11
Photovoltaic Concentrators

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11.1 INTRODUCTION

Photovoltaic (PV) concentrators use lenses or mirrors to concentrate sunlight onto PV cells. This allows for a reduction in the cell area required for producing a given amount of power. The goal is to significantly reduce the cost of electricity generated by replacing expensive PV converter area with less expensive optical material. This approach also provides the opportunity to use higher performance PV cells that would be prohibitively expensive without concentration. As a result, concentrator modules can easily exceed 20% energy conversion efficiency. In the future, the use of multijunction cells is expected to increase this to over 30%. While the concept is simple, and has been examined since the time of the earliest interest in terrestrial photovoltaics, the practice has proven to be deceptively difficult. Concentrator research has focused much effort on the PV cells themselves, which are now largely developed and available commercially. The main remaining technical barriers, however, are due to the difficult cell packaging requirements stemming from the high heat flux and electrical current density, plus the need for more cost-effective and reliable tracking systems and module designs.

The main market barriers have been due to the fact that concentrating systems, which in most cases must track the sun, are not well suited to the existing PV market that serves small remote loads and, more recently, are building integrated applications. Concentrators were conceived of as a vehicle to generate large amounts of nonpolluting renewable energy. As yet, costs are still too high to compete with fossil fuel–fired generation, or even the most direct renewable competitor – wind power. The cost gap is narrowing, however, and there appears a strong likelihood that in the future concentrator systems will find cost-effective niche applications that will continue to expand as natural gas prices rise and concern over power-plant emissions increases. This chapter discusses the current state of the art in concentrating PV cells and systems and outlines issues remaining before full commercialization is possible.

Handbook of Photovoltaic Science and Engineering. Edited by A. Luque and S. Hegedus
 ISBN: 0-471-49196-9

This chapter is written for researchers and interested developers to be an instructive guide to the original literature in order to aid them in further development. It is not intended to be a stand-alone document. Most of the literature can be found in the various *Proceedings of the IEEE Photovoltaic Specialists Conferences* and the *European Photovoltaic Solar Energy Conferences*, along with a number of important books. Some of the material is less easily accessible in the form of various publications and reports of the US Department of Energy (DOE) and the Electric Power Research Institute (now called EPRI). Use of this latter type of material will be minimized.

The reader will be amazed at the variety of concentrator systems that have been explored. The concentration ratio (ratio of module aperture area to cell area) varies from 2 to 4 in static concentrator designs that require no sun tracking to over 1000 times in some two-axis tracking systems. The means of optical concentration includes a variety of two-axis and one-axis reflective and refractive approaches, as well as many novel means such as luminescent and holographic concentrators. While this wide variety gives support to the notion that a cost-effective approach will surely emerge, it nevertheless reminds the author of the early stage of many technology developments (such as airplanes) prior to the eventual emergence of the dominant concept (single wings with trailing rudder and elevator in the case of airplanes). In the same way as aircraft, the development of concentrators has been aided and impacted by the parallel development of materials and other technologies. For example, the once cumbersome aspect of finding and tracking the sun is now made relatively straightforward by the emergence of very low-cost computing technology, the Global Positioning System, and the like. On another path, developments in the global semiconductor industry often have direct application to concentrator cells. Examples include larger wafers, improved processing equipment, the emergence of organo-metallic chemical vapor deposition (OMCVD) for fabricating multijunction III-V cells, and improved packaging materials with superior thermal properties (e.g. AlN). Many of the technical issues facing further concentrator development can be thought of as material issues. These include the development of polymer reflectors with improved weatherability, lower cost molding methods for Fresnel lenses, and such. In other words, concentrator development takes place in the larger technology arena. New material and technology developments can come from any direction and make possible what was only a dream previously. Unfortunately, tracking the sun is still effected by the distinctly nineteenth-century technology of gears and motors. The necessity for tracking remains concentrating PV's Achilles heel.

11.1.1 The Concentrator Dilemma

In the 1970s, concentrators were originally conceived of as a technology for large power plants that provide wholesale electricity in competition with, or as replacement for, fossil fuel–generated power, that is, as a vehicle for reducing green house gasses, pollution, and for providing a renewable energy source as fossil fuels were depleted. PV markets, however, have evolved since the 1970s in a somewhat unexpected manner. Flat-plate (nonconcentrating) PV has emerged as an important and viable power source for small remote loads. In parallel, a subsidized, but vital and fast-growing, grid-connected market has emerged in many developed countries. Concentrators are not particularly suitable for these markets and have never gained a foothold in them. The issues of reliability and suitability for remote markets have plagued them from the start, and the new grid-connected markets most often use building-integrated or roof-mounted panels, for which concentrators have been found generally unsuitable. Meanwhile, fossil fuel prices have remained low in the face of abundant supply, and the international inability to seriously confront global warming and the external costs associated with pollution have limited the market for large PV power plants.

Several additional interesting factors have compounded the hurdle facing concentrators. First, semiconductor silicon material costs have declined in inflation-adjusted dollars to a level that is only 50% more than the long-term DOE goal for "solar grade silicon" set in 1975. Second, wire sawing has evolved as a far more cost-effective wafering solution than imagined at the onset. Third, nonconcentrating cell efficiencies are higher than envisioned because of the development of cost-effective back-surface fields, screen-printed grids, and the like. Standard modules have evolved as a more competitive power source than it was thought possible. In short, the incumbent technology, wafered silicon flat-plate modules, has been enjoying the benefits usually associated with an incumbent technology.[1] Continued improvements can be expected as manufacturing experience grows ever more rapidly. Finally, electric power markets have evolved in a manner that supports small amounts of nonpolluting distributed generation as opposed to large central plants, be they fossil-fueled or PV.

Today, developers of concentrators face a dilemma – what market to target. There are two possibilities: develop highly reliable systems for smaller applications or continue with the quest for large systems that displace significant power. Several major difficulties face the small remote market. One is that the module cost is only a fraction of the total installed system cost. Having a dollar per watt less module cost, as a concentrator module might offer, results in perhaps only a 10 to 20% overall reduction in total installed system cost. Second, the requirement for tracking structures restricts installation options and applications (for instance, it limits rooftop applications that are the biggest market for grid-connected systems), and begs the need for periodic maintenance. Another is the need for the manufacturer or installer to maintain a service network that can provide periodic maintenance. The prospects do not look too good for small concentrator installations, unless cost-effective low concentration static concentrators are developed, which eliminates the need for tracking. For large installations, the issue is more closely *cost*. Here installations compete with standard generation technologies (which have established low cost, but are vulnerable to fossil fuel depletion, cost escalation, and perhaps pollution concerns) and other renewables such as biomass and wind. Wind clearly has the lead with energy costs less than 5 cents/kWh at good sites. PV can easily coexist alongside the other options owing to its unique capabilities, competitive cost, and widespread applicability and scalability. Against wind, however, PV must look more to its particular advantages. These are easier siting close to the load, more distributed resource availability, less visual impact, and the like. Can concentrating PV get costs close enough to wind to compete, given its other advantages? This is a technology and market issue that is yet to be sorted out.

It is the author's opinion that concentrator developers can beneficially focus efforts on two approaches. The first is to continue to explore for cost-effective static concentrators

[1] In fairness, it should be noted that the other major alternative to wafered silicon, namely, thin film modules, has suffered from the same force.

that can compete in the standard flat-plate market and that use existing silicon solar-cell manufacturing infrastructure. The second is to focus on large installations and relentlessly seek lower cost through high-concentration, high-performance cells and designs that benefit from the economy of scale of large systems through artifices such as on-site assembly, automated installation, and the like. The goal must be to get large system costs below \$2.00/W. Attaining this goal is necessary, but not sufficient. Other market requirements are capturing some measure of social costs into the value stream, supportive utility transmission environment that enables renewable generators to effectively provide service, and eventually the development of new storage technologies and energy transport vectors such as hydrogen or global superconducting grids. Seen in this light, concentrators are not an immediate solution, but rather a long-range option of vital importance to the energy security of the world. Cost analyses indicate that it certainly has the possibility of becoming the low-cost PV approach in large installations. It is likely to find attractive niches initially in sun-resource-rich areas with little wind. Considerable risk investment will be needed to make it a reality. How the energy and investment climate evolves over the next few years, in the face of pollution concerns, global warming, and eventual fossil fuel depletion, is likely to dictate whether such capital will actually become available. It is hoped that this chapter helps guide researchers, policy makers, and investors to make it a reality.

This chapter begins by presenting an overview of the various types of concentrators. Then the history of concentrators is covered, followed by a section on the optical theory of concentrators, and finally a section on current concentrator research. Concentrator cells themselves operate by the same principles as nonconcentrating cells. Because of this, as well as space limitations, the design of concentrator cells is not covered in this chapter. The reader interested in the details of cell design specifically for concentrator applications is referred to the relevant literature [1, 2]. The methodology of concentrator cost projections is also not covered, although some results of this type of analysis are quoted. Further information on costs can be found in [3], as well as in many of the cited references.

11.2 BASIC TYPES OF CONCENTRATORS

Concentrators may be divided into different classes, depending on the optical means used to concentrate the light, the number of axes about which they move to track the sun, the mechanical mechanism that effects the tracking, and so forth. The major types are discussed below to acquaint the reader with the terminology. Detailed analysis of the operation of these devices can be found in Section 11.4.

11.2.1 Types of Optics

Most concentrators use either refractive lenses or reflective dishes and troughs. Lenses of any size over 5 cm in diameter will be too thick and costly to be practical; therefore, Fresnel lenses are usually chosen. A Fresnel lens may be thought of as a standard plano-convex lens that has been collapsed at a number of locations into a thinner profile. The facets may be either flat, if they are small and numerous enough, or actual sections of a curved lens surface. Fresnel lenses may be made either point-focus, in which case they have circular symmetry about their axis, or linear focus, in which the lens has a constant cross section along a transverse axis. Such lenses focus the light into a line. Point-focus lenses usually use one cell behind each lens, whereas line-focus lenses have a linear array of cells. A particularly successful linear configuration is the domed Fresnel lens. As will be seen in the section on concentrator optics, this minimizes the image dispersion coming from chromatic aberration and flexural distortion. It also provides the lens with greater rigidity. Domed point-focus lenses have also been developed. These variations are illustrated in Figure 11.1.

The material of choice for the lens is usually Acrylic plastic (polymethyl methacrylate or PMM), which molds well and has shown good weatherability. Nevertheless, there remain some long-term durability concerns for PMMA, and so attempts to make the lens from glass, or to mold the lens material to the underside of a glass substrate, have been made. So far, these ideas have remained in the laboratory.

