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Photovoltaic conversion of solar energy using optical concentration systems

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Joint Research Centre
Ispra Establishment - Italy

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PHOTOVOLTAIC CONVERSION OF SOLAR ENERGY USING OPTICAL CONCENTRATION SYSTEMS

by

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ABSTRACT

Solar radiation is the largest inexhaustible and environmentally acceptable source of energy, but whereas thermodynamically speaking solar energy is of high quality, it is at the same time a source of low energy density. These aspects indicate the great potential but also the difficulty to use this form of energy economically. Basically there are two approaches to cope with this problem : development of low-cost energy converters and/or concentration of the incident radiation before conversion.

In the following paper we are treating briefly the economical aspect of photovoltaic converter/concentrator devices. A more detailed discussion will then be given concerning conditions which have to be fulfilled in order to make the concentration concept viable. These conditions are related to the quality of incident radiation, the behaviour of a photoelectric converter at high light intensities and to the availability of efficient low-cost concentrator devices.

The analysis of problems encountered in these three areas indicates that there is no major obstacle preventing a successful exploitation of the concept. The final assessment of the true economic impact of this approach will depend mainly on the further development of economic high intensity solar cells. The available light quality is for many areas sufficient and (partially new) solutions for concentrating devices do exist. Thus the combination of low cost cells and optical concentration is a possible way to shorten the time to reach the break-even point for a large scale utilization of solar electricity, it might even be the best way to reach that goal.

RESUME

La radiation solaire est la source d'énergie la plus importante, à la fois inexhaustible et acceptable du point de vue de l'environnement. Mais tandis que l'énergie solaire thermodynamiquement parlant est de haute qualité, elle est en même temps une source de faible densité d'énergie. Ces aspects montrent le grand potentiel mais aussi la difficulté d'utiliser cette forme d'énergie économiquement. Fondamentalement il existe deux approches pour résoudre ce problème : dévelopement de convertisseur d'énergie à bas prix et/ou concentration du rayonnement incident avant conversion.

Dans l'article qui suit nous traitons brièvement de l'aspect économique des systèmes conversion/concentration photovoltaiques. Une discussion plus détaillée est donnée ensuite au sujet des conditions qui doivent être remplies de façon à rendre le concept

de concentration viable. Ces conditions sont liées à la qualité du rayonnement incident, au comportement du convertisseur photo-electrique aux hautes intensités lumineuses et à la possibilité d'utiliser des systèmes de concentration efficace et bon marché.

L'analyse des problèmes rencontrés dans ces trois domaines indique qu'il n'y a pas d'obstacle majeur s'opposant à une exploitation de ce concept couronnée de succès. L'évaluation finale de l'impact économique réel de cette approche dépend principalement du dévelopement approfondi de cellules solaires économiques à haute intensité. La qualité de la lumière disponible est suffisante dans de nombreuses regions et des solutions (partiellement nouvelles) pour les systèmes de concentrations existent réellement. Ainsi la combinaison de cellules bon marché et de la concentration optique est un moyen possible de raccourcir le temps nécessaire pour arriver au point d'équilibre pour l'utilisation sur une large échelle de l'electricité solaire. C'est peut-être la meilleure façon d'atteindre à ce but.

1. INTRODUCTION

The large scale utilization of solar radiation could eventually be used to substitute to a large extent fossil fuels and even nuclear power. The time at which a transition from non-renewable energy sources to this virtually inexhaustible and environmentally attractive source will make an impact depends in first place on the economics of solar energy conversion systems.

Since solar radiation is energy of high quality direct conversion to electricity is a possible and efficient process. This has been shown most clearly and since many years by its application in space technology. Now, in space there is little or no competition from other energy sources, whereas on earth the competition is enormous and especially by techniques which have been developed for long time and by big industry. On earth solar cells have proven their usefulness especially for those small energy applications where competitive energy sources have either high cost to energy ratios or where problems exist with maintenance or accessibility. Present panel costs are in the order of 20-30 $/peak watt. A look at the cost distribution of a complete panel (Fig. 1) indicates that the problem of reducing the price by two or three orders of magnitude in order to be competitive with conventional large scale electricity producers might be a task which could be beyond our technological possibilities for a long time. Mass production or economy of scale alone will certainly not solve this problem and even a substantial improvement in large area silicon single crystal production might not be sufficient.

Since one of the main reasons for the high cost of solar energy lies in its low energy density a reduction of costs could be expected from concentrating the incident radiation [1-5]: The increase of energy flux on the converter would reduce the necessary solar cell area and may even lead to an improvement of the economy of scale of solar systems.

It has been stated that for very large solar power plants focusing thermal systems might offer an advantage because of their potentially better conversion efficiency (about 50-60% of the Carnot value). However, at least for smaller and especially for distributed applications photovoltaic systems could still be the better

COST DISTRIBUTION FOR PHOTOVOLTAIC ENERGY CONVERSION SYSTEMS

COMPONENTS	1975 $/W peak	1980 $/W peak	1985 $/W peak	1990 $/W peak
SOLAR CELL	12	3	1	0.25
purified Si	0.2 (70 $/kg)	0,15	0.1	0.05
single cystal cell blanks	2	1	0.5	0.1
cell manufacture (labour + materials)	10 (6+4)	2	0.5	0.1
ARRAY ASSEMBLY (labour + materials)	10 (8+2)	2	1	0.2
ADD. SYSTEM COMPONENTS	2	1	0.5	0.2
TOTAL SYSTEM	24	6	2.5	0 65
c/kWh for $E_{in} = 1600 \frac{kWh}{m^2 y}$	210	53	22	6

Figure 1

choice, it is also expected that the maintenance and especially the cooling of these conceptionally simpler systems would be less expensive. The decisive argument to favour one or the other version would be of course the power rate per kilowatt-hour which could be achieved in a prototype installation.

An important advantage for solar cell/optical concentrator systems versus conventional photoelectric systems lies in the reduction in energy pay-back time. At present one estimates [6] that the energy needed to produce a solar cell array amounts to about 3000 kWh/m^2. Thus one would need about 20 years of operation at an average input of 4 kWh/m^2d to recover the energy which was needed to produce that panel : At 5 c/kWh the cost for this energy corresponds even so to only about 5% of the actual panel price. Since the energy to produce concentrators can be much smaller, substantial energy savings could be expected if one would use the concentration concept.

Under certain assumptions on converter behaviour, incident radiation, money cost etc., one can estimate the economic impact of this concept on specific energy costs (Fig. 2). One sees that - depending on the cost per converter area - low, medium or high concentration factors will be necessary to meet certain objectives.

However, the concentration approach could become a viable solution only if a number of necessary conditions are fulfilled : (1) the incident radiation must be of sufficient quality, (2) the photoelectric system must be able to work efficiently at high light intensities and (3) one has to find economic optical systems which concentrate the radiation from a time and position variable source. The following sections are mainly concerned with a discussion of these conditions, they are partially based on a more detailed report [7], which will contain also results of experimental work done at Ispra.

2. INCIDENT RADIATION

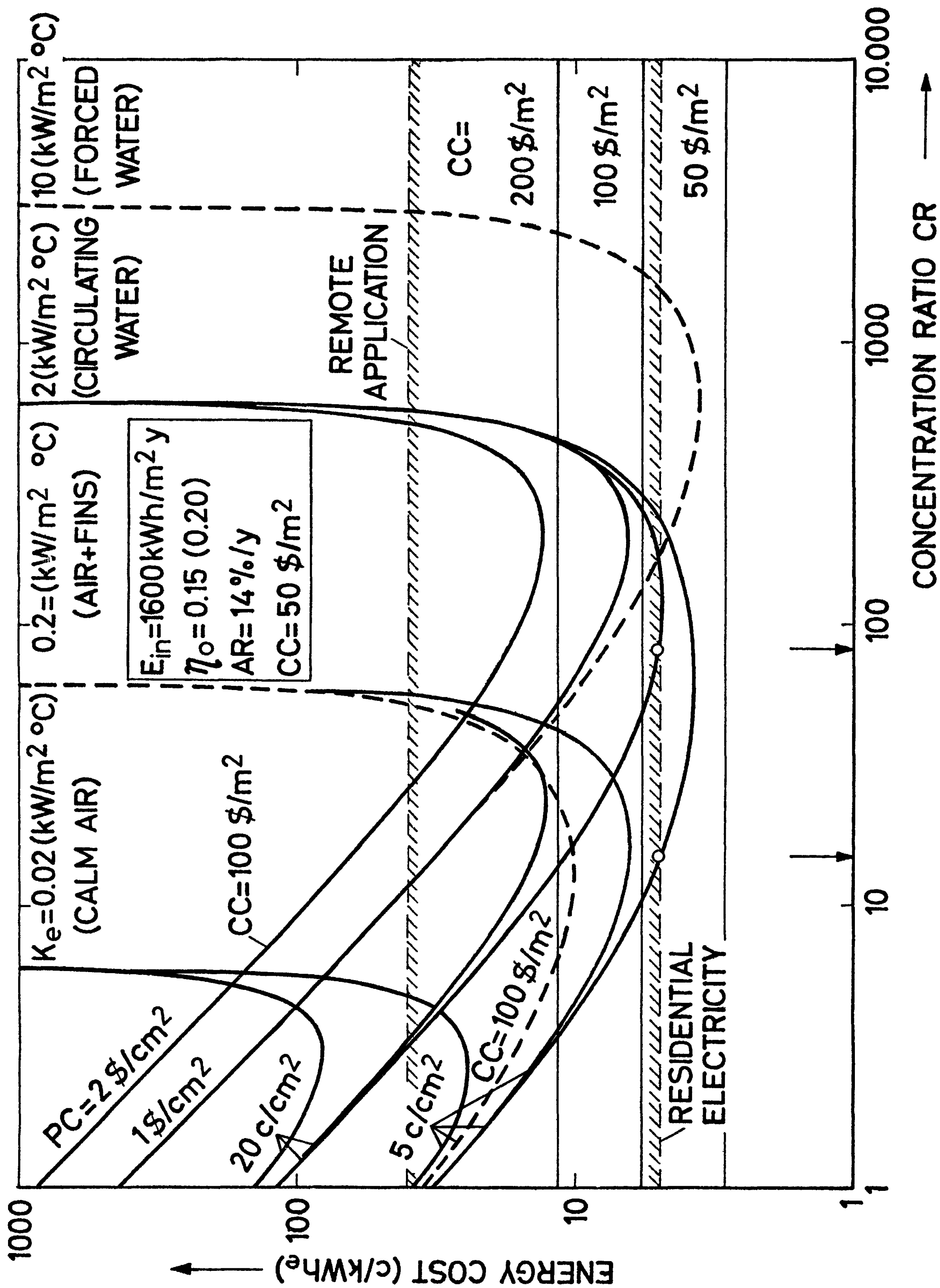
The incident radiation should be of a quality useful to concentrators, i.e. the direct component (HDIR) must be sufficiently intense. Its value determines the necessary minimum concentration ratio of the system. Assuming that the concentrator works only with direct light, then we would observe a net energy gain if $CR_{th} > HTOT/HDIR$, where CR_{th} is the theoretical concentration ratio of a given system. The ratio HDIR/HTOT determines also the effective CR which is observed for a given light composition and a given CT_{th},

$$CR_{eff} \equiv \frac{HTOT(C)}{HTOT(R)} = CR_{th}\frac{HDIR(R)}{HTOT(R)} + DR\,\frac{HDIF(R)}{HTOT(R)} \tag{1}$$

