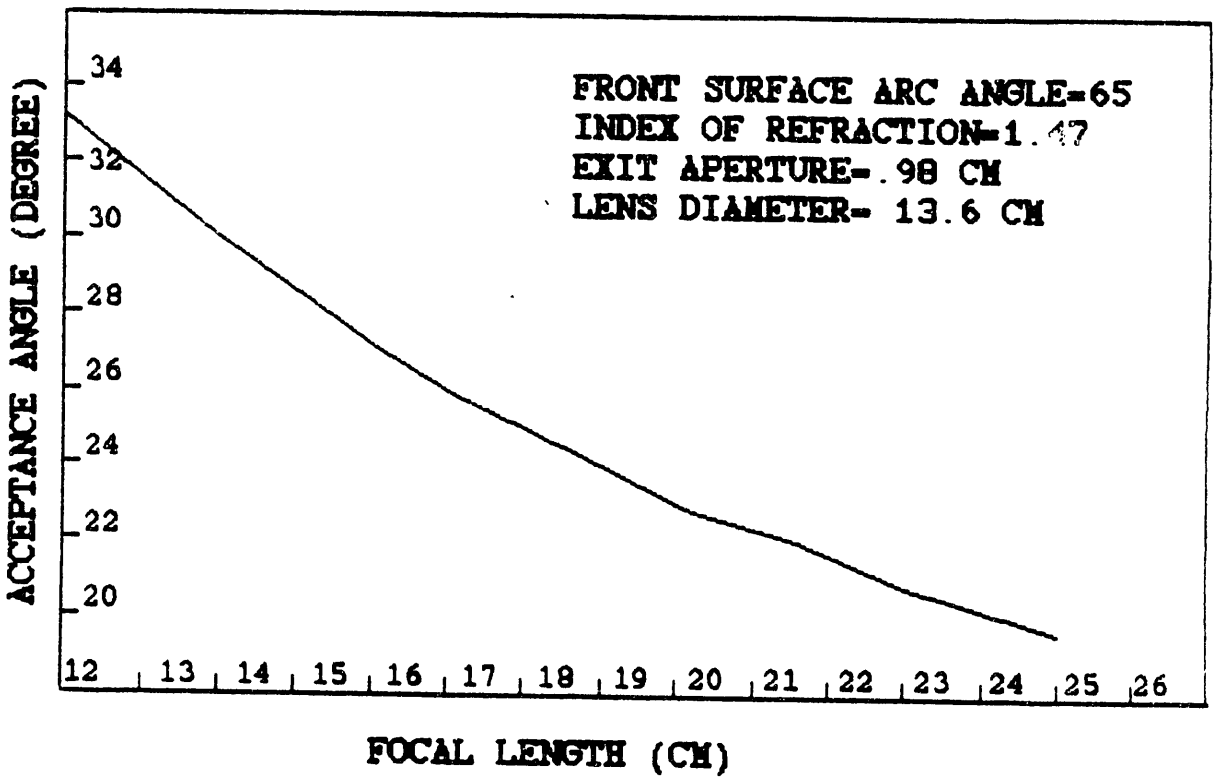



FIG. IV.4 **ACCEPTANCE ANGLE VS. FOCAL LENGTH**

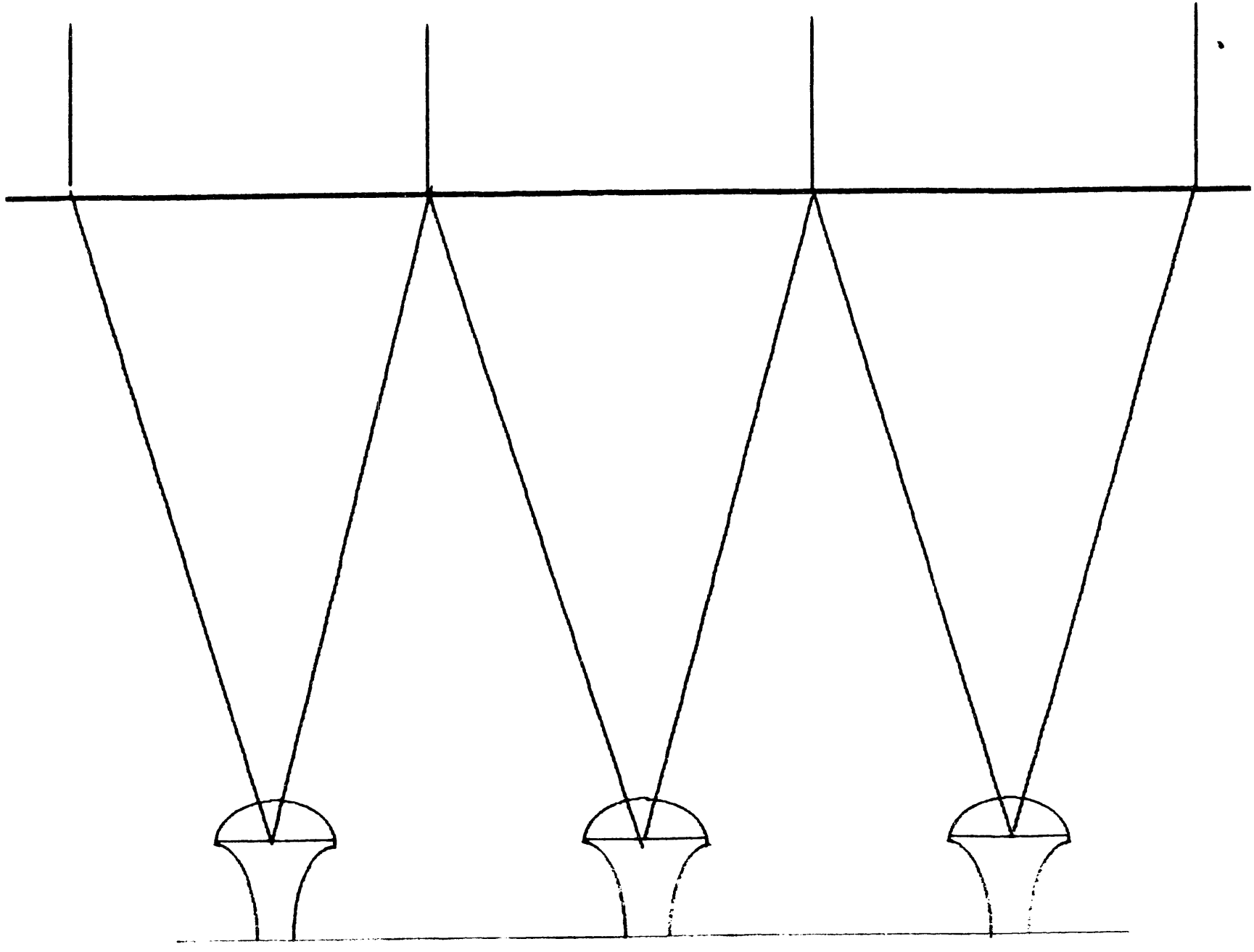


Fig.U.1 A MODULE CONCEPTUAL DESIGN

DATE
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12/22/92