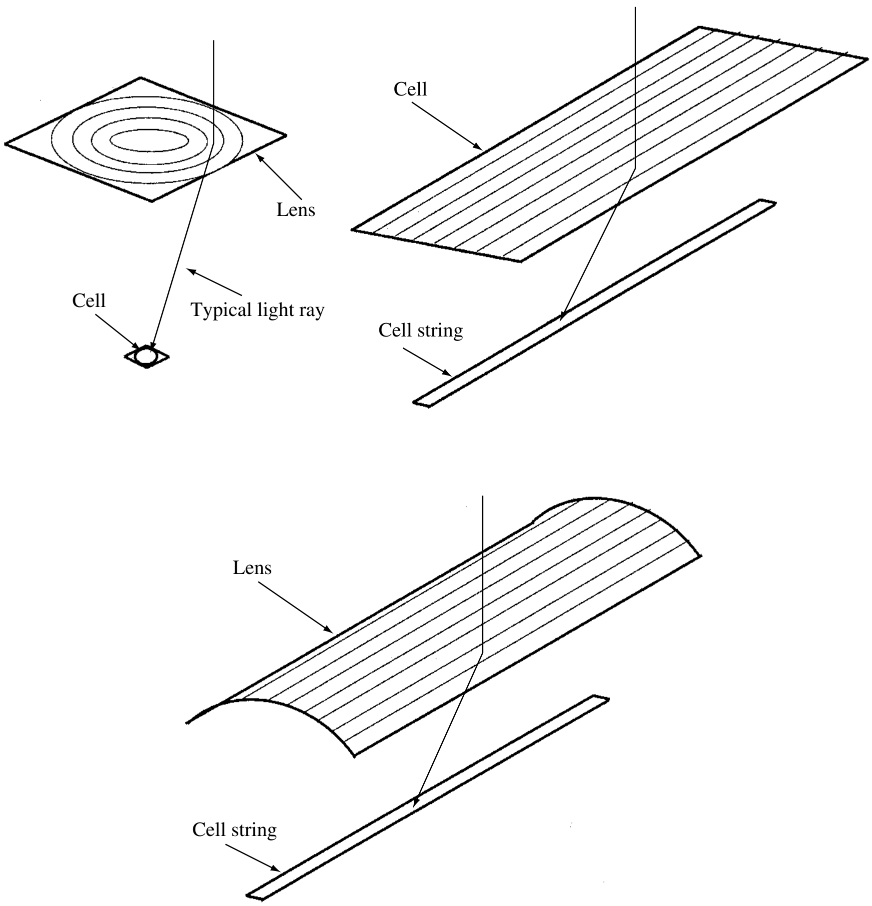


Figure 11.1 Fresnel lens configurations. (a) Point focus Fresnel lens showing a typical ray hitting the circular active area of the solar cell. (b) Linear, or one-axis, Fresnel lens focusing on a line of solar cells in a string. (c) Domed linear Fresnel Lens

Fresnel lenses are usually incorporated into modules that contain a lens, or multiple lenses in parquet, a housing to protect the backside of the lens, which is difficult to clean due to the sharp facets, and the cells. The cell may incorporate a secondary optical element (SOE) whose purpose is to further concentrate the light or to make the image more uniform. A typical Fresnel lens module is shown in Figure 11.9.

An alternative to refractive lenses is to use reflective lenses or mirrors. As is well known, a reflective surface with the shape of a parabola will focus all light parallel to the parabola's axis to a point located at the parabola's focus. Like lenses, parabolas come in a point-focus configuration (which is formed by rotating the parabola around its axis and creating a paraboloid) and line-focus configuration (which is formed by translating the parabola perpendicular to its axis). These configurations are illustrated in Figure 11.2.

Another approach is the compound parabolic concentrator (CPC) shown in Figure 11.24. Here the sides of the concentrator are parabolas; however, the focus for each side is at the opposite side of the cell and the axis of parabola *a* is along the direction of maximum acceptance angle, θ_{max}. The CPC is interesting in that it is a class of concentrator called "ideal," in that it provides the maximum possible concentration given the region of the sky it sees, or alternatively for a given maximum acceptance angle. It is also termed a "nonimaging" concentrator in that output bears no relation to the image of the sun. For high concentration, a CPC is rather tall and thin, and thus its use

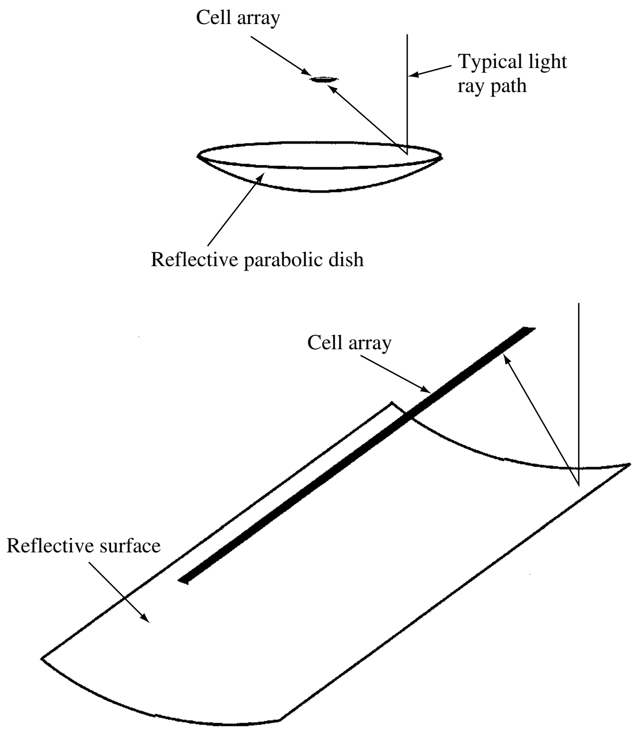


Figure 11.2 Reflective concentrator configurations. (a) Reflective paraboloid, or dish, focusing on a cell array. (b) Linear parabolic trough focusing on a line of cells

is restricted to either low concentration applications or as a secondary optical element. Nonimaging concentrators will be discussed more fully in Section 11.4.

11.2.2 Concentration Ratio

There are several definitions of concentration ratio in use. The most common is "geometric concentration ratio." This is defined as the area of the primary lens or mirror divided by the active cell area. The active cell area is the region of the cell that is designed to be illuminated. Unlike in most nonconcentrating systems, the entire cell need not be illuminated by the primary lens. The nonilluminated edge of the cell is often provided with buss bars for electrical connection, and this need not result in an efficiency loss as would be the case in a flat-plate module. Another measure of concentration is intensity concentration, or "suns." Since standard peak solar irradiance is often set at 0.1 W/cm^2, the "suns" concentration is defined as the ratio of the average intensity of the focused light on the cell active area divided by 0.1 W/cm^2. For example, if 10 W were focused onto a cell of 2-cm^2 active area, the intensity concentration would be 50 suns. If all the insolation from the direction of the sun (the so-called direct beam insolation), or more accurately from the region of the sky that is focused on the cell, had an intensity of 0.1 W/cm^2 and if the lens had 100% transmission, the geometric and intensity concentration would be the same. In actuality, whereas the global insolation is often close to 0.1 W/cm^2, the direct beam insolation is typically less. The difference is the diffuse insolation, the radiation that is scattered by the atmosphere or clouds, and comes from directions other than the sun. Typically, the direct beam radiation is around 0.085 W/cm^2 on a clear day, so many concentrator systems are rated at this level. If the lens has a transmission of 85%, then the intensity concentration will be $0.85 \times 0.85 = 0.72$ of the geometric concentration. In the above example the cell will be illuminated at 36 suns.

The reader will note that the reduction cell area through concentration, and hence cost for a given power, is not by a factor of one over the geometric concentration, but rather even less than the intensity concentration. First, the active area of the cell is often less than the actual cell area. A typical 1 cm $\times$ 1 cm cell will have an active area of around 0.8 cm $\times$ 0.8 cm = 0.64 cm^2. When it is also recognized that most concentrator cells are cut from a round wafer, much of the edge of the wafer cannot be used.[2] A 10-cm wafer will produce 52 cells of 1 cm $\times$ 1 cm (assuming 100% yield). Suppose this cell is operated at 100X geometric concentration. This means the primary lens is 8 cm $\times$ 8 cm = 64 cm^2. The total power on the cells from this wafer is then, assuming an 85% lens transmission, $0.85 \times 0.085 \times 64 \times 52 = 240$ W. If the wafer had been made into a flat-plate cell, it would have an area of 78 cm^2 and would receive a power of 7.8 W. Thus, the effect of the concentration is to increase the potential output by a ratio of 240 to 7.8, or 31. Our 100X concentrator is really only giving us a 31 times reduction in wafer usage.[3] This could still be very useful; however, sometimes, simplistic economic analyses of concentrators overlook this difference.

[2] Also in single crystal one-sun cells, silicon ingots are round (cylindrical) and they are rendered almost square (prismatic) by cutting off lateral silicon chips.

[3] This assumes equal cell efficiency in both cases. In actuality, it will be seen below that most concentrator cells have a higher efficiency than flat-plate cells. Weighed against this advantage is the fact that, except in the sunniest of regions, concentrating systems have lower annual capacity factor (ratio of annual output to rated power times the length of a year).