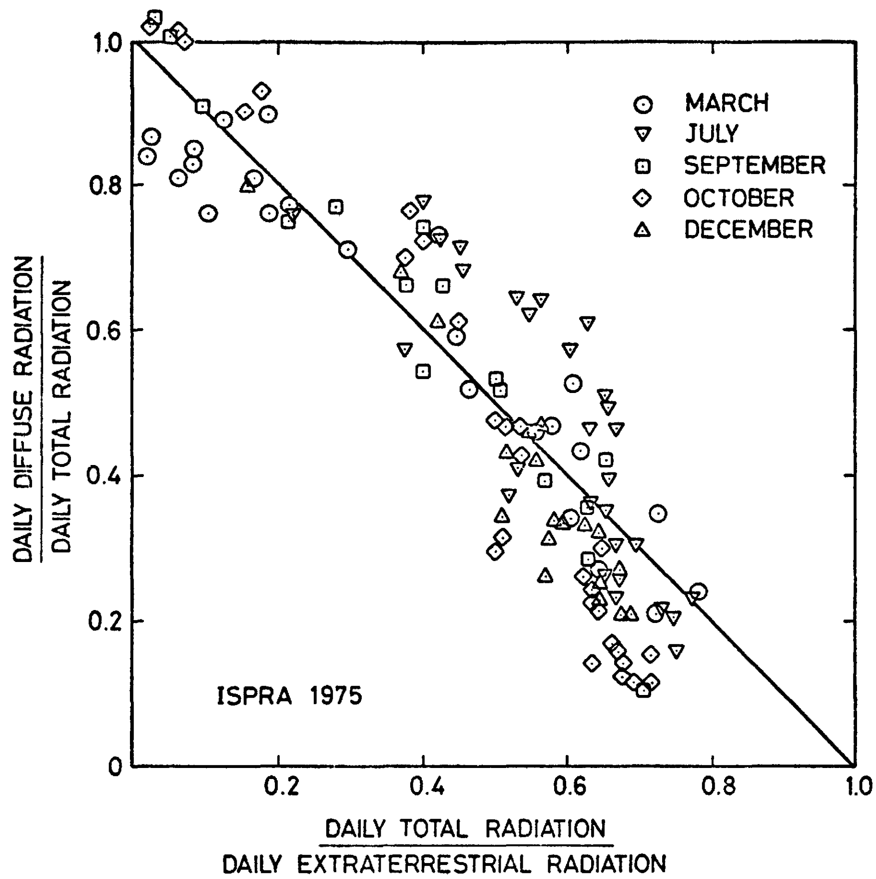
(C : concentrator, R : reference, DR : fraction of diffuse light accepted by the concentrator). If no measurements of direct (or diffuse) radiation or of sunshine duration are available, the Liu-Jordan approximation [8] might be used to obtain HDIR/HTOT :

$$\frac{HDIR}{HTOT} = 1 - \frac{HDIF}{HTOT} \approx 1 - \frac{HTOT}{HO} \quad , \tag{2}$$

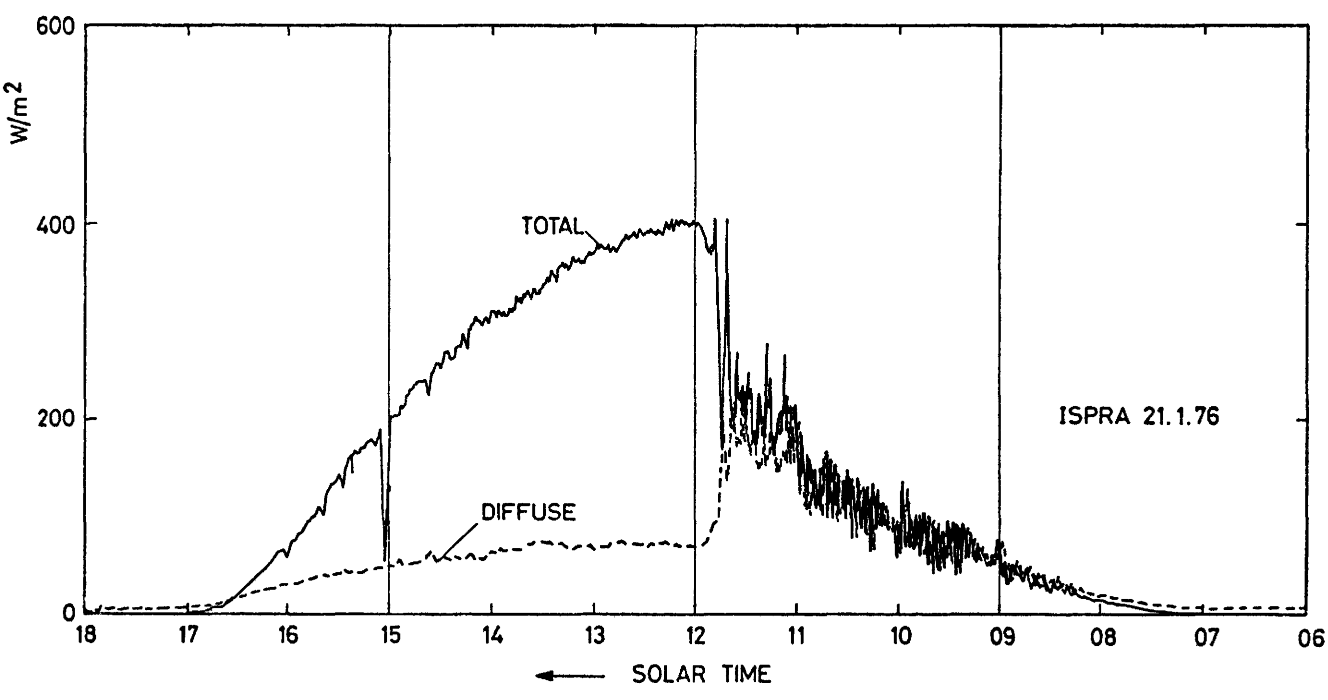
where HO is the radiation on a horizontal surface in absence of an atmosphere. Fig. 3 shows measurements taken at Ispra ($\lambda = 45.8°N$)



K_e=0.02 (kW/m^2 °C)
(CALM AIR)
0.2=(kW/m^2 °C)
(AIR+FINS)
2(kW/m^2 °C)
(CIRCULATING WATER)
10 (kW/m^2 °C)
(FORCED WATER)
E_{in}=1600 kWh/m^2 y
η_o=0.15 (0.20)
AR=14%/y
CC=50 \$/m^2
CC=100 \$/m^2
CC=100 \$/m^2
PC=2 \$/cm^2
1\$/cm^2
20 c/cm^2
5 c/cm^2
REMOTE APPLICATION
RESIDENTIAL ELECTRICITY
CC=
200 \$/m^2
100 \$/m^2
50 \$/m^2
1000
100
10
1
ENERGY COST (c/kWh$_e$)
1
10
100
1000
10.000
CONCENTRATION RATIO CR



MARCH
JULY
SEPTEMBER
OCTOBER
DECEMBER
ISPRA 1975
DAILY DIFFUSE RADIATION / DAILY TOTAL RADIATION
DAILY TOTAL RADIATION / DAILY EXTRATERRESTRIAL RADIATION
0
0.2
0.4
0.6
0.8
1.0



W/m2
600
400
200
0
TOTAL
DIFFUSE
ISPRA 21.1.76
18
17
16
15
14
13
12
11
10
09
08
07
06
SOLAR TIME

Figure 3a

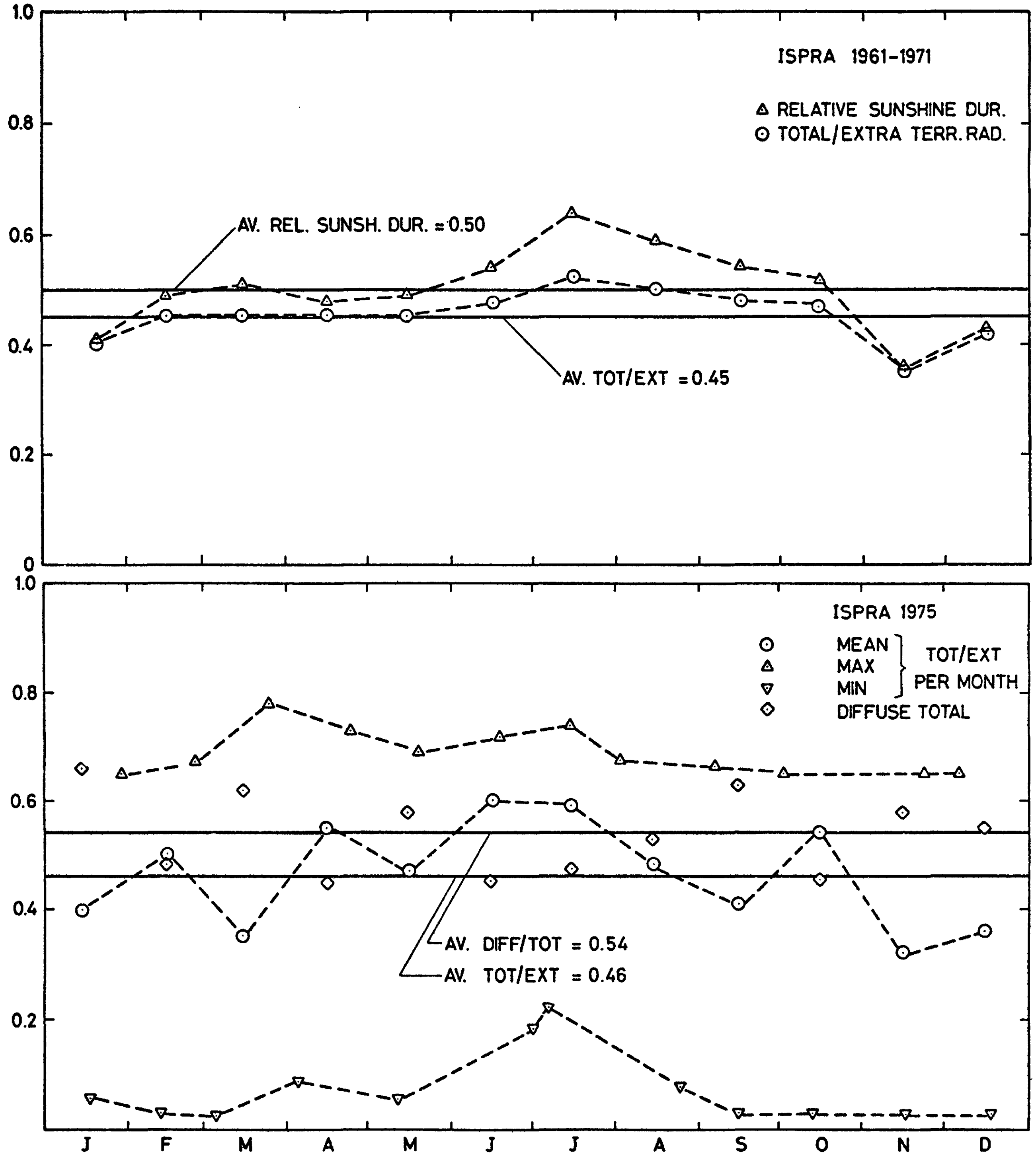

ISPRA 1961-1971
RELATIVE SUNSHINE DUR.
TOTAL/EXTRA TERR. RAD.
AV. REL. SUNSH. DUR. = 0.50
AV. TOT/EXT = 0.45
ISPRA 1975
MEAN
MAX
MIN
TOT/EXT PER MONTH
DIFFUSE TOTAL
AV. DIFF/TOT = 0.54
AV. TOT/EXT = 0.46
1.0
0.8
0.6
0.4
0.2
0
J F M A M J J A S O N D

Figure 3b

which confirm that relation. In a 10y (monthly) average (1962-1972) HTOT/HO was 0.46 at that station. For the same time period the relative sunshine duration was 0.5. Thus in Ispra only systems with $CR_{th} > 2$ could in principle offer an advantage on a yearly basis. Since in general also some part of the diffuse radiation will be accepted by a concentration system, this CR-limit may be correspondingly smaller, on the other hand, one should be aware of the additional cost of the concentrator.

A large part of the world will have HDIR/HTOT - ratios between 0.4 and 0.8 : for all those areas the incident radiation would thus be of sufficient quality if the CR-values would be chosen above about 1.3 to 2.5.