11.2.3 Types of Tracking

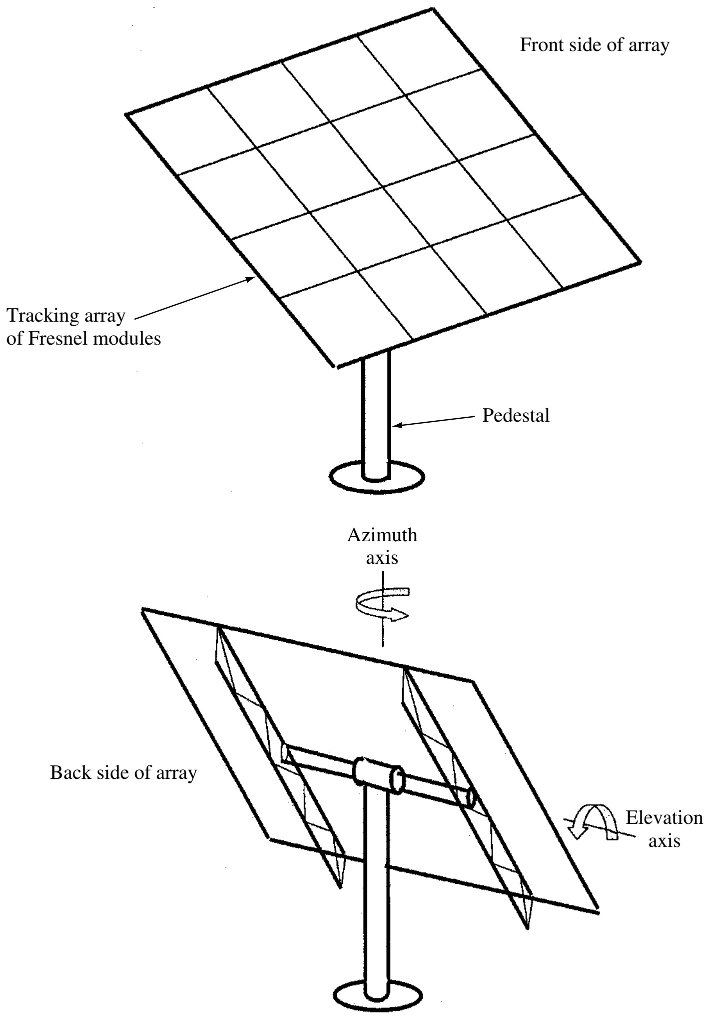
Point-focus optics generally require that the concentrator track about two axes so that it is always pointed at the sun, and the focused light falls on the cell. From a mechanical standpoint, two-axis tracking is more complex than one-axis tracking; however, point-focus systems are also capable of higher concentration ratio and hence lower cell cost. Line-focus reflective troughs need only track along one axis such that the image falls along the focus line. Linear Fresnel concentrators suffer severe optical aberrations when the sun is not perpendicular to the lens' translation axis. (Basically the focal length decreases as the sun's angle moves from normal to the lens.) This generally limits linear Fresnel systems to two-axis tracking. Modest geometric concentration ratios of around 10 are possible, however, if the lens tracks on a polar axis, which limits the sun's angle off normal to 23° maximum [4].

There are three common types of two-axis trackers as shown in Figure 11.3. The pedestal form uses a central pedestal supporting a flat tracking array structure. Tracking is usually effected by a gearbox, which tracks the array along a vertical axis (the azimuth rotation) and along a horizontal axis (the elevation rotation). An advantage of this configuration is the simplicity of installation (basically drilling a single hole, inserting the pedestal into the hole, back-filling with concrete, and placing the array and gear drive on the pedestal). A disadvantage is that wind loads are translated to the central gear drive in the form of very large torque, necessitating large capacity gears. Another form of two-axis tracking is the roll-tilt structure of Figure 11.3(b). Here wind loads on drive components are considerably reduced; however, there are now more rotating bearings and linkages required. Obtaining the required stiffness along the roll axis can necessitate a rather large-section horizontal support member. The structure also requires multiple foundations that must be aligned, complicating installation. The roll axis is most usually placed in a north–south direction, as this minimizes shadowing by adjacent modules along the roll axis. Another roll-tilt configuration uses a box frame with the Fresnel modules pivoted between the upper and the lower frame. This is shown in Figure 11.3(c). The final common configuration is the turntable of Figure 11.3(d). This structure provides for the lowest profile and lowest wind loading, and can use rather small drive components and support members. On the other hand, it presents the most complex installation scenario.

One-axis trackers are generally configured with either a horizontal axis of rotation or a polar axis of rotation as shown in Figure 11.4. A horizontal axis provides for lower profile and larger area per tracking structure, as compared to the polar-axis approach. Horizontal-axis trackers usually use reflective troughs. It can be seen that the sun can be at a fairly large angle to the array, especially in the winter with a north–south axis or early and late in the day with an east–west axis. This causes the image to move a distance down the focus axis and can result in significant end losses and image broadening. The polar-axis configuration, on the other hand, gives higher intercepted annual energy and limits the incoming sun angle to a maximum of 23° from the plane of the concentrator. The simplicity and low profile of the horizontal-axis configuration makes it the more common choice over the polar-axis approach.

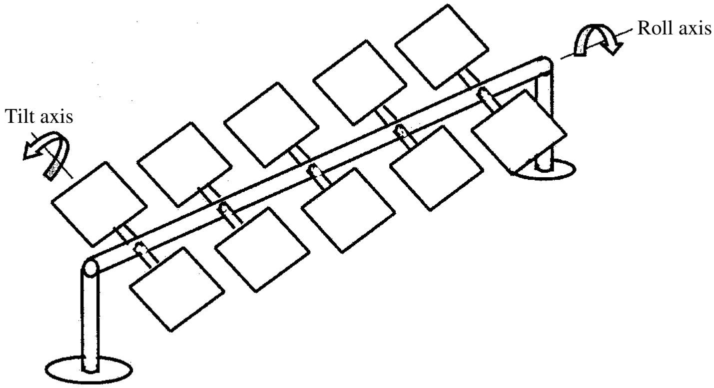
11.2.4 Static Concentrators

In principle, it is possible to provide some concentration without any tracking at all. The reasons for this are severalfold. First, the sun appears in only a restricted portion of the sky. For example, it will never be due north at zero-degree elevation to the horizon. This means that the ability of a flat-plate module to receive light from every direction is somewhat wasted. It can be seen in the section on concentrator optics that the maximum attainable concentration is related to the angular regions where the system can accept light in such a manner that if it can accept a fraction f of the diffuse light falling on it from all directions, then the maximum possible concentration is $1/f$. This relation is further enhanced by a factor of n^2 if the cell is immersed in a dielectric of index of refraction n. Since it is possible to build cells that can receive light from both sides, so-called bifacial cells, another factor of 2 is available by using bifacial cells. The sum result of these



(a)

Figure 11.3 Two-axis tracking configurations. (a) Two-axis tracker with elevation and azimuth tracking mounted on a pedestal. (b) Roll-tilt tracking arrangement using central torque tube. (c) Roll-tilt tracking arrangement using box frame. (d) Turntable two-axis tracker



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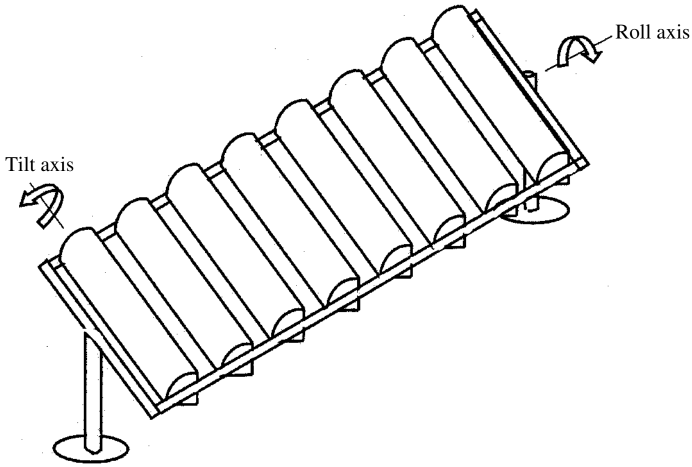

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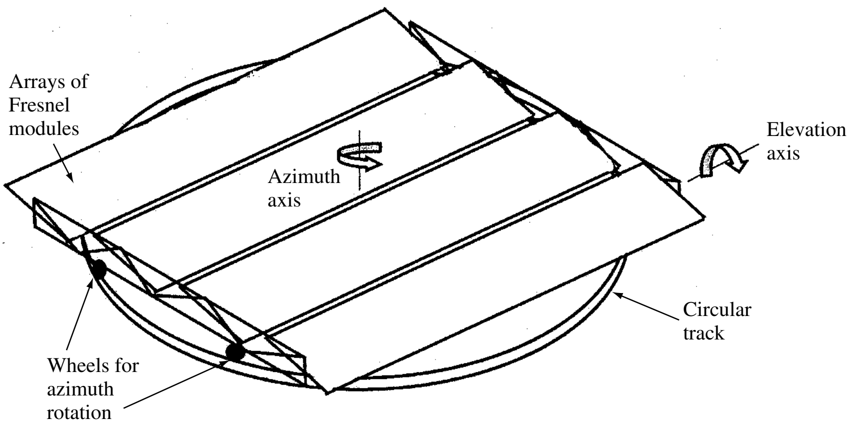

(d)

Figure 11.3 (*continued*)

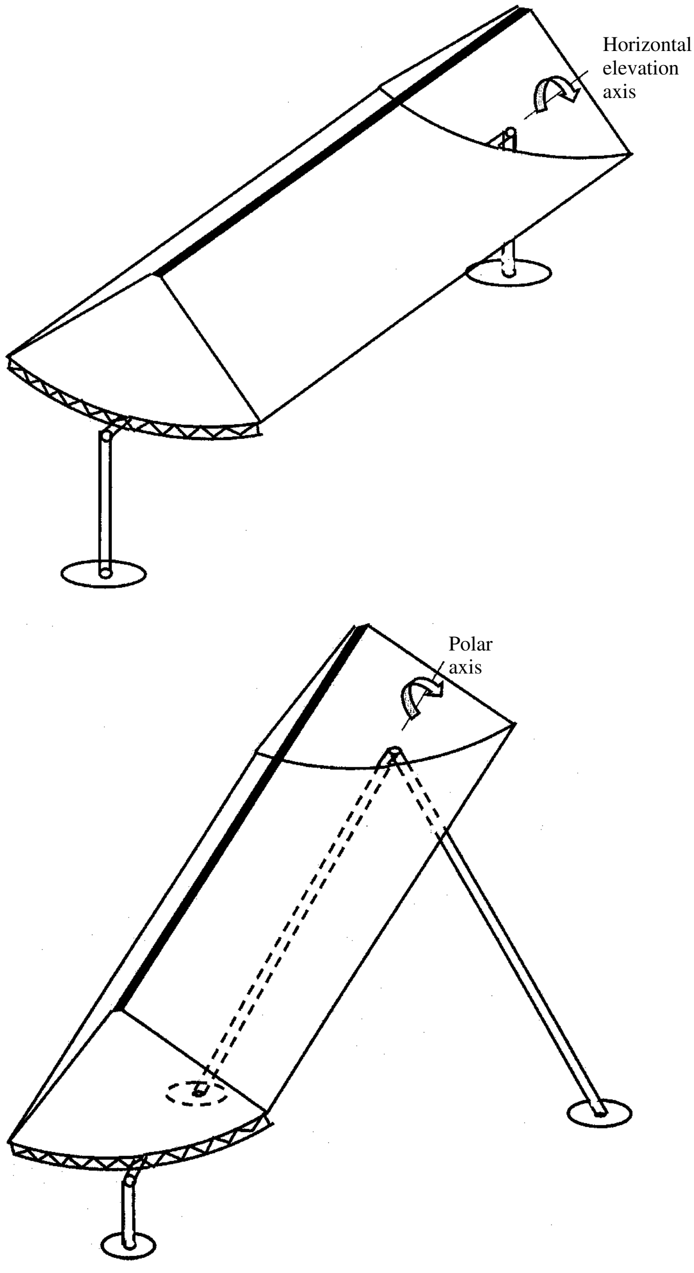

Figure 11.4 One-axis tracking configurations. (a) One-axis horizontal tracker with reflective trough. (b) One-axis polar axis tracker with reflective trough

effects is that static concentrator design with concentration ratios in the range of 2 to 12 have been proposed and researched. Usually they employ nonimaging optics such as the compound parabolic concentrator (CPC) shown in Figure 11.5 or total internal reflecting concentrators that will be discussed in Section 11.4.

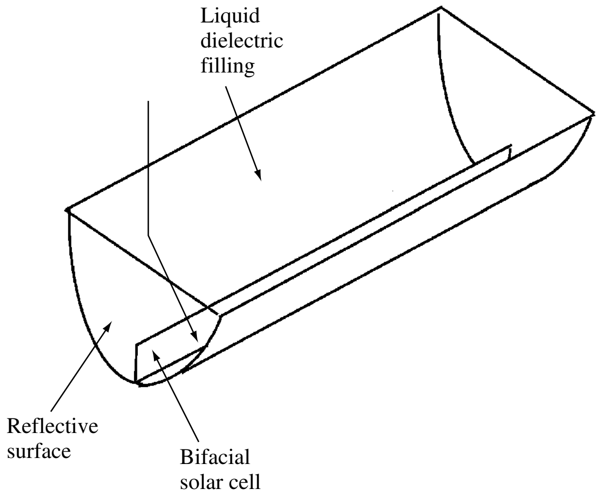

Figure 11.5 One of many static concentrator configurations. In this case a bifacial cell, which is sensitive to light from both surfaces, is mounted in a reflective CPC-like trough that is filled with liquid dielectric. The dielectric forms the dual role of cooling the cell and providing additional concentration

The allure of static concentrators is indeed great because of the elimination of the tracking requirement and, hence, the opening of the general PV marketplace to their use. Unfortunately, no static concentrator design has yet been found where the decrease in cell cost through concentration is sufficiently more than the added cost of the concentrator to warrant widespread commercialization. The discovery and development of a practical, cost-effective static concentrator would be a significant contribution to photovoltaics.

11.3 HISTORICAL OVERVIEW

This section reviews the early efforts to develop concentrators in order to put into context the issues facing current development efforts. The concept and practice of concentrators were well known to early workers in photovoltaics because many of the early solar thermal electric systems used concentrators to generate the high temperatures needed for efficient conversion. These systems generally relied on reflective concentrators that could benefit from the relatively mature technology of glass mirrors. Shuman's oft-mentioned solar electric system built in Egypt in 1913 used reflective troughs, and reportedly attained a conversion efficiency of 3 to 4% from sunlight to electricity [5]. It would be another 40 years before solar cells attained such performance.[4]

Bell Laboratories demonstrated the silicon solar cell in 1952 and developed it into a practical device of 10% conversion efficiency by 1955 [6]. The high cost of the cell precluded its use as a primary source of terrestrial energy, except in small, remote applications. Work on concentrating PV systems as a means to reduce cost began shortly

[4] Indeed, as discussed later, photovoltaic concentrators based on reflective troughs were able to achieve only 5% conversion efficiency in 1980.

thereafter. In the early 1960s, the Wisconson Solar Energy Center researched the performance of solar cells under concentrated sunlight. They showed that cells could operate at intensities of several hundred times normal sunlight [7]. The critical issues proved to be (1) reducing series resistance to enable efficient handling of the large currents involved and (2) maintaining low-enough cell temperature. Much of the improvement in concentrating systems since these early days has come from reducing the negative impact of these two factors. The Wisconson group went on to design a working 50-W system using a parabolic dish concentrator, thereby demonstrating the feasibility of the concept [8].

In 1965, Eugene Ralph, then with the Heliotek Division of Textron (later Spectrolab), proposed several approaches to concentrating systems, from low-concentration reflective cones to high-concentration heliostat fields. He clearly articulated the vision that concentrating PV systems might one day supply large amounts of terrestrial power [9]. At a time when flat-plate systems cost hundreds of dollars per watt, Ralph projected that megawatt-sized systems could be built in the future for less than $1.00/W. Interestingly, this is $5.40/W in current dollars, which is about what current concentrator systems would cost in megawatt production quantities.[5]

Despite these early efforts, not much happened in the development of practical concentrating systems until the energy crisis of 1973 renewed concerns about the availability and depletion of fossil fuels.

11.3.1 The Sandia National Laboratories Concentrator Program (1976 to 1993)

One of the US Government's responses to the issues raised by the 1973 oil crisis was to upgrade the status and funding of energy research, first, through the National Science Foundation's Research Applied to National Needs program, then through the Energy Research and Development Administration (a renamed and remissioned Atomic Energy Commission), and finally through the DOE, which was created in 1977. From the beginning, concentrators played a significant role in the mission to develop cost-effective PV power. Sponsored research began in 1976 and included university research at Arizona State University headed by Professor Charles Bacus, plus a variety of industrial laboratories. Sandia National Laboratories in Albuquerque, New Mexico, became the lead agency for managing the concentrator program. The first Project Integration Meeting was held in 1978 [10]. Already 19 subcontractors were under contract to develop cells and systems, and they reported their plans and progress. DOE established a goal of having commercial systems available in 1981 at $2.00/W. This proved wildly optimistic, but was in a grand tradition with other wildly optimistic projections about PV cost reductions. In fact, in constant dollars, this goal was achieved about 20 years later.[6]

[5] Unfortunately, this is only marginally less than the cost of today's flat-plate systems, and is still too expensive for large-scale power production. Another factor of three-cost reduction is needed. In later sections, this chapter discusses possible avenues for realizing this cost reduction; however, the reader should keep in mind that concentrator manufacturers are able to achieve these prices at rather small, almost prototype production volumes, whereas flat-plate modules are now produced in automated factories producing up to 100 MW/year.

[6] $2.00/W is $5.60/W in 2001 dollars, about what today's concentrators and flat-plate systems cost in large installations.

Almost every type of concentrating technology was explored during this period, including reflective dishes (Boeing), reflective troughs (Acurex, GE), point-focus Fresnel lenses (RCA, Varian, Motorola, Martin Marietta), linear Fresnel lenses (E-Systems), luminescent concentrators (Owens-Illinois), compound parabolic concentrators (Sun Trac, University of Chicago), and small heliostat fields with a central receiver (AAI). Silicon cell research was conducted at Purdue University, Arizona State University, RCA, GE, Applied Solar Energy Corporation, Spectrolab, and Motorola. Gallium arsenide cells were also researched at Varian, Hughes, The Research Triangle Institute, and Rockwell International. In addition to these outside contractors, Sandia conducted in-house research on cells, lenses, and systems. A dynamic research program was created that was coordinated and documented through annual review meetings.

In 1978, DOE initiated a program to test concentrator concepts called the *Photovoltaic Concentrator Applications Experiments*. Seventeen projects ranging in size from 20 to 500 kW were awarded Phase I contracts to do feasibility studies. These projects to a large extent covered the gamut of possible system options. Eight concepts were awarded continuing funding to build prototype systems. By 1980, system efficiencies for these prototypes ranged from 5% for the reflective trough systems to 10% for point-focus Fresnel systems, and 12% for linear Fresnel systems [11].

Early experience indicated that reflective approaches were much more problematic and difficult compared with Fresnel lenses, mainly due to flux uniformity issues [12]. This, along with funding constraints, led Sandia to focus on Fresnel lens systems for continued development. Flux uniformity remains a critical factor to be considered in all concentrator system designs.[7]

Two system approaches survived the cut and were deployed in large (for the time) demonstration projects. These were the point-focus Fresnel modules of Martin Marietta (later Intersol) and the line-focus Fresnel approach of Entech.

11.3.2 The Martin Marietta Point-focus Fresnel System

Martin Marietta participated throughout the Sandia program developing a series of point-focus Fresnel modules and systems.[8] First-generation units had four lenses per housing. The housing was made of injection molded plastic and each lens was 30 cm × 30 cm. The cells were round and of approximately 6-cm diameter (having been made from 2.25-inch diameter wafers), resulting in a concentration ratio of 33X, rather low for a point-focus system. These modules demonstrated efficiencies in the 9 to 10% range, placing the concept at the upper end of efficiencies at that time (1978). Figure 11.6 shows the overall design concept. The large extruded aluminum heat sink doubled as the structural mounting support. First-generation modules were deployed in two significant demonstration projects as discussed in the section describing the Sandia National Laboratories Concentrator Program.

[7] The reader will note that in a line-focus system in which the cells are connected in series along the focus, the source current will be limited by that of the cell receiving the least illumination. Minor flux nonuniformities thus have a serious impact on overall efficiency.

[8] In 1984, this work was "spun out" of Martin Marietta to a start-up dedicated to commercializing the technology by the name of Intersol.

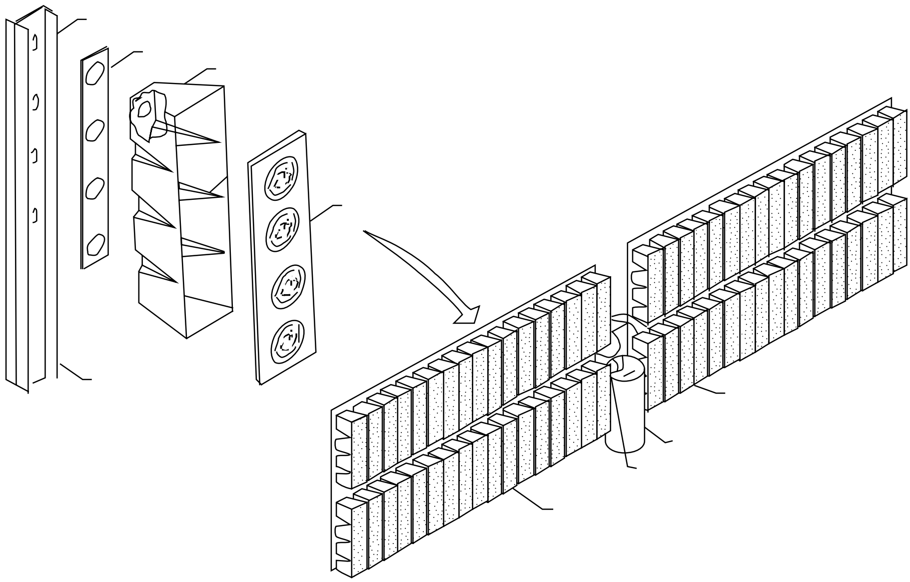

Figure 11.6 First-generation Martin Marietta point-focus design concept [13]. Reproduced with permission by Sandia National Laboratories

Martin Marietta and Intersol continued developing concentrator modules with support from Sandia. It was determined that the large lens and cell sizes resulted in a difficult situation regarding cell mounting and cooling. Therefore, the lens size was reduced to 23 cm × 23 cm and the concentration ratio increased to 70X. Reflective secondary concentrators were eventually incorporated to improve tolerance to tracking errors. There were now 14 lenses per parquet in a 2 × 7 arrangement and still mounted with a plastic housing. Now each cell was mounted on individual aluminum heat sinks. Figure 11.7 shows the second-generation unit introduced in 1983 [14].