3. THE PHOTOVOLTAIC CONVERTER

The solar cell should be able to convert incident radiation of increased energy density not only effectively but also economically into electricity. The increase in flux level gives rise to two main difficulties : higher intensities mean higher cell temperatures and increased currents. Both have a negative influence on the conversion efficiency and may thus invalidate the whole concept. The I-V characteristic of a n-p junction is usually written as

$$J = J_0 \left[\exp \frac{e(V - IR_s)}{kT} - 1 \right] - J_L \, . \tag{3}$$

The open circuit voltage and short circuit current density are then

$$V_{oc} = \frac{kT}{e} \ln \left(1 + \frac{J_L}{J_0} \right) \tag{4}$$

and

$$J_{sc} = - J_L = - e \int_0^{\lambda_g} Q(\lambda)\, N(\lambda)\, d\lambda \tag{5}$$

(J_L : light generated current density, $Q(\lambda)$: collection efficiency, $N(\lambda)$: incident spectrum, $\lambda_g = hc/\Delta E$, ΔE : energy gap). With these terms the conversion efficiency becomes

$$\eta = CF \, \frac{J_{sc} V_{oc}}{P_{IN}} \, , \tag{6}$$

where the curve factor is defined as $CF = J_m V_m / J_{sc} V_{oc}$.
(J_m, V_m : current density and voltage at optimum working point, P_{in} : incident power density).

If we neglect for a moment temperature and series resistance effects, we see that V_{oc} increases logarithmically with J_L. This leads to an increase in conversion efficiency with concentration and follows also from the thermodynamic reason [9] that concentrated radiation is basically of higher (Carnot) quality. For concentration ratios in the order of 1000 one expects theoretically [10] an increase in efficiency by 30 to 40%.

3.1. Temperature Effect

An increase in temperature influences mainly the open circuit voltage and there the main effect is due to an increase in the reverse saturation current density

$$J_0 = CT^3 \exp\left(-\frac{\Delta E}{kT}\right)\left[\frac{1}{N_D}\left(\frac{D_p}{\tau_p}\right)^{1/2} + \frac{1}{N_A}\left(\frac{D_n}{\tau_n}\right)^{1/2}\right] \quad . \tag{7}$$

If we consider two temperatures T_1 and T_2 the corresponding open circuit voltages at constant short circuit current are related by [11]

$$\frac{V_2}{\Delta E} = 1 - \left(1 - \frac{V_1}{\Delta E}\right)\frac{T_2}{T_1} - 3\frac{kT}{e\Delta E}\ln\frac{T_2}{T_1} + \frac{1}{\Delta E}\left(\frac{d\Delta E}{dT}(T_2 - T_1)\right) , \tag{8}$$

which indicates the usually observed approximatively linear decrease of V_{oc} with T. One observes also that semiconductors with a larger energy gap show a relatively slower decrease of V_{oc} with increasing temperature.

If we now neglect other (and in general smaller) temperature effects (e.g; on J_{sc}) the conversion efficiency will also be a linearly decreasing function of T. Which temperature and thus which η will be actually obtained under a given irradiation depends on the cooling properties of our system [12-15]. Approximately we may write (radiation losses being neglected)

$$\eta = \eta_0 \left(1 - \frac{a\beta}{K_e} P_{in}\right) , \tag{9}$$

where K_e is the thermal conductivity per unit area (in KW $m^{-2}K^{-1}$), a is the absorptivity and β the temperature coefficient of V_{oc}, $\beta \approx (\Delta E - V_0)/T_0$ (≈ 2 mV/grad). The influence of K_e on η was shown implicitly in Fig. 2.

It is obvious that sufficient cooling can reduce efficiency losses to tolerable values. A very interesting solution is the photovoltaic-thermal (or hybrid) system [16, 17], where the absorbed heat is used as in a solar thermal panel. Since the money value of the absorbed heat is roughly of the same order as the value for the electrical energy output, system costs can be reduced by a factor 2. Another special case is the solar electric pump, where the system may be constructed in a way that it is able to cool itself by the pumped water [18], therefore neither additional energy nor additional water is needed.

3.2. Series Resistance

The second and more critical influence on conversion efficiency and power putput of a cell is due to its finite series resistance. If the light level falling onto a photovoltaic converter is increased from L_1 to L_2 the corresponding I-V characteristics are related to each other by (taking I positive) [19]

$$I_2 = I_1 + \Delta I_L \tag{10}$$

and

$$V_2 = V_1 - R_S \Delta I_L \quad , \tag{11}$$

where

$$\Delta I_L = \left(\frac{L_2}{L_1} - 1\right) I_{L1} = (CR - 1)\, I_{L1} \tag{12}$$

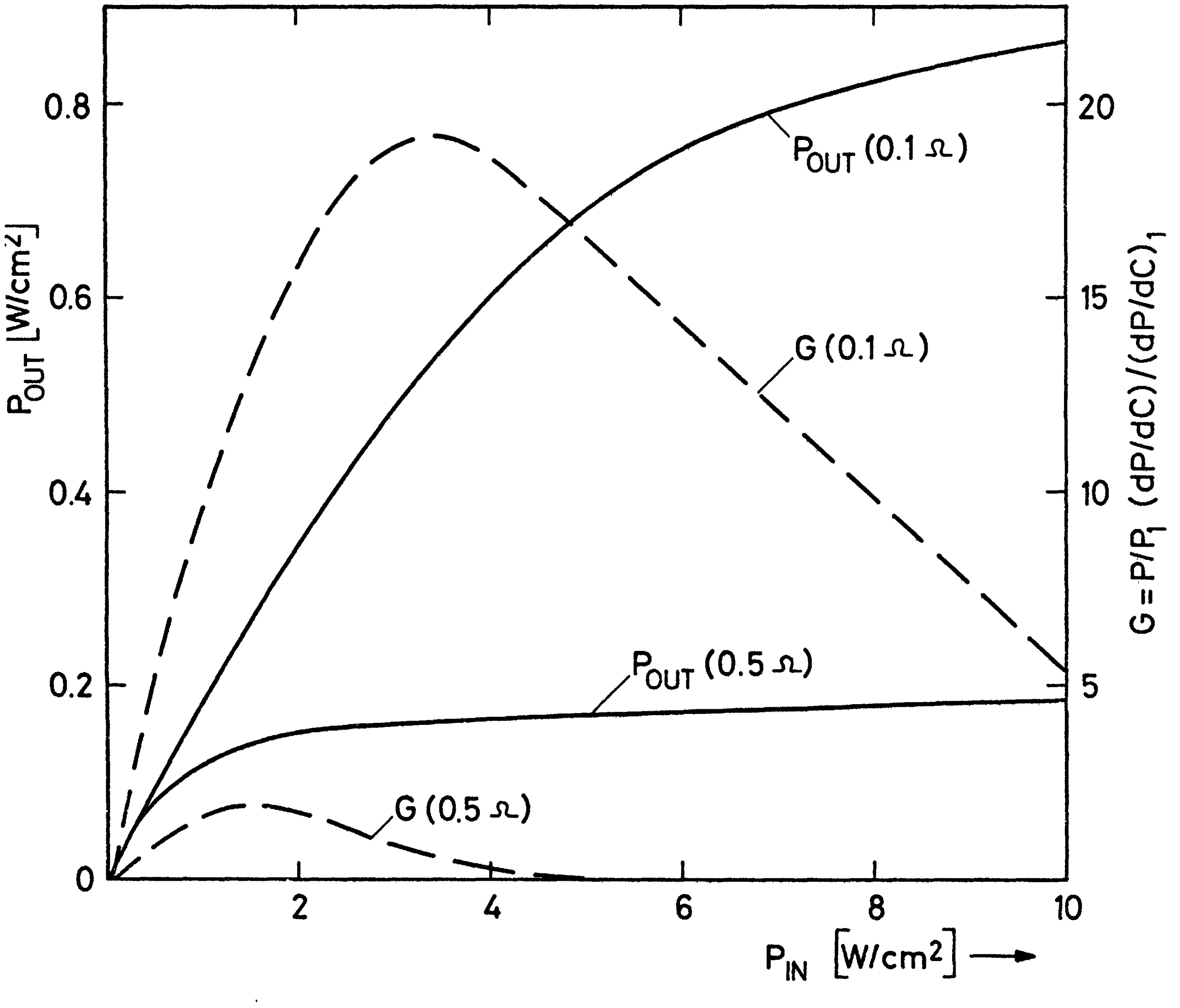
(I_{L1} : light generated current at level L_1).

This means that the second I-V curve is obtained from the first one by two translations of the coordinate system by amounts - ΔI_L (voltage axis) and $\Delta I_L \cdot R_s$ (current axis). From this procedure one may derive the behaviour of the power output as function of incident intensity (Fig. 4) [14]. One sees that depending on R_s for higher CR-values the relative gain in power output decreases more and more, this indicates that higher concentration can be applied economically only if the series resistance of the cell can be kept correspondingly lower. The eventual success of the concentration concept depends to a large extent on the possibility to achieve this goal in an economic way.

The series resistance of modern cells is determined predominantly by the resistance of the front grid and of the highly doped surface layer. The first improvement lies in a modification of the grid (Fig. 5) and in a modification in doping and thickness of the surface layer. It has been shown [20] that in this way cells working under a 25-fold concentration show good I-V curves. The series resistance of a grided surface layer varies like n^{-2}, where n is the number of grid lines [21, 22]. Thus the distance between lines should be chosen proportional to $CR^{-1/2}$, or in other words, the unit cell must decrease in size as CR increases. Difficulties with the resistance of the grid itself may be avoided by means of a superimposed coarser grid [12, 15]. Using a suitable fine grid (90 μm spacing and 4 μm width) and a surface doping density of 5×10^{20} cm^{-3} it has been possible to obtain 8% conversion efficiency at CR > 800 for silicon [15].

Another idea, which has been exploited quite successfully with Ga As cells [11, 23] consists in the application of a transparent conductive semiconductor window on top of the surface layer [24, 25]. This window acts as a resistance parallel to the surface sheet resistance. So far the heighest intensities have been used with p-Al GaAs /p - GaAs/n - GaAs cells : at 1735 suns and 19% efficiency output power densities of 24 W/cm^2 have been reached [11, 23]. Materials like In_2O_3 might eventually be used on silicon if cracking and peeling can be avoided [26]. The problem with the highly doped front layer might eventually also be solved by growing thicker and less doped surface layers epitaxially. [27]

The front-layer can be eliminated altogether in another concept, the vertical junction arrangement of the HI cell [28] (Fig. 6). This system has the additional advantage of being a low current series connected converter, it can be irradiated from two sides



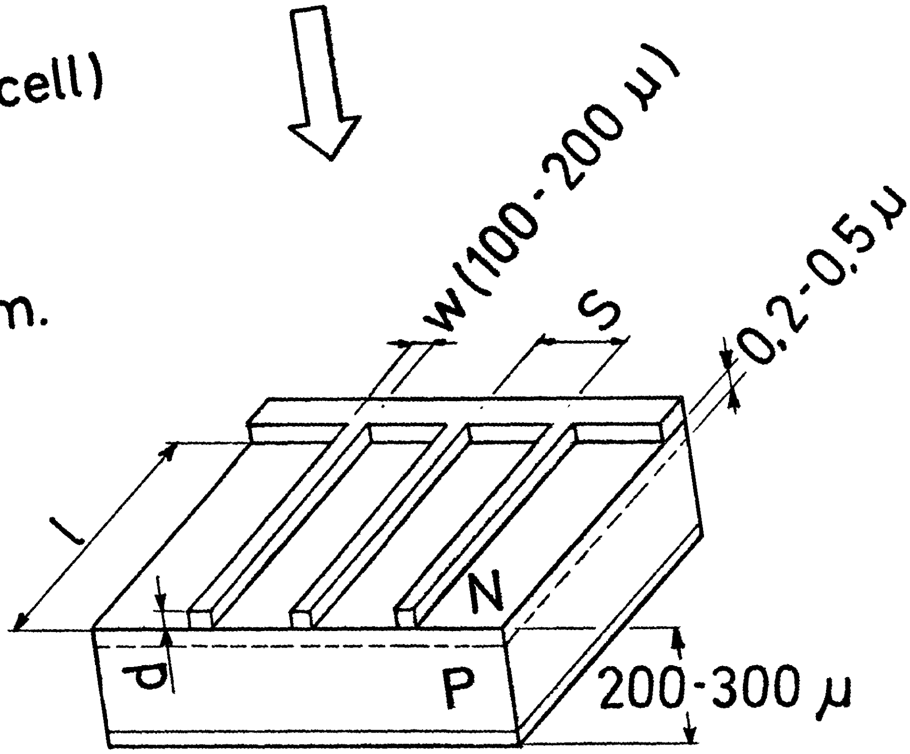
0.8
0.6
0.4
0.2
0
P_{OUT} [W/cm²]
20
15
10
5
G = P/P₁ (dP/dC)/(dP/dC)₁
P_{OUT} (0.1 Ω)
G (0.1 Ω)
P_{OUT} (0.5 Ω)
G (0.5 Ω)
2
4
6
8
10
P_{IN} [W/cm²]