Intersol improved the module performance to over 15% by 1984 [15], which clearly demonstrated the feasibility and promise of point-focus Fresnel concentrators. Despite this, no further large deployments were made using this technology, and Intersol ceased operations around 1986.

11.3.3 The Entech Linear-focus Fresnel System

Sandia also supported the continued development of a linear-focus Fresnel concentrator at Entech.[9] The heart of the Entech concept is an innovative domed Fresnel lens. Figure 11.8 shows a cutaway section of the Entech module. The principle of lens operation is similar to the SEA Corporation extruded lens shown in Figure 11.10. This lens has larger facets and so the operation is easier to see from a drawing. As illustrated, the domed shape allows the rays to have equal angles to the Fresnel surface at both incidence and exit. This has

[9] This concept was initially proposed by E-Systems in Dallas, Texas, and later spun out to a start-up company, Entech.

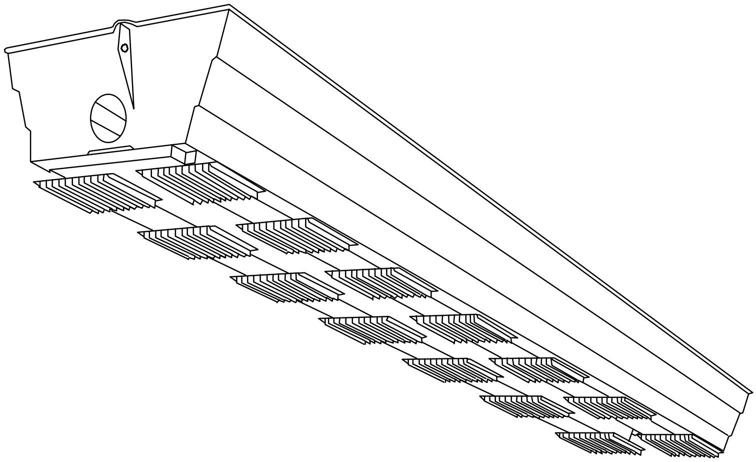

Figure 11.7 Drawing of Intersol second-generation module [14]. Reproduced with permission by Sandia National Laboratories

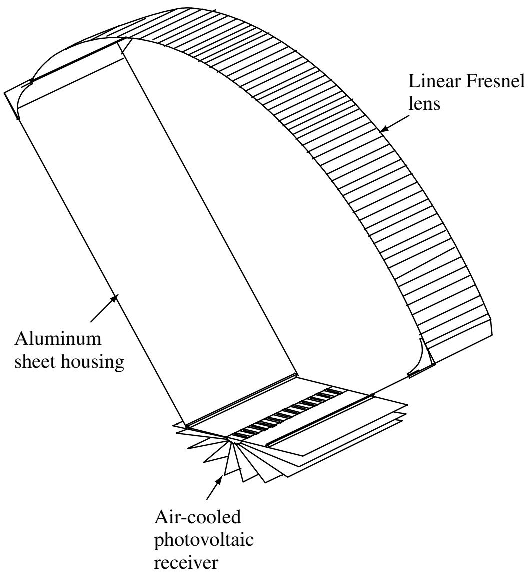

Figure 11.8 Cutaway view of the Entech domed Fresnel module [17]. Reproduced with permission by Sandia National Laboratories

four beneficial effects. First, it minimizes chromatic aberration caused by the index of refraction variation throughout the solar spectrum. Second, the angle of deflection of the ray is independent to the first order of the orientation of the prism. This minimizes the required tolerances in lens shape and minimizes the impact of lens deformation. Third, it minimizes the overall loss in transmission due to reflection. Finally, the nonplanar domed shape makes for a more rigid, self-supporting lens structure. 3M developed a roll forming process for the manufacture of Fresnel lenses that provided for a high speed, low-cost production method. Entech worked closely with 3M to develop Lensfilm™ versions of their lens. This proved to be an excellent combination, and early lenses exhibited transmissions of over 90% with reasonable manufacturing cost. Early versions of the Entech module had an efficiency of over 15% at standard test conditions (STC) [16], and this continued to improve throughout the program. Entech built four significant demonstration projects, as described below.

11.3.4 Other Sandia Projects

Throughout the 1980s, Sandia maintained a research program that included both in-house research and research sponsored at companies and universities. In-house activities included solar cell modeling and device research, module development, lens design and testing, cell packaging, and system testing and evaluation. Along with the large programs at Intersol and Entech, sponsored research included cell development at ASEC, Boeing, Varian, and university research at Purdue, Stanford, and the UNSW in Australia. This work was generally reviewed in periodic presentations at the IEEE Photovoltaic Specialists Conference. An illustrative discussion of this work toward the end of the program can be found in the 1988 review by Boes [18]. Rather than detail this work here, it will be covered in the relevant sections below.

Sandia developed a laboratory test module that demonstrated 20% conversion efficiency (STC), which pointed the way to eventual 20% commercial modules [19]. The Sandia module development culminated the Sandia Baseline III module [20]. This was intended as a concept design to be adopted and modified as needed by interested companies. Efficiency at STC was around 16 to 17%, placing it among the highest demonstrated performance for a manufacturable design at that time. Figure 11.9 shows the concept. Most commercial attempts at high-concentration modules have great similarities to this design.

11.3.5 The Concentrator Initiative

Despite over 15 years of sponsored research, no viable concentrator industry had emerged by 1990. Therefore, the DOE decided to create the Concentrator Initiative. This was

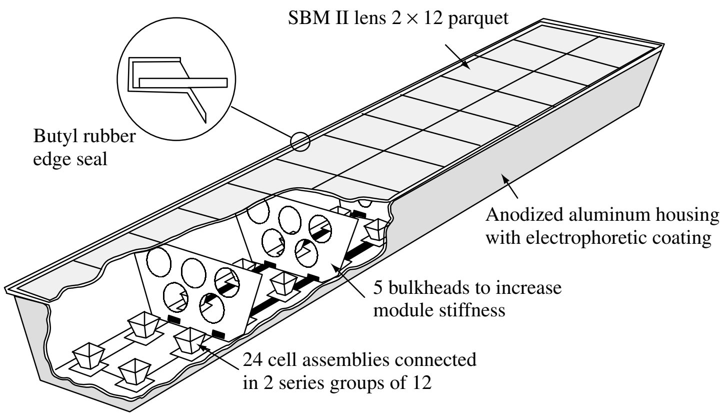

Figure 11.9 The Sandia Baseline III point-focus Fresnel module design. Reproduced with permission by Sandia National Laboratories

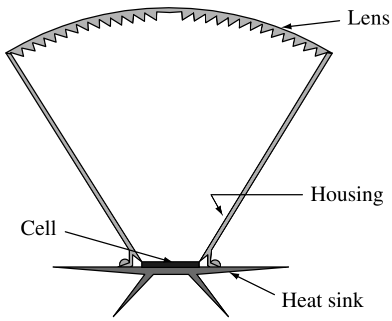

Figure 11.10 Cross-section of the SEA Corporation extruded lens linear Fresnel module. Reproduced from Kaminar N, Curchod D, "SEA 10X Module Development", Presented at *1990 DOE/Sandia Crystalline Photovoltaic Technology Project Review Meeting* (1990) with permission by Sandia National Laboratories

envisioned as a final push to jump-start a concentrator industry. Eight research contracts were let, four in cell development and four in collector development. The program was split between two low-concentration, linear-focus approaches and two high-concentration approaches. The low-concentration approaches were pursued by Entech, further refining the previous work they had done, and by SEA Corporation (later Photovoltaics International). SEA Corporation had developed an innovative extruded Fresnel lens, shown in Figure 11.10, which promised further cost reductions [21]. This lens is domed similarly to the Entech lens, and has therefore similar benefits.

The two high-concentration point-focus modules were developed by Alpha Solarco of Cincinnati, Ohio, and Solar Kinetics of Dallas, Texas. Both used modules similar to the Sandia Baseline 3 module, shown in Figure 11.9.

The high-concentration cell contracts were to Applied Solar Energy Corporation (ASEC), Spectrolab, and SunPower Corporation. SunPower was a new company created to commercialize concentrators based on the point-contact cell developed under EPRI funding described below. ASEC and Spectrolab adapted for concentration use the passivated emitter rear contact (PERC) cell developed by the University of New South Wales. Solarex worked on adapting the buried contact cell process from the UNSW to low concentration use. This program was reviewed by Maish in 1993 [22]. Despite excellent technical progress, funding shortfalls forced the termination of the program in 1993, and no long-lasting commercial effort resulted.[10]

11.3.6 Early Demonstration Projects

First-generation Martin Marietta modules were deployed in two significant demonstration projects. The first was the 350-kW SOLERAS system in Saudi Arabia and the second was a 225-kW system at the Phoenix Sky Harbor Airport. The SOLERAS system, which operated from 1981 to 1998, is shown in Figure 11.11. These systems demonstrated the

[10] SEA Corporation (later Photovoltaics International) continued under reduced funding for a period and deployed several demonstration projects prior to exiting the business in 2000. In addition, SunPower Corporation continues to market high concentration solar cells and Entech is working on space concentrator systems.

Figure 11.11 Photograph of the Martin Marietta 350-kW SOLERAS system in Saudi Arabia

viability of the concentrator concept, and despite being first-generation demonstration units, had a remarkably reliable operating history [23].

Entech built four significant demonstration plants. The first was a 27-kW combined heat and electricity unit at the Dallas Fort Worth Airport and the second was a 300-kW unit on the roof of a 3M parking structure in Austin, Texas. In 1991 they installed a 20-kW test system at PVUSA, a test facility operated at that time by PG&E. This system demonstrated an overall efficiency of 11% at PVUSA Test Conditions (PTC), making it the most efficient system tested at PVUSA [24]. Similar results were obtained for a 100-kW system installed at the Central and Southwest Services (CSW) site in Fort Davis, Texas. This is shown in Figure 11.12. Another 100-kW system was installed at the TU Electric Power Park in Dallas, Texas. Entech predicted an installed price of under \$3.00/W for their systems when produced at over 20 MW/year production rate [25]. Entech continued to participate in sponsored R&D through the Concentrator Initiative (discussed below) and PVMaT.