Figure 4

Cell A

(conventional cell)

$N_D = 5 \times 10^{19}$ cm.$^{-3}$
$N_A = 2 \times 10^{15}$ cm.$^{-3}$
$\rho_B = 1 - 10$ Ω cm.
$t_p = 0.2$ n sec
$t_n = 10$ µ sec



Cell B

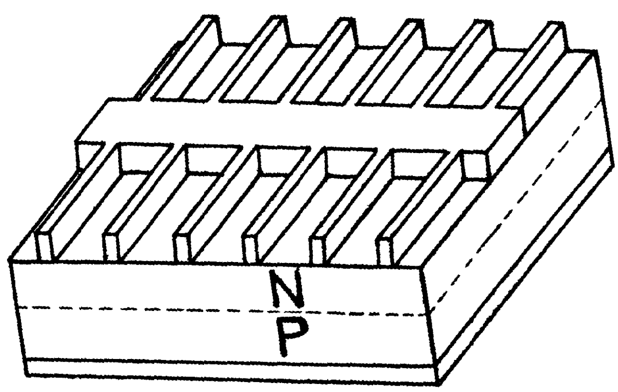
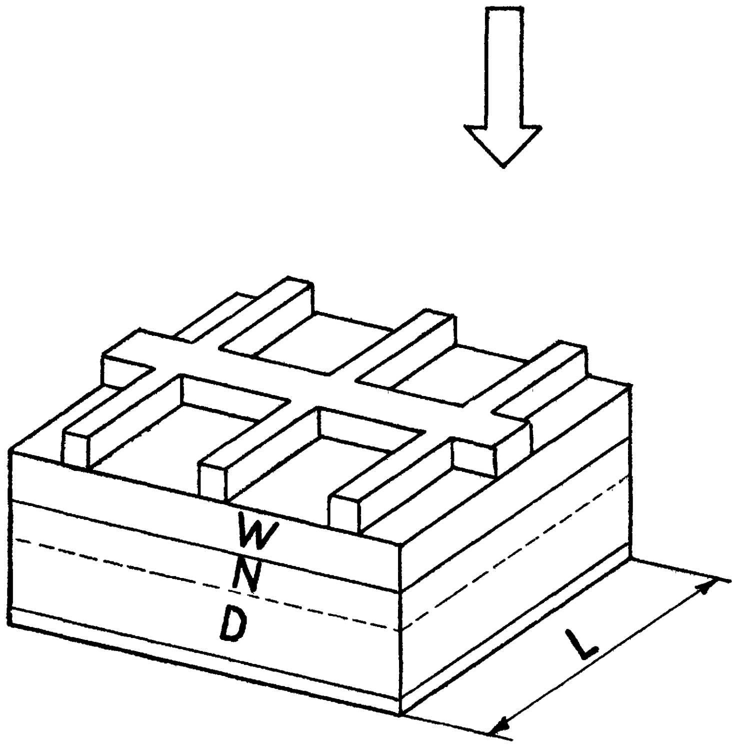


Figure 5

Cell C



Cell D

(HI cell)

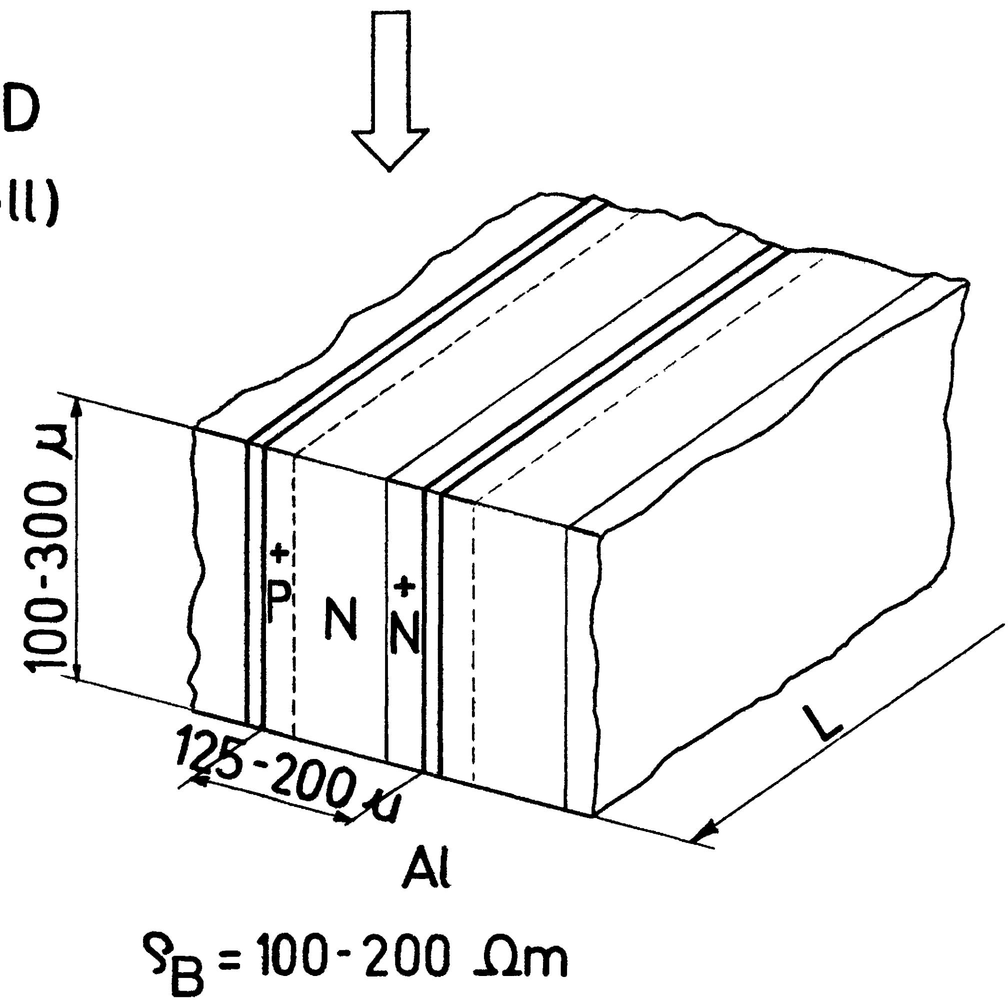


Figure 6

and due to light modulation of the conductivity there is even a decrease in series resistance with concentration. Measurements with concentration ratios up to 300 have shown that with the vertical structure silicon can work with high CR-values, similar high concentration ratios have also been reached with the Russian Photovolt cell [29].

The main draw back of very high concentration cells consists (1) in their high production costs and (2) that they require more accurate concentrating devices. If we remember Fig. 2, one finds that high CR-values in connection with expensive converters do not lead to lower cost levels than it can be reached with silicon at moderate concentration. This implies, of course, that indeed efficient silicon concentrator cells could be developed, say, below 5 $/ peak watt : For medium CR-values this seems to be possible [12].

Fig. 7 sums up some of the output power densities which have been reached so far by various authors. This figure proves the principle physical feasibility of the concept.

4. OPTICAL CONCENTRATION

The exploitation of the concentration concept shifts the emphasis to develop low cost cells somewhat to the problem of finding the most economical optical concentrator.

Since the light source is non-stationary and of varying intensity, one might ask what should be defined as optimum concentrator under these conditions. For a Lambert law source the irradiance of a surface element dF' is related to the radiant emittance of a disk like source S into half space (L_0 : radiance of source) by (Fig. 8a)

$$D = \frac{d^2E}{dt\,dF'} = \pi L_0 \sin^2\delta \quad . \tag{13}$$

Thus we would say a concentrator is "geometrically ideal", if it compensates fully for the geometrical loss, i.e. if

$$\frac{D_c}{D} = CR_g = \frac{1}{\sin^2\delta} \qquad (\sin\delta_c = 1) \quad . \tag{14}$$

This relation implies the sine condition of geometrical optics [30] (Fig. 8b)

$$Y_0 \sin u_0 = Y_1 \sin u_1 \quad . \tag{15}$$

Maximum reduction in size is obtained for $u_1 = 90°$, i.e. if

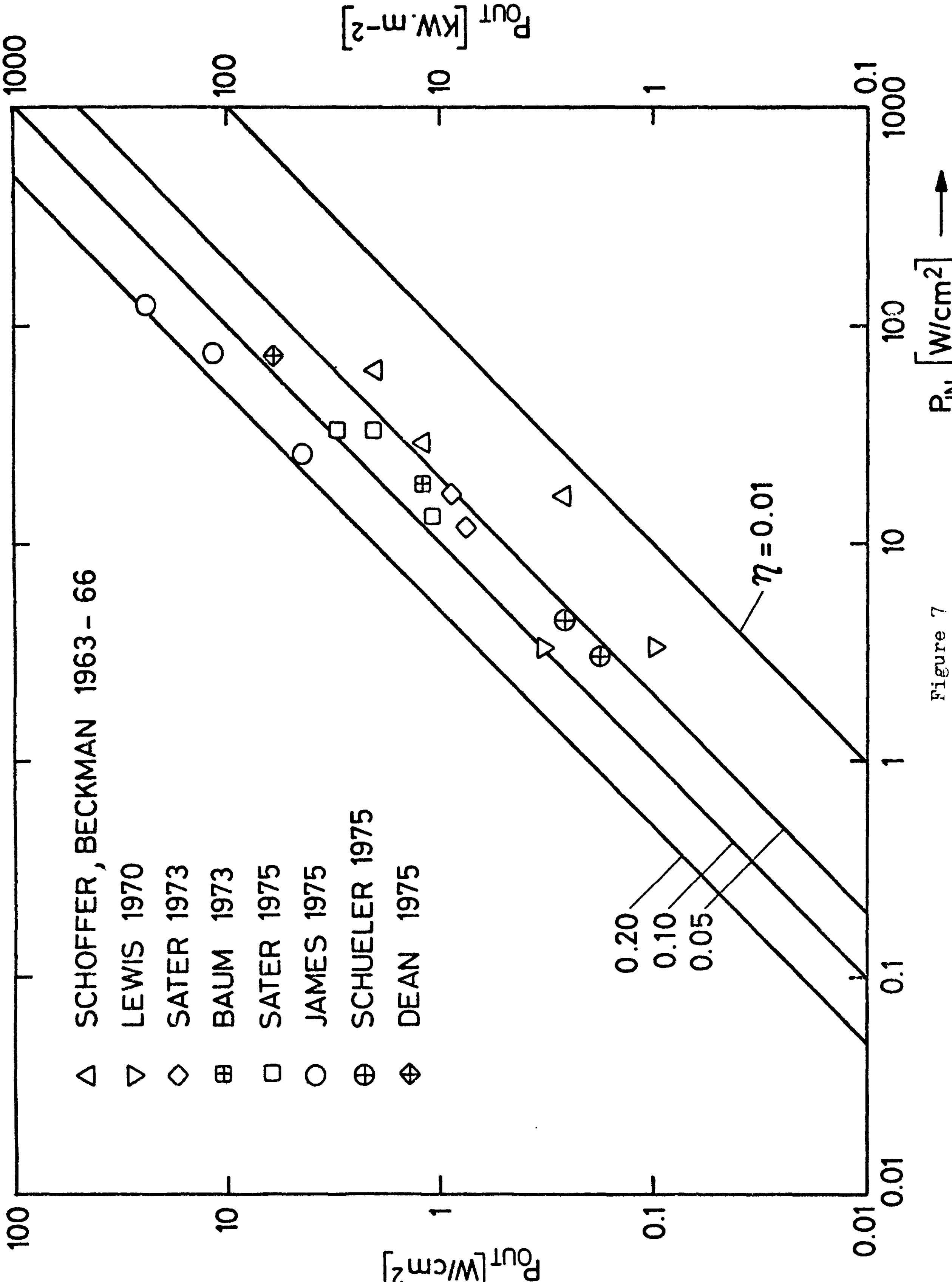
$$\left(\frac{Y_0}{Y_1}\right)^2 = \frac{1}{\sin^2 u_0} \quad , \tag{16}$$

If the object is at infinity, the sine condition becomes [29, 31] (Fig. 8c)

$$h = f \sin u_1 \quad . \tag{17}$$

Since

$$Y_1 = f \tan u_0 \; , \tag{18}$$



SCHOFFER, BECKMAN 1963 - 66
LEWIS 1970
SATER 1973
BAUM 1973
SATER 1975
JAMES 1975
SCHUELER 1975
DEAN 1975
η = 0.01
0.20
0.10
0.05
P_{OUT} [W/cm^2]
P_{OUT} [KW.m^{-2}]
P_{IN} [W/cm^2]
100
10
1
0.1
0.01
1000

Figure 7

SINE CONDITION

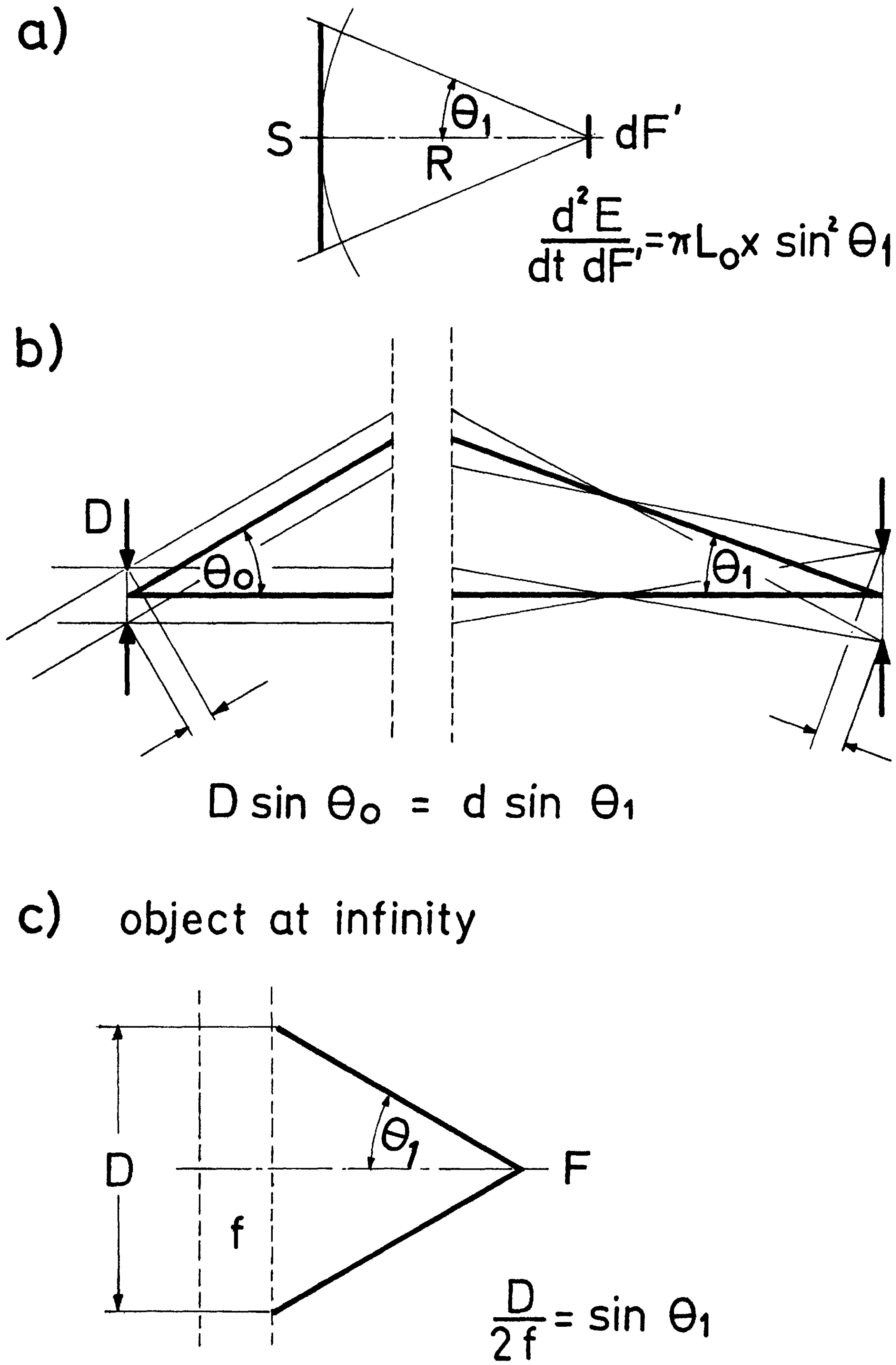


Figure 8

one has also

$$\left(\frac{h}{y_1}\right)^2 = \frac{\sin^2 u_1}{\tan^2 u_0} \rightarrow \frac{1}{\sin^2 u_0} \tag{19}$$

for small u_o and $u_1 \rightarrow 90°$.

From these relations we obtain with the sun's half angle $\delta = 16'$ a maximum concentration ratio of CR = 215^2 = 46200, which for instance with CR x $I_o = \sigma T_s^4$ leads to T_s = 5700°K (I_o : solar constant).

Our main aim is the optimization of the energy gain, thus not only the concentration ratio but also the energy collection time [32] plays a part. Since we are looking for inexpensive concentrators, we limit at first our consideration to stationary or quasi-stationary systems. For such systems the collection time is determined by the total acceptance angle 2δ , and δ itself is defined not by the extension of the solar disk but by an average over the apparent daily solar motion across the sky. From a plot of the projection angle of the solar motion in the meridional plane as function of time (Fig.9), we see that δ-values between 5° and 10° lead to acceptable collection times. Of course, for linear systems this means that CR will then remain below 12.

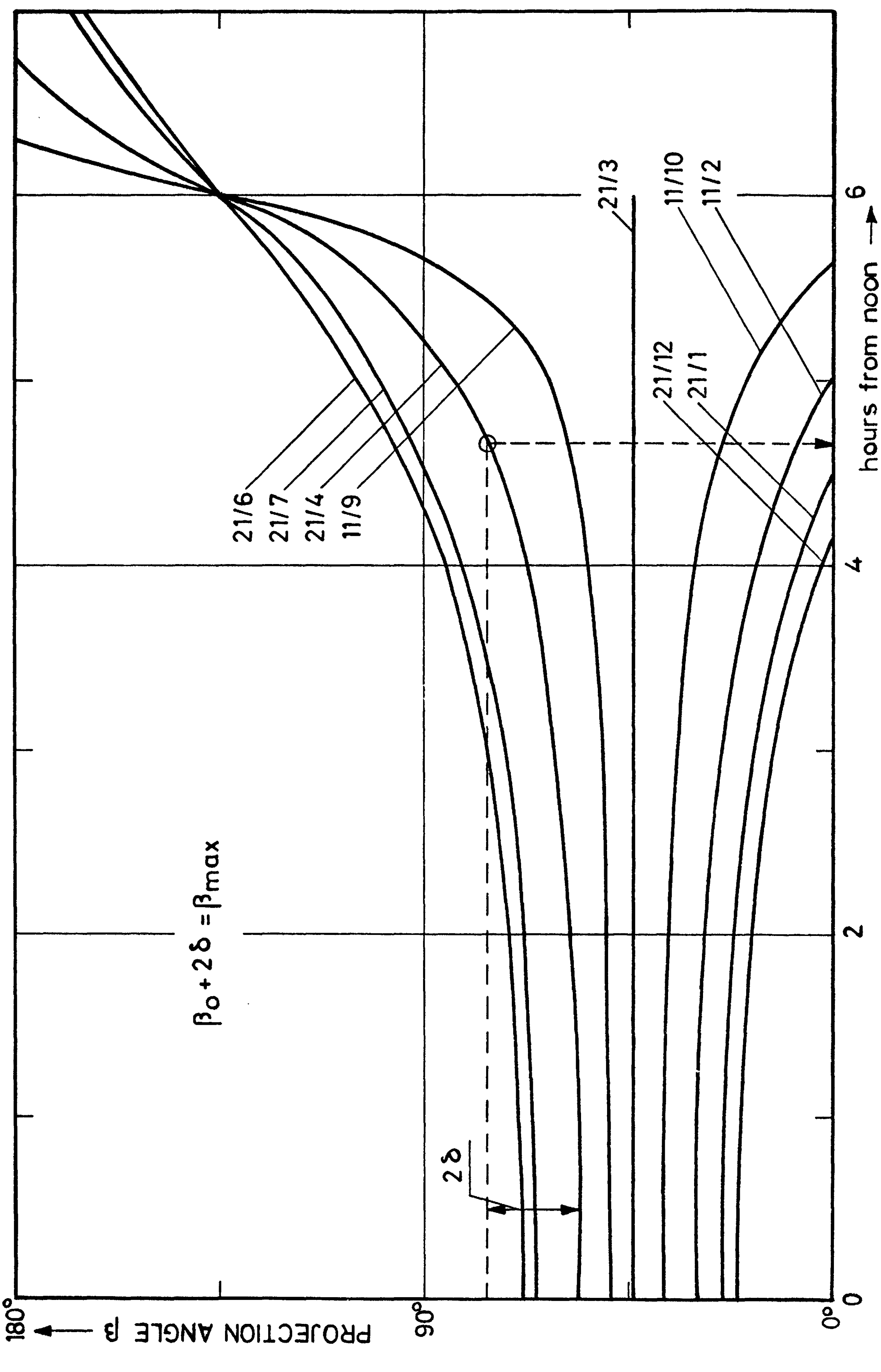
Let us consider briefly the properties of some typical (quasi) - stationary linear systems :