11.3.7 The EPRI High-concentration Program

The Electric Power Research Institute (EPRI) was formed in 1974 in response to the first energy crisis. It is sponsored by a consortium of member utility companies. EPRI was conceived to fill the void in utility-related R&D that existed because utilities traditionally had very limited R&D budgets. After reviewing the field, EPRI selected high-concentration systems as the centerpiece of its PV activity. These appeared most suited for achieving the low costs needed for large PV solar farms, which was the market application envisioned at the time. (Later, the EPRI program was expanded to include amorphous silicon and ribbon silicon.) EPRI began sponsoring research on high-efficiency cells at Stanford

Figure 11.12 Entech 100-kW line-focus concentrator system in Fort Davis, Texas. Reproduced with permission by Entech, Inc.

University in 1975. At first this was targeted toward ThermoPhotoVoltaic (TPV) conversion [26]. The concept was to use highly concentrated sunlight to heat a radiating surface to incandescence, and to use the resulting thermal radiation to produce electric power with a PV device. This was shown in principle to permit very high efficiencies, perhaps over 50%. The laboratory conversion of radiant energy to electric energy reached a high of 26% [27].

The concept in TPV conversion is to have the solar cell absorb light only for photon energies near the semiconductor band gap. The remainder of the spectrum is reflected back to the radiator. This creates the concept of "photon recycling" whereby photons with energies less than optimum for conversion are sent back to the radiator for recycling until they come back at the proper energy.[11] This recycling can be effected by several means, such as having a selective filter between the cell and the radiator or by having a reflector behind the cell and making the cell as transparent as possible to below–bandgap photons. In the EPRI/Stanford program, the latter approach was taken. Experiments showed that major losses in below band gap reflectance came from free carrier absorption in the doped junction regions as well as from absorption in the metal-semiconductor contact area. It was found that when the metal back contact was separated from the silicon by a thin, one-fourth-wavelength silicon oxide layer, the reflectance was very high. This led to the concept of the "point-contact cell" shown in Figure 11.13. The doping has been removed from the base, that is, very high resistivity silicon is used for the starting material and the diffused, highly doped junction regions are made as small as possible to reduce free carrier absorption to a minimum.

It was found that the point-contact cell structure had many unanticipated advantages, the understanding of which emerged over the following years. It was ideal for promoting light trapping in the silicon because of the reflective back contact, and contact-area recombination is reduced by restricting the contact coverage fraction. In addition, the

[11] The reader can see the reason for the requirement for a radiator in between the sun and the cell. If this was not present, nonoptimal photons would be reflected back to outer space. Interestingly, if the cell was at the focus of an optimal concentrator (Section 11.4), the reflected photons would be returned to the sun. This would be a reasonable proposition if we were paying to fuel the sun, but of course we are not. It can also be seen that the radiator and cell area must be large compared to the entrance aperture for concentrated light so that energy lost through the entrance will be small.

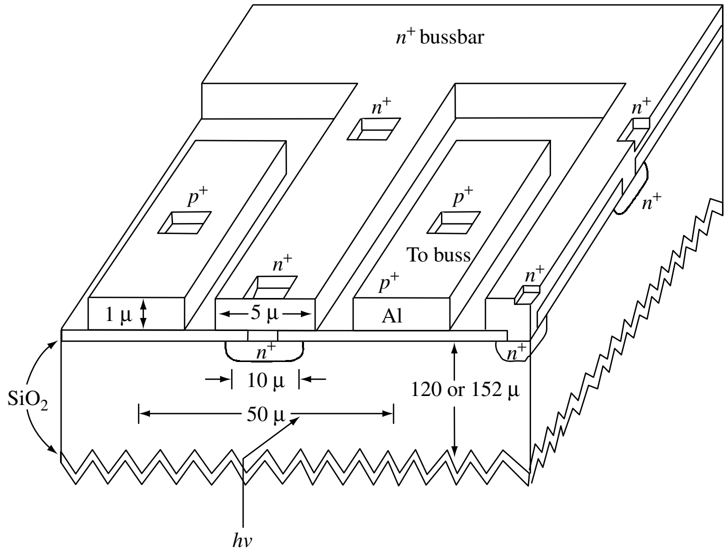

Figure 11.13 The point-contact cell design. Reproduced from Sinton R, Swanson R, "An Optimization Study of Si Point-Contact Solar Cells", Presented at *Nineteenth IEEE Photovoltaic Specialists Conference* (New Orleans, LA, 1987) with permission by © 1987 IEEE

oxide layer was found to produce very good surface passivation, which further reduced recombination. Many high-efficiency cell concepts such as the UNSW PERL (Passivated Emitter Rear Localized) cell [28] adopted these concepts to attain their performance. Solar TPV was found to have serious practical drawbacks, however. These included (1) ancillary absorption problems such as from radiator support mounts, (2) the difficulty of the very high concentration required (over 10 000X), and (3) material problems from the very high radiator temperatures of over 2000°C. The resulting high performance of point-contact TPV cells in normal sunlight was very compelling, however, and so in 1980 EPRI elected to abandon solar TPV and began developing normal high-concentration systems in which the sunlight impinges directly on the cell. The point-contact cell was further developed and reconfigured with all contacts on the back. These cells eventually reached a conversion efficiency of 28% [29]. Having all contacts on the back of the cell provides two main advantages. First, the shadowing of the top surface is eliminated. Second, the metal may be made to cover the entire back, reducing series resistance considerably (a particular advantage in concentrator cells).

EPRI funded the development of systems based on the point-contact cell starting in 1980. The initial system conceptual design work was performed by Black & Veatch. Figure 11.14 shows the resulting design. The design concentration ratio was 500X; geometric and reflective secondaries were used in a Fresnel module consisting of a 6 × 6 array of Fresnel lenses, each lens being 18 cm on a side [30].

Several large test arrays were built to check the mechanical and thermal performance of the structure. Unfortunately, these were not populated with cells because the point-contact cell was found to be unstable. The problem was traced to the generation of interface recombination centers at the $Si-SiO_2$ interface by ultraviolet photons. Several

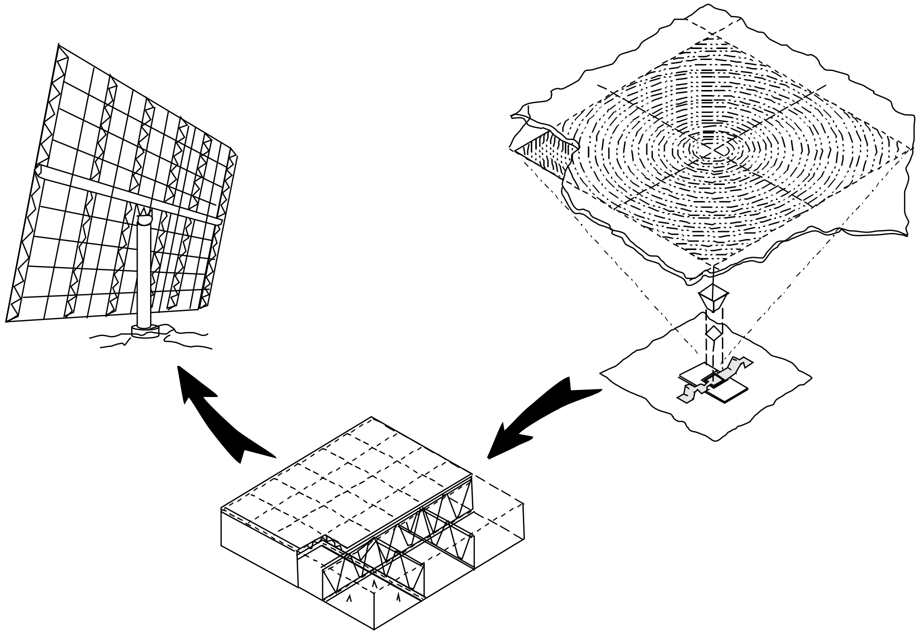

Figure 11.14 The Black & Veatch conceptual design for a high-concentration photovoltaic array. (Copyright © 1984. Electric Power Research Institute. *AP-3263. Conceptual Design for a High-Concentration (500X) Photovoltaic Array*. Reprinted with permission)

Figure 11.15 Static concentrator formed by an oil-filled CPC with bifacial cells

years of research were required to develop a UV-stable interface that had sufficiently low surface recombination velocity [31].

In 1989, EPRI decided to have a contract solicitation to continue commercialization of high-concentration systems. Two companies, SunPower Corporation and MACom/Phi (later spun out into a start-up called Amonix), were awarded contracts. SunPower explored reflective optics using parabolic dishes as well as heliostats [32] and Amonix continued the development of Fresnel modules using a simplified approach, the integrated backplane array [33]. EPRI terminated funding in 1993. Since then, Amonix and SunPower have continued development using other sources of funds. Both companies have since demonstrated modules with efficiency around 20%, showing the potential of point-contact silicon cells [34, 35]. These companies will be discussed in more detail in Section 11.5.

11.3.8 Other Concentrator Programs

Most PV concentrator activity, until recent times, was centered in the United States, probably because of the large direct normal solar resource located in the desert southwest region of that county. Cloudier regions were less prone to see an advantage in concentrators. Nevertheless, there were significant activities in Spain and small activities scattered elsewhere. The Spanish group at the Polytechnic University of Madrid, headed by Professor A. Luque, developed since 1975 bifacial cells for static concentrators, in order to achieve more concentration in static concentrators of the CPC type in Figure 11.5. Three different cell approaches were investigated with the support of the Spanish funding Agency CAICYT: a vertical multijunction cell, similar to the one developed in the United States by Sater and Brandhorst [36], and two more original structures, one n^+pn^+ interdigitated in the back [37] and another one n^+pp^+ [38], were examined and the latter was retained as the most promising and commercialized by the start-up Isofotón, today the seventh world cells manufacturer.[12]

The retained cell structure was based on the long base lifetime found in lowly doped silicon. Lowly doped silicon was thought at the time to produce low voltages, but as the cell operated in high injection the pp^+ homopolar junction provided additional voltage to the existing level of voltage in ordinary cells [39].

A module of size similar to a flat module was built [40], as shown in Figure 11.15. The optics is a derivation of the Winston's CPC. The concentrator was filled with transparent oil that allowed the concentration to increase and provided convective cooling to the bifacial cells. A geometrical concentration over 4 for a static system that collected the sunbeam for the full year was achieved.

The potential of concentrators based on diffusive reflectors of the sunlight, that is, of surfaces painted on white (or just snowed) were used with bifacial cells. This gave rise to the so-called albedo-collecting modules that consisted of flat modules of bifacial cells that collected the diffusely reflected light of a white background on its rear face. In some optimal cases the extra output due to the albedo was over 50% [39] but in most cases it was limited to around 20 to 30%. Figure 11.16 shows an example of such albedo-collecting fields.

Stimulated by the Sandia program, several groups in Europe developed similar approaches. In particular, three modules were developed by the LAAS of Toulouse, France, the Spanish Group of the Polytechnic University of Madrid, and the Italian company Ansaldo. A later additional effort was made at the Fraunhofer Institute for Solar Energy, Frankfurt, Germany. Both of these groups are active in concentrator systems today. Their activities will be covered in Section 11.5. One noteworthy concept from the

[12] This company, founded in 1981, stopped the production of bifacial cells around 1986, to fabricate the more conventional monofacial cells that they found cheaper to manufacture.

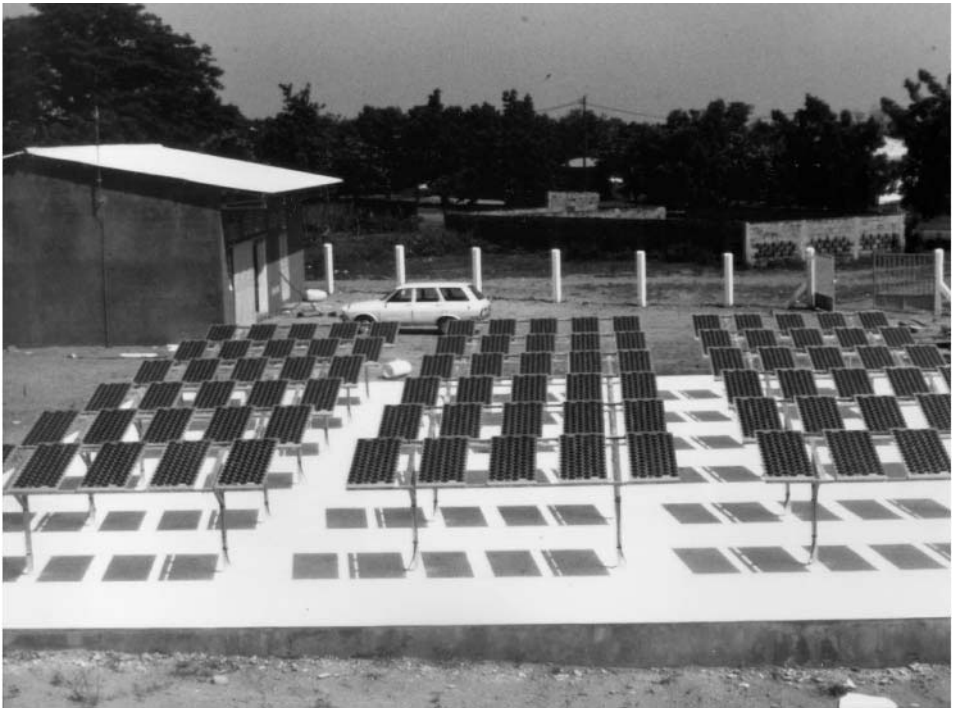

Figure 11.16 Albedo-collecting modules in a 10 kWp installation in the Senegalese village of Noto

Fraunhofer group is a one-axis tracing approach that achieves high concentration through the use of secondary optical elements [41]. The concept is shown in Figure 11.17.

11.3.9 History of Performance Improvements

The performance on concentrator cells and modules has steadily improved over time, as would be expected. Figure 11.18 presents the independently verified efficiency records from 1977 to 2001. Early silicon concentrator cells were basically 1-sun cells redesigned for high current by providing a fine, high metal coverage grid. The efficiency of this approach rapidly achieved 20% by 1982 [12]. The Swanson group at Stanford University introduced the back point-contact cell in 1984 with an efficiency of 22% [42]. The point-contact cell has maintained the efficiency record for silicon concentrator cells to the present. GaAs-based cells have always had superior performance to silicon. Varian introduced a 26% GaAs cell in 1980, and increased this to 29% in 1988. Unfortunately, it was eclipsed in 1988 by the first multijunction cell to set a record – a 31% mechanically stacked GaAs cell on a silicon bottom cell [43]. This result was eclipsed by a mechanically stacked GaAs on GaSb, which set a record that lasted until 2001. In 2000, Spectrolab announced a 32% monolithically stacked GaInP on GaAs cell [44]. They followed this up with a 34% result in 2001 (Spectrolab press release), finally outdoing the 1988 mechanically stacked record with a fully monolithic triple-junction cell.

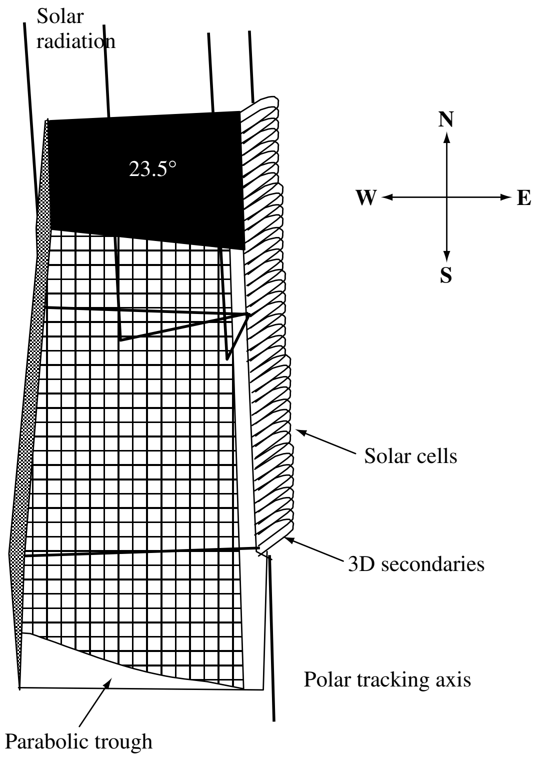

Figure 11.17 A two-stage concentrator permitting 300X concentration with one-axis tracking. Reprinted from *Sol. Energy*, **56**, Brunotte M, Goetzberger A, Blieske U, 285–300, © (2002), with permission from Elsevier Science

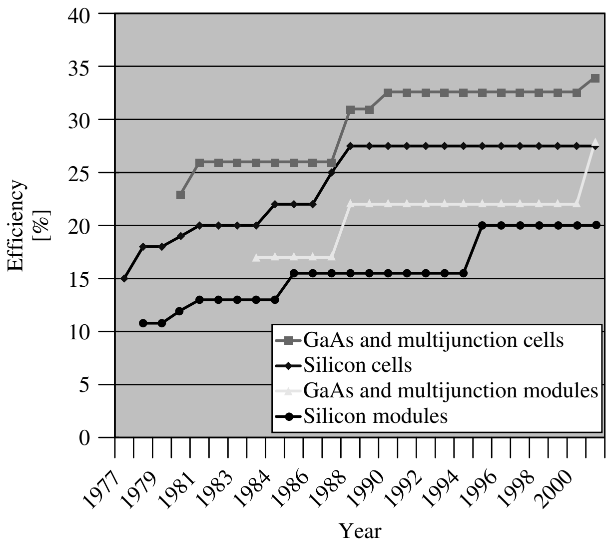

Figure 11.18 Record concentrator cell and module efficiencies

Generally, module improvements have followed the increase in cell efficiencies, with a lag in time to incorporate the cell into suitable packages. Noteworthy recent results are the 20% record held by point-contact silicon-based modules since 1995 [34, 35], and the recent 28% multijunction module based on an Entech domed Fresnel lens [45].

11.4 OPTICS OF CONCENTRATORS

The basic concept of light concentration by reflective or refractive means is conceptually simple and straightforward. Simple lenses are generally imaging devices. Some thought, however, will reveal that in a concentrator system, an image of the sun is not needed, or even desired. What is desired is to gather the light as efficiently as possible onto a receiver that is smaller than the concentrator's entrance aperture. As a further requirement, it is often desirable to have the receiver illuminated as uniformly as possible. Another important consideration is that it is generally desirable to have the concentrator accept light from as large an angular region as possible. This minimizes the accuracy at which the concentrator must be pointed toward the sun and thereby relaxes structural requirements and assembly tolerances. These factors, which are generally different from the ones encountered in traditional optical system design, spurred a whole new discipline called *nonimaging* optics. This field was pioneered by Professor Roland Winston and his group at the University of Chicago [46]. Another center of excellence in nonimaging optics developed at the Polytechnical University of Madrid. It is beyond the scope of this chapter to cover the principles of nonimaging optics, for that is a difficult topic that is well covered in textbooks [2, 47].

11.4.1 Basics

One of the remarkable theorems of nonimaging optics is that there exists a relationship between the maximum angle that is accepted by the concentrator and the maximum possible concentration that is attainable, $C_{\max}$. Consider the schematic representation of a general concentrator shown in Figure 11.19. Here the light that hits the entrance aperture, of area A_{conc}, at an angle less than $\theta_{\max,\text{in}}$ from the normal is transmitted to the exit aperture where the receiver of area A_{rec} is located (PV cells in our case), emerging at an angle less than $\theta_{\max,\text{out}}$ to the normal of the receiver. For one-axis, or two-dimensional, concentrators the following relationship holds:

$$C = A_{\text{conc}}/A_{\text{rec}} \le C_{\max} = \sin(\theta_{\max,\text{out}})/\sin(\theta_{\max,\text{in}})$$

For two-axis, or three-dimensional, concentrators the corresponding maximum is

$$C = A_{\text{conc}}/A_{\text{rec}} \le C_{\max} = \sin^2(\theta_{\max,\text{out}})/\sin^2(\theta_{\max,\text{in}})$$

If the receiver is immersed in a dielectric medium of index of refraction n, then these relationships become

$$C = A_{\text{conc}}/A_{\text{rec}} \le C_{\max} = n\sin(\theta_{\max,\text{out}})/\sin(\theta_{\max,\text{in}})$$

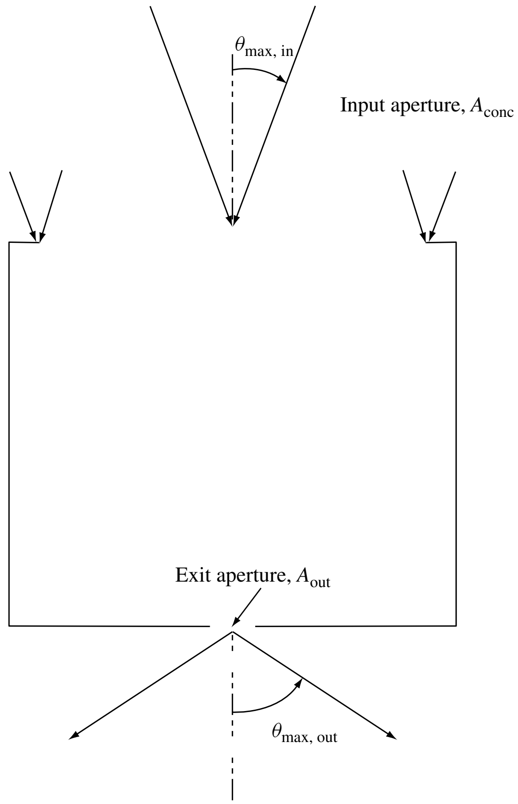

Figure 11.19 Schematic representation of a generalized concentrator

and

$$C = A_{\text{conc}}/A_{\text{rec}} \leq C_{\text{max}} = n^2 \sin^2(\theta_{\text{max,out}})/\sin^2(\theta_{\text{max,in}})$$

respectively. A concentrator that achieves this maximum is called an *ideal* concentrator.