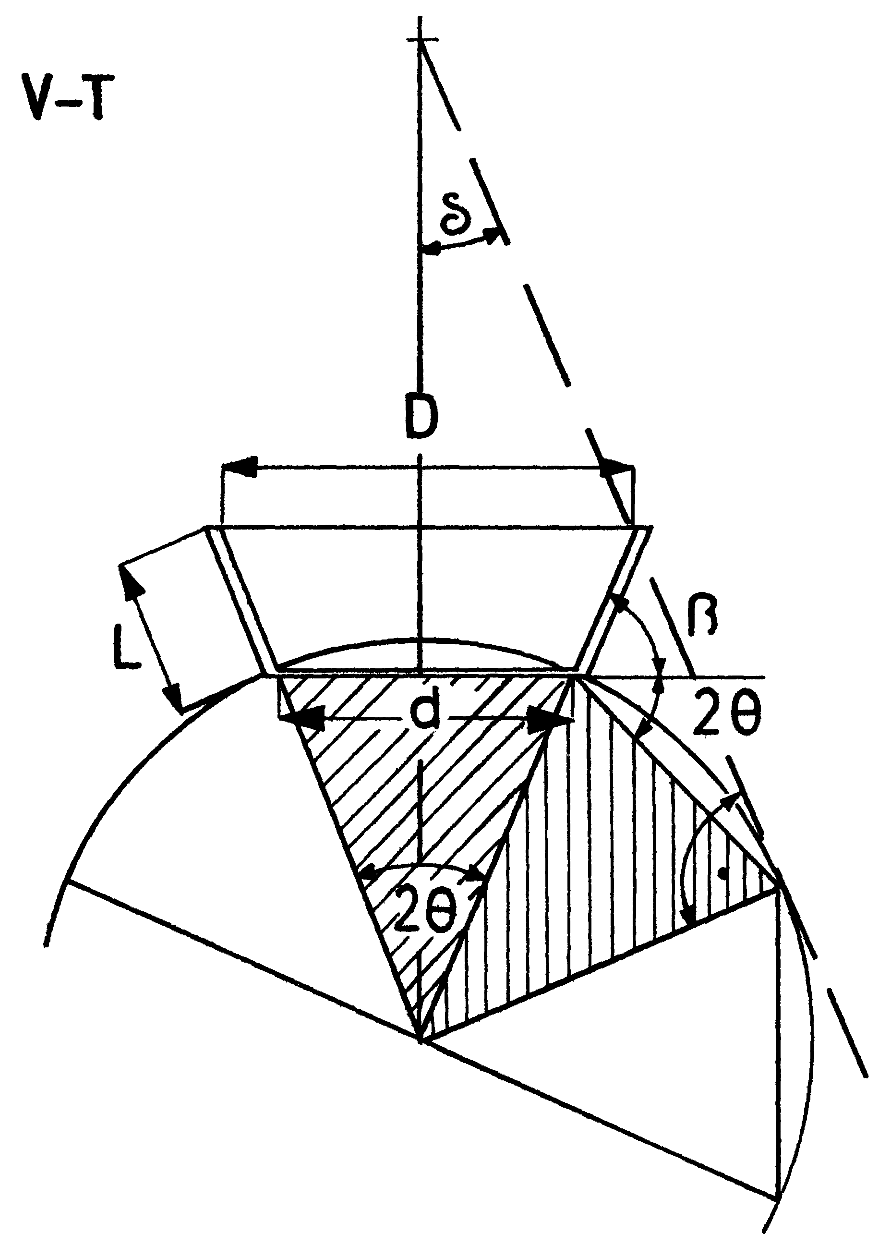
a) V-Trough.

The simplest device to obtain a low concentration factor is the V-trough arrangement with two flat mirrors. We can distinguish between various types of V-concentrators by the way how one defines the length L of the side mirrors. In one version L is defined by the requirement that perpendicular rays undergo one [33] or more [34] reflections, in another version [35] L is determined by the condition that all rays within an acceptance angle 2δ should be concentrated (Fig. 10). This last system approaches the ideal case (eq. (14)) if the cone angle goes to zero. Another way to meet the ideal concentration condition is the combination with a field lens [36] (Fig. 11) : We consider this case as very promising, since it allows now to obtain even for short systems larger ideal CR-values.

b) Parabolic Trough.

The simple V-trough may be improved by using curved side mirrors. The curvature profile of the reflectors may be obtained as solution of a first order differential equation for the case that one specifies the radiation distribution across the receiver [37]. If this distribtuion is specified in such a way that rays of a certain maximum deviation against the normal to the receiver are focused to the edges of the receiver, the profiles of the side mirrors are two inclined parabolas (Fig. 12) : this type of concentrator has therefore been called compound parabolic concentrator [32], [38]. It is an ideal concentrator in the sense of eq.(14) : it concentrates with constant CR for the maximum possible time. One disadvantage of this system is the large reflector area which is needed to reach higher concentration ratios. Moreover, the non-uniform radia-

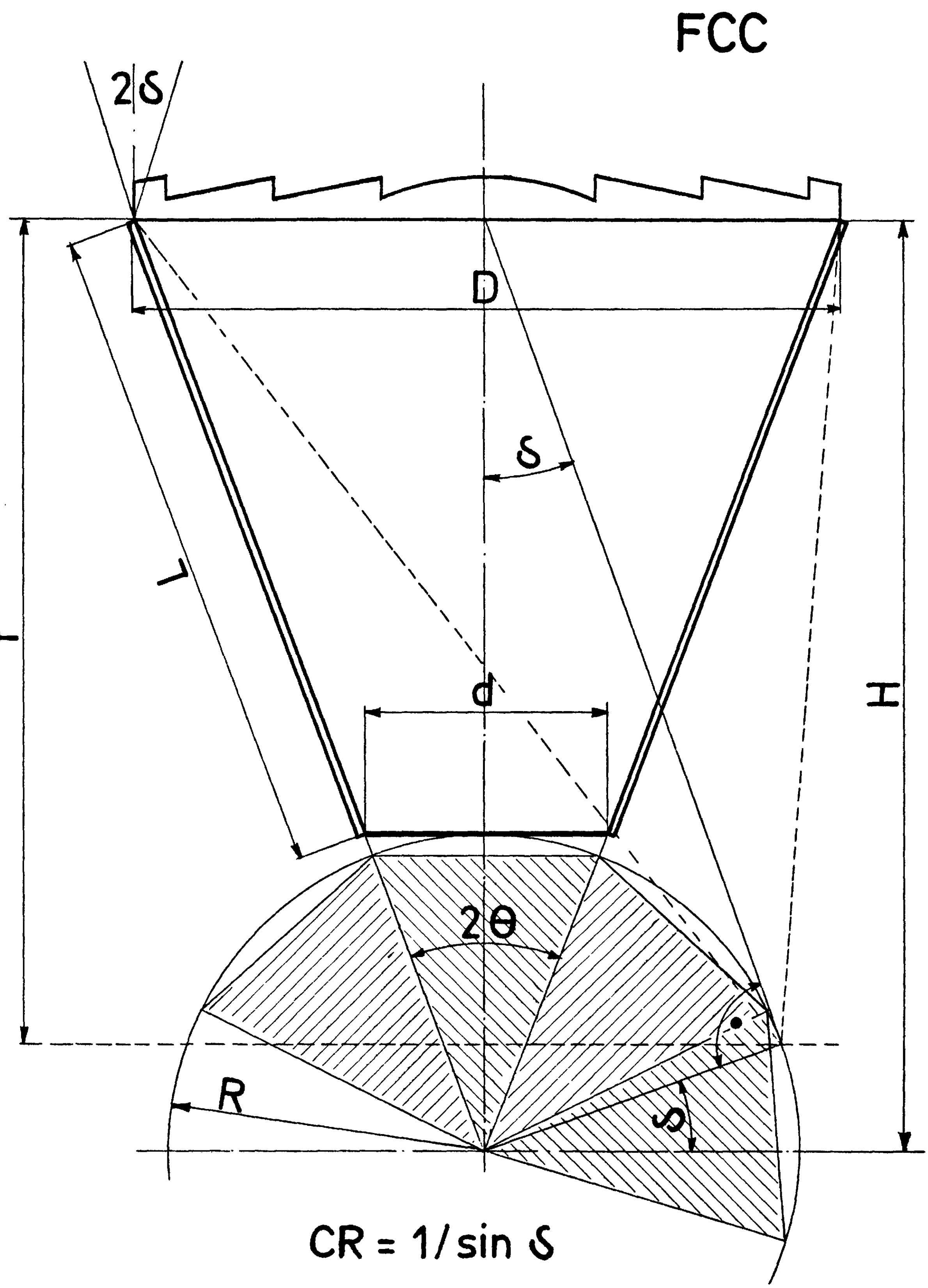

180°
90°
0°
PROJECTION ANGLE β
hours from noon
0
2
4
6
$\beta_o + 2\delta = \beta_{max}$
2δ
21/6
21/7
21/4
11/9
21/3
11/10
11/2
21/12
21/1



$$CR = 1/\sin(\theta+\delta)$$

$$L/d = \left(1-\sin(\theta+\delta)\right)/2\sin\theta\ \sin(\theta+\delta)$$

Figure 10

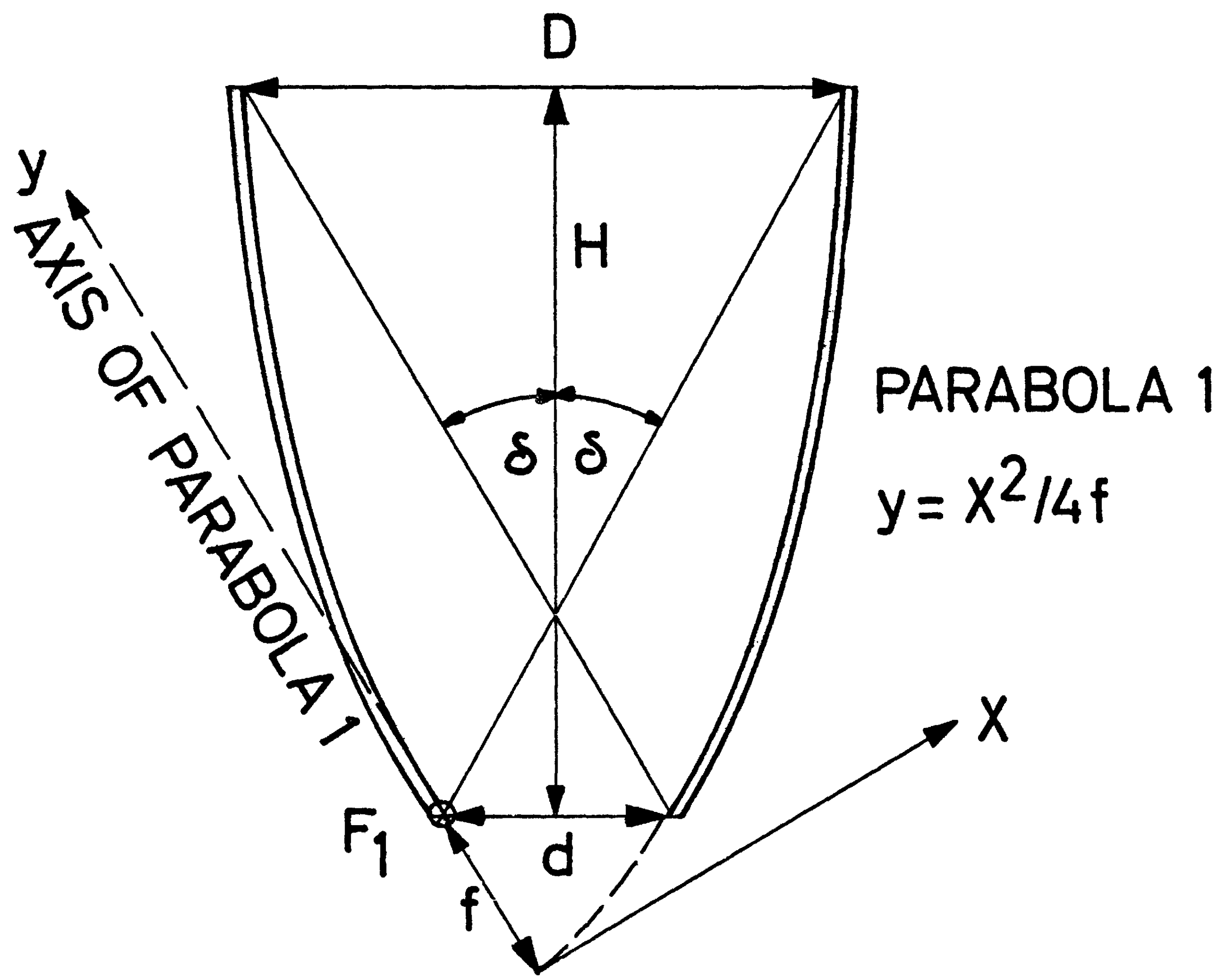


$$CR = 1/\sin\delta$$

$$\frac{L}{d} = \frac{1-\sin\delta}{2\sin\delta\sin\theta}$$

Figure 11

CP-T



$$CR = 1/\sin\delta \qquad f/d = 1/2\,(1+\sin\delta)$$

$$H/d = 1/2\,(1+ 1/\sin\delta)\,\mathrm{ctg}\,\delta$$

Figure 12

tion distribution may cause difficulties if used with solar cells.

The ratio of reflector area to aperture is smaller for the classical parabola [31), 39)] (Fig. 13). However, such a system stays well below the ideal concentration limit. Some disadvantage is also related to the vertical motion of the focal plane with the angle of incidence.

c) Linear Fresnel Lens.