Some observations are in order. First, in order to attain the maximum concentration, it is necessary to have $\theta_{\text{max,out}}$ as large as practical. The maximum it could be is 90°, but even angles approaching this result in many rays striking the receiver at grazing angles. This may prove impractical, as such rays are prone to have high reflectance and can easily miss the target owing to mechanical alignment errors. The above equations are often stated when $\theta_{\text{max,out}} = 90°$, whereby they become

$$C = A_{\text{conc}}/A_{\text{rec}} \leq C_{\text{max}} = n/\sin(\theta_{\text{max,in}})$$

and

$$C = A_{\text{conc}}/A_{\text{rec}} \leq C_{\text{max}} = n^2/\sin^2(\theta_{\text{max,in}})$$

in the two and three-dimensional case, respectively. The designer is cautioned, however, not to persist in designing concentrators with very large exit angles just to gain higher concentration ratio.

If one designs a concentrator that accepts as a maximum input angle the half angle of the sun as seen from the Earth, about 1/4°, then it could have a maximum concentration of about 200 in the two-dimensional case and 40 000 in the three-dimensional case. Such a concentrator would accept light only directly from the surface of the sun. Regions of the sky outside this area would be rejected by the concentrator; that is, it would not reach the receiver. Interestingly, the concentration of 40 000 restores the radiative power density at the receiver to that at the surface of the sun. This leads to a simple proof of the above equations. Suppose we have a hot spherical radiator, which could be the sun but need not be, that is radiating black-body radiation. A portion of the radiation is intercepted by a concentrator as shown in Figure 11.20.

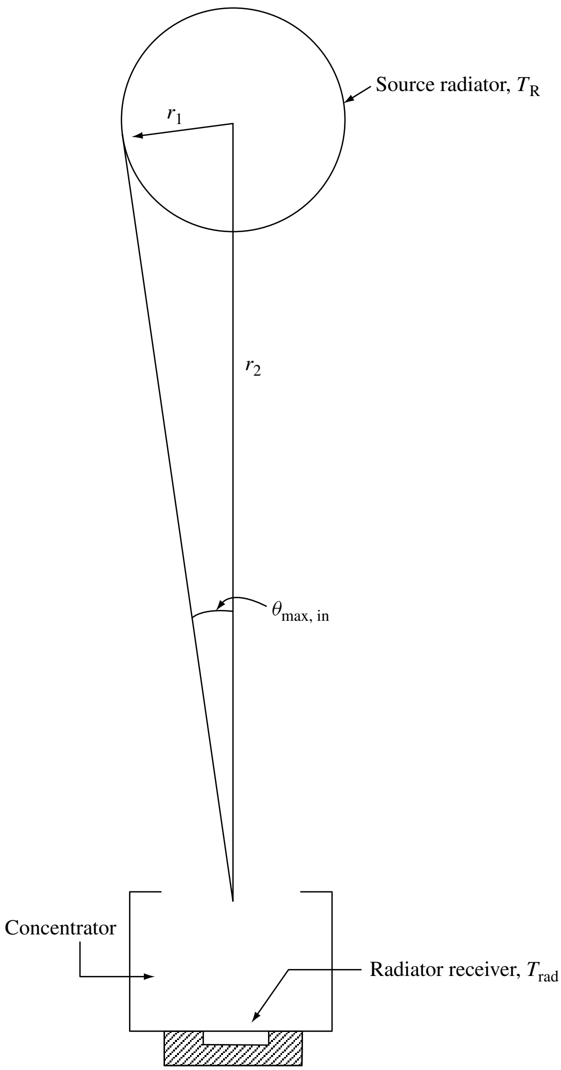

Figure 11.20 Geometry of a spherical radiator and concentrator

If r_1 is the radius of the radiator and r_2 is the distance from the center of the radiator to the concentrator input, then it is clear from Figure 11.20 that $\sin\theta_{\mathrm{max,in}} = r_1/r_2$. If we assume that the radiator is radiating as a black body, then the total power density at the surface of the radiator is $P_{\mathrm{rad}} = \sigma T_{\mathrm{s}}^4$, where σ is the Stefan Boltzmann constant and T_{s} is the radiator source temperature. Simple geometry gives the power density at the entrance to the concentrator as $P_{\mathrm{canc}} = (r_1/r_2)^2 P_{\mathrm{rad}} = \sin^2\theta_{\mathrm{max,in}} P_{\mathrm{rad}}$. The power density at the receiver is simply that at the concentrator entrance, multiplied by the concentration ratio, so $P_{\mathrm{rec}} = C\sin^2\theta_{\mathrm{max,in}} P_{\mathrm{rad}}$. Now, imagine that the receiver is a black body insulated so that its only heat loss is by thermal radiation back from the receiving surface. Then the receiver will heat up until it is losing power by thermal radiation at the same rate it is receiving it. This will occur when the receiver is at a temperature such that $P_{\mathrm{rec}} = \sigma T_r^4$. Equating this to the received power above

$$P_{\mathrm{rec}} = \sigma T_{\mathrm{r}}^4 = C\sin^2\theta_{\mathrm{max,in}} P_{\mathrm{rad}} = C\sin^2\theta_{\mathrm{max,in}}\sigma T_{\mathrm{s}}^4$$

or

$$C = \frac{T_{\mathrm{r}}^4}{T_{\mathrm{s}}^4}\frac{1}{\sin^2\theta_{\mathrm{max,in}}}$$

Now, here is the thermodynamic part. It must be that $T_{\mathrm{r}} \le T_{\mathrm{s}}$, for otherwise heat would be transferred from the source at a lower temperature to the receiver at a higher temperature without the use of work, in violation of the second law of thermodynamics. In other words, if the receiver was hotter than the source, one could build a perpetual motion machine. Inserting this inequality into the above equation gives

$$C \le C_{\mathrm{max}} = \frac{1}{\sin^2\theta_{\mathrm{max,in}}}$$

The origin of the n^2 in the concentration equation can be seen from the fact that in a dielectric medium, the Stefan Boltzmann law becomes $P = n^2\sigma T^4$. The factor n^2 comes from the fact that the three-dimensional electromagnetic mode density is increased by n^3 owing to the decrease in wavelength by $1/n$, but the speed of light is decreased by $1/n$. Therefore, in thermal equilibrium, the density of photons is increased by n^3, but the number of photons crossing a surface per unit time, and hence the power crossing this surface, is increased by only n^2.

If a concentrator can accept light from anywhere in the upper hemisphere, then $\theta_{\mathrm{max}} = 90^\circ$ and $C_{\mathrm{max}} = 1$, or $C_{\mathrm{max}} = n^2$ if the receiver is immersed in a dielectric. The history of concentrators is replete with proposed concentrators that achieve high concentration without tracking the sun; that is, it will accept light from any point in the sky. In each case the concept is supposed to skirt the maximum concentration theorem by some means. Examples are the use of diffraction (as with holograms), or bent light fibers, or quantum dyes (as in luminescent concentrators[13]). Most derivations of the maximum concentration theorem are based on geometric optics, and so it is conceivable that it could be

[13] The case of luminescent concentrators requires more care because of the spectral shift. This can be done by incorporating spectral filters into the thermodynamic analysis, but the finding is that they have rather limited concentration and efficiency potential.

violated by diffraction, for example. But the thermodynamic basis of this theorem shows that the search for a nontracking concentrator with high concentration is doomed to fail.

By restricting the acceptance angles to the region of the sky where the sun is actually found, modest concentrations on the order of 2 to 3 are possible. A further factor of 2 is obtained by using bifacial cells that can accept light from both top and bottom. If the cell is immersed in a dielectric of $n = 1.4$, then yet another factor of 2 is possible. This means that it is possible in principle to obtain concentration ratios of up to around 8 to 12 without tracking the sun. The search for practical, cost-effective static concentrators is ongoing and discussed in Section 11.5.

11.4.2 Reflection and Refraction

Most concentrators use reflection, refraction, or a combination of both to effect their concentration, and standard geometric optics is appropriate for their analysis. Some concepts use diffraction gratings or graded index materials, but that is beyond the scope of this discussion. It is assumed that the reader is familiar with elementary optics. The laws governing light rays at reflective and refractive interfaces are well known; the angle of reflection equals the angle of incidence in the case of reflection and Snell's law in the case of refraction. For three-dimensional analysis, a vector formulation is convenient. Figure 11.21 shows the incident and reflected rays at a reflective surface where the unit vector normal to the surface, and pointing in the direction from which the rays are coming, is **n**. The following vector equation is easily derived relating the reflected ray to the incident ray and **n**:

$$\mathbf{r}_r = \mathbf{r}_i + 2(\mathbf{n} \cdot \mathbf{r}_i)$$

In the case in which a ray is incident at a boundary between two dielectric media, Snell's law applies. This is usually expressed as $n_2 \sin\theta_2 = n_1 \sin\theta_1$, where the coplanarity of the rays is understood. A vector form that expresses this is

$$n_1\mathbf{r}_1 \times \mathbf{n} = n_2\mathbf{r}_2 \times \mathbf{n}$$

Simple geometric shapes can be analyzed analytically using these relations, but modern practice is to use one of the many available ray-tracing packages that solve these equations numerically. This allows for incorporating various imperfections such as surface waviness and imperfections, and can give plots of the intensity profile at the receiver, and so on.

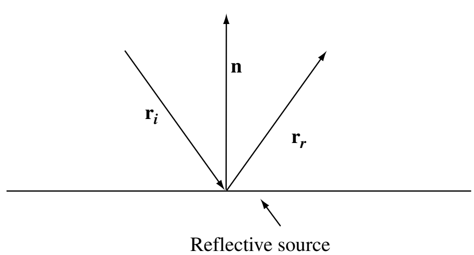

Figure 11.21 Relationship of the incident and the reflected rays to the surface normal