Diffraction systems have the advantage that aperture and concentration area are nearly the same, thus they require less material. Moreover with Fresnel lenses such systems are relatively compact. (Fig.14). Of course, also linear Fresnel lenses show the variation of focal plane for inclined rays 40) . This difficulty can be reduced by the use of an additional V-shaped trough, cone or pyramidal reflector, which again - as already has been stated above - would lead to an ideal and at the same time compact system. Another possibility for an effective increase of the acceptance time without loss of concentration may be obtained by the addition of a flux redistributor around the position of the (moving) focus [29), 41)].

Fig. 15 shows concentration factors for the above systems as function of acceptance angle. In Fig. 16, we have plotted CR x (t_A/t_s) for the days of a year (t_A : acceptance time, t_s : length of the day).

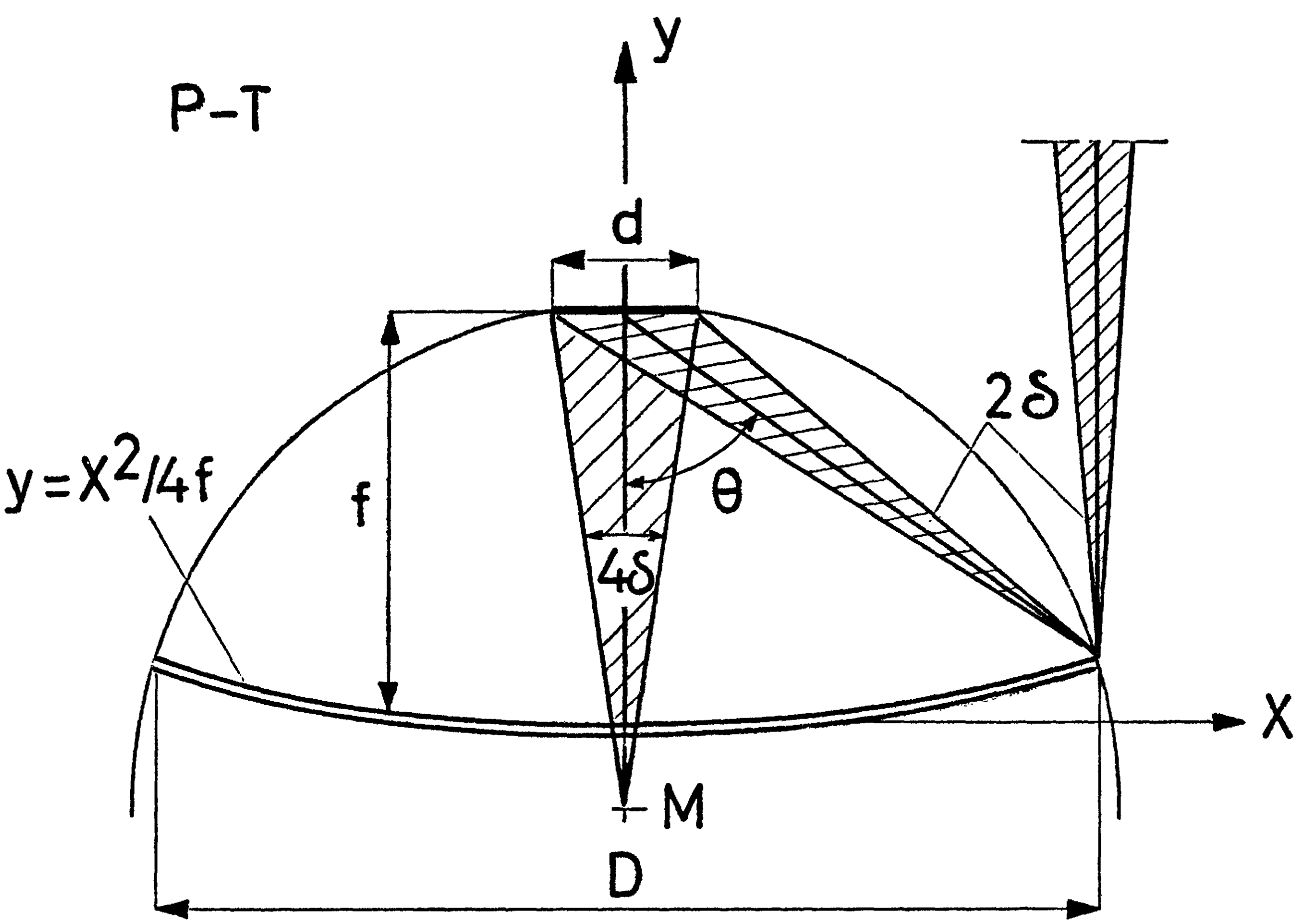
So far we have mentioned only linear quasi-stationary systems, which would be oriented e.g. in East-West. If higher CR-values are needed, one has to use concentrators (or receivers) which rotate daily at least around one horizontal, vertical or equatorial axis. Limitation to one axis could be combined with relaxation for concentration along another axis, i.e. one would again use linear concentrators : this time, however, with much smaller δ's and correspondingly higher CR-values. Fig. 17 is a sketch of such a rotating system. The individual concentrators are linear and the waste heat is used for thermal applications.

Ultimate values of concentration are obtained with true heliostatic systems. A drawback of such systems might be their cost and the protection they need against wind loading [42)]. However, cost reductions are to be expected from the development work for large solar thermal power stations. In this context, costs of 34 $/m² - based on very large scale production - have been quoted in literature [43)]. If such 2-axis - systems will have an advantage also for photovoltaic applications, depends on the requested concentration factors : for silicon very high CR-values might not be necessary.

5. CONCLUSION

The discussion in the foregoing chapters has shown that a successful application of the concentration concept will require that certain conditions on incident radiation, on characteristic parameters of the photovoltaic converter and on the optical properties of the concentrator can be fulfilled.

Concerning the radiation sufficient knowledge of the amount of direct intensity must be available, since this determines critically the minimum and the effective concentration factor. The direct com-



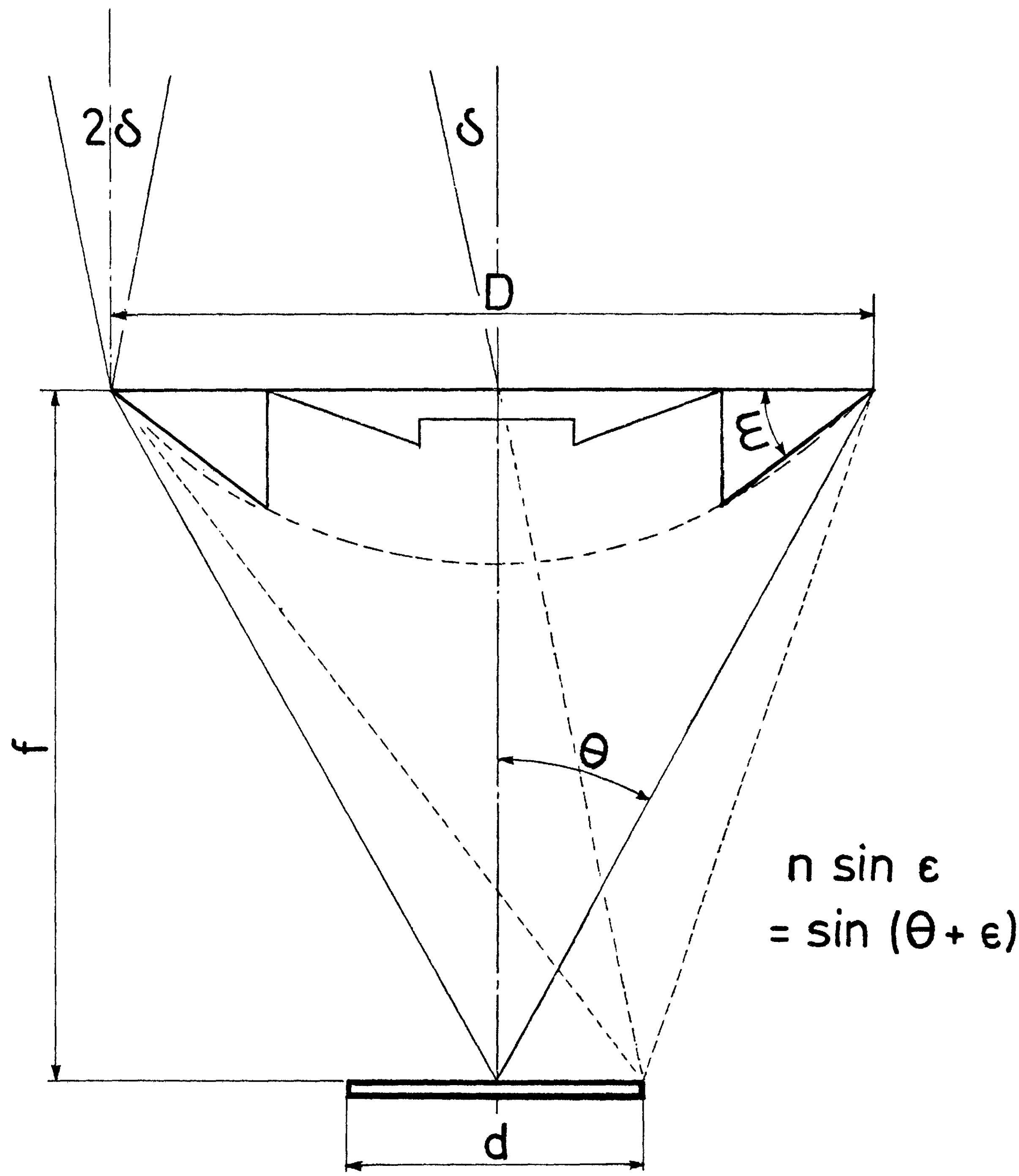
$$CR = (1/\sin\delta)(\sin 2\theta / 2\cos\delta) - 1$$

$$\text{or} \quad \left(\sin\theta\cos(\theta+\delta)/\sin\delta\right) - 1$$

$$f/d = (1+\cos\theta)\ \cos\theta / 2\sin 2\delta$$

Figure 13

LFR



$$CR = \sin\theta \,/\, \mathrm{tg}\,\delta$$

Figure 14

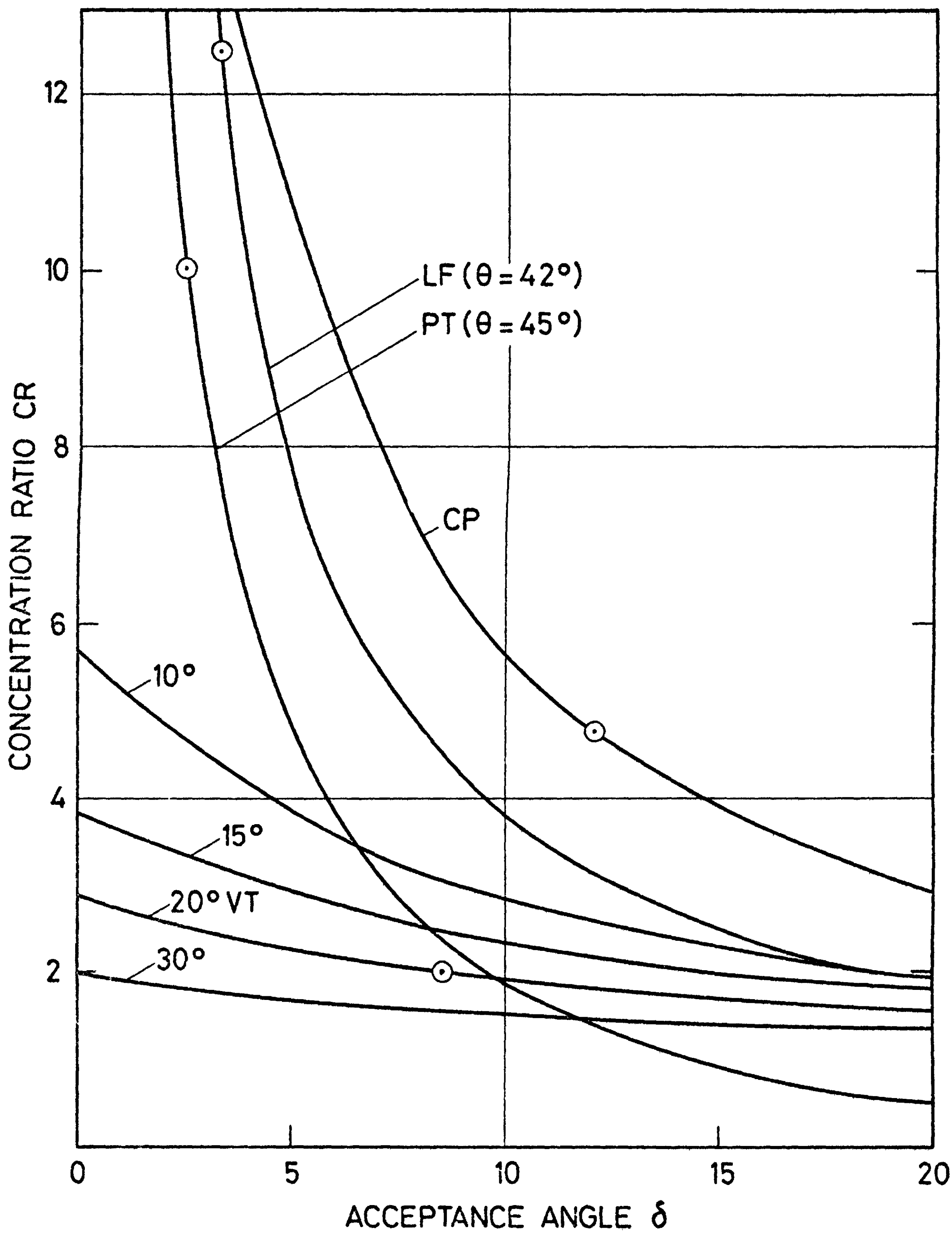

LF (θ = 42°)
PT (θ = 45°)
CP
10°
15°
20° VT
30°
12
10
8
6
4
2
CONCENTRATION RATIO CR
0
5
10
15
20
ACCEPTANCE ANGLE δ

Figure 15

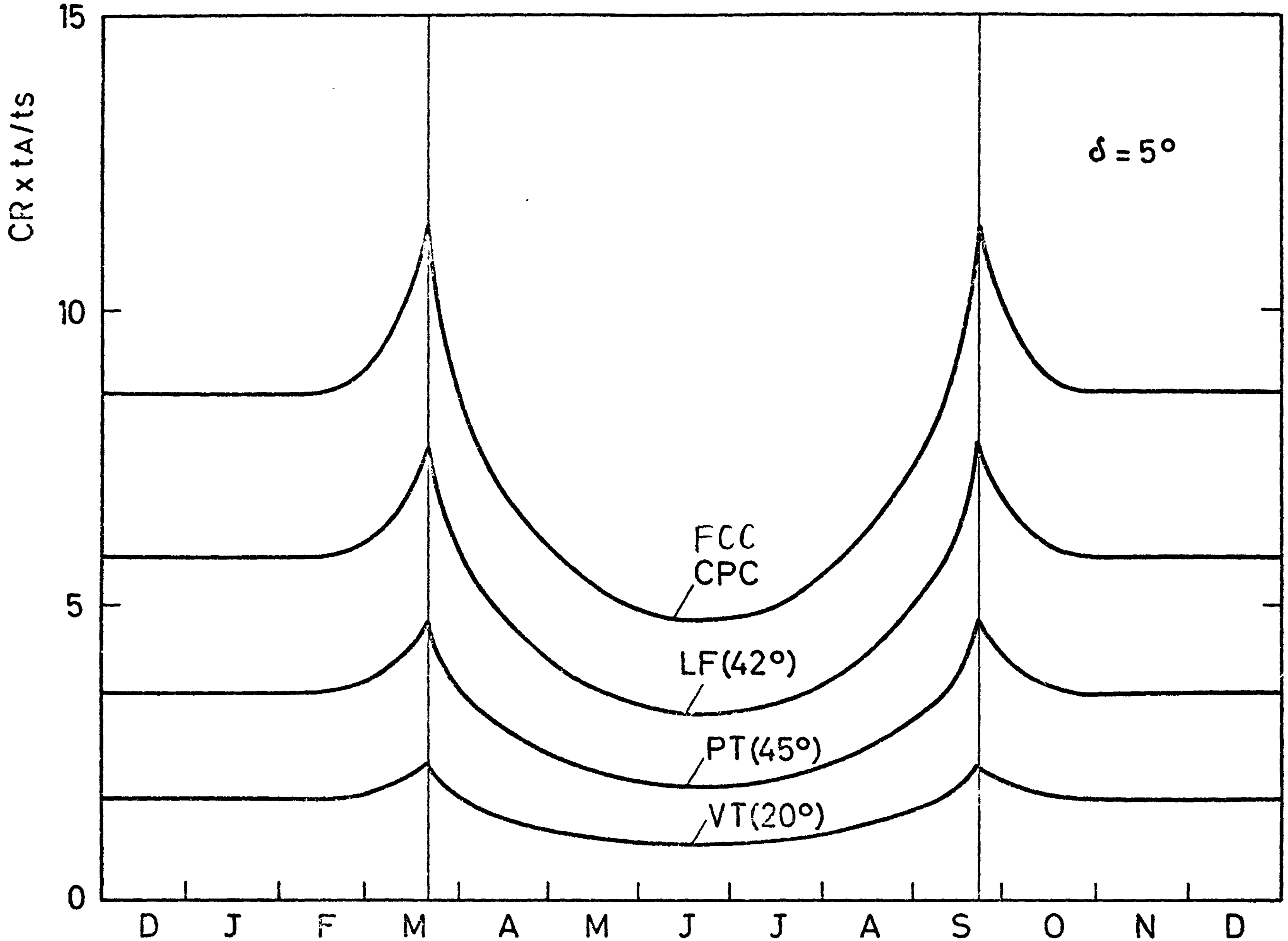
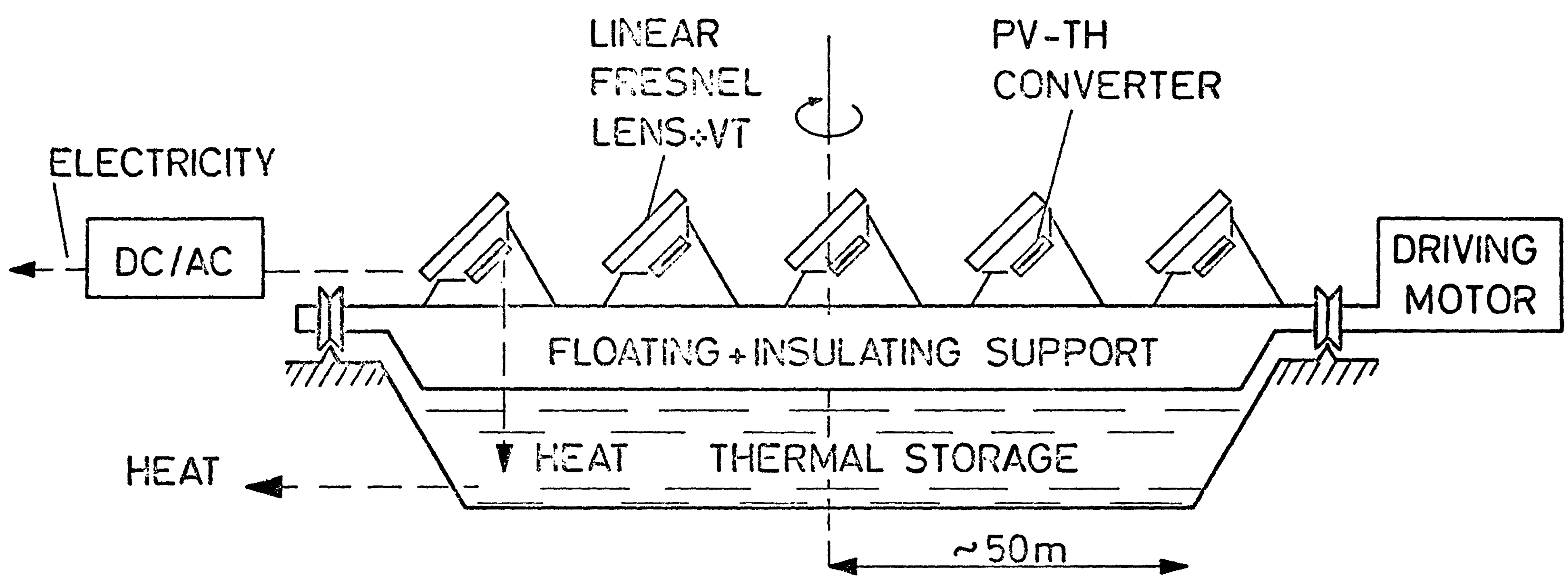


Figure 16

PHOTOVOLTAIC - THERMAL ENERGY CONVERSION SYSTEM



5000 m^2 (for 100 homes)

2000 $kWh_e/d + 18000\ kWh_{th}/d$

Figure 17

ponent may be estimated with sufficient accuracy from total horizontal radiation measurements using the (local) Liu-Jordan relation. Thus for many places the necessary information concerning the input can be found.

The second problem area concerns the photovoltaic converter. Whereas a few experiments indicate that silicon cells could be used for a wide range of concentration factors the economic aspects of a production of such cells still has to be investigated. For higher concentrations new designs like epitaxially grown cells or cells with window layers or very fine grids look promising. For still higher CR-values vertical junction silicon cells or III - V and II - VI cells should be investigated further. However, there is little doubt, that viable solutions can be found.

It remains the problem of the concentrator itself. For any large scale production of electricity one has to put rather stringent requirements on the allowable concentrator cost. Thus solutions on the basis of quasi-stationary systems or at maximum of systems with one axis rotation could have an economic advantage. Since long acceptance times and not too low CR-values are desirable, too simple optical systems will probably not be the final choice. But also in this area solutions will be possible : if these solutions will be economically valid has to be verified by extended tests under real conditions.

It is obvious, that even if our analysis indicates, that there is no major obstacle which prevents a success of the concentrator concept, the real proof that concentrator-converter systems are providing economical solutions, has to be obtained from demonstration projects of sufficient size. These alone could show that this concept leads really to those additional savings which probably would still be necessary even after the development of low cost solar panels. Concentration and cheaper cells, e.g. of the ribbon type for linear concentrators, could then allow us to reach that ultimate goal : the break-even point for solar electricity.

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FIGURE CAPTIONS

Fig. 1. Present and possible future cost distribution of photovoltaic energy conversion systems.

Fig. 2. Estimation of energy cost in c/kWh of various photoelectric concentration systems for a typical set of input parameters.

Fig. 3. a) Daily diffuse and daily total radiation, b) relative sunshine duration and monthly averages of daily diffuse/total and daily total/extraterrestrial radiation.

Fig. 4. Power output as function of incident intensity.

Fig. 5. Solar cell structures. A : conventional cell, B : cell with high intensity grid and modified front layer.

Fig. 6. Solar cell structures. C : window layer cell, D : vertical junction HI cell.

Fig. 7. Power output densities as function of light input. Points correspond to measurements by various authors.

Fig. 8. Optimum concentration ratio : a) irradiance at distance R from source S, b) sine condition of ray optics, c) sine condition for imaging systems with object at infinity.

Fig. 9. Projection angle β in function of hours from noon for various days in the year. The dashed line indicates an example for the acceptance time of a concentrator with total acceptance angle 2δ.

Fig. 10. V-trough concentrator with cone angle $2\ \Theta$.

Fig. 11. V-trough concentrator with Fresnel field lens.

Fig. 12. Compound parabolic concentrator.

Fig. 13. Parabolic trough concentrator with rim angle Θ.

Fig. 14. Linear Fresnel lens concentrator (in "collimator" mounting).

Fig. 15. Concentration factors as function of acceptance time for various linear devices.

Fig. 16. Concentration factor x relative acceptance time for various linear systems as function of date.

Fig. 17. Sketch of a photovoltaic-thermal converter system.

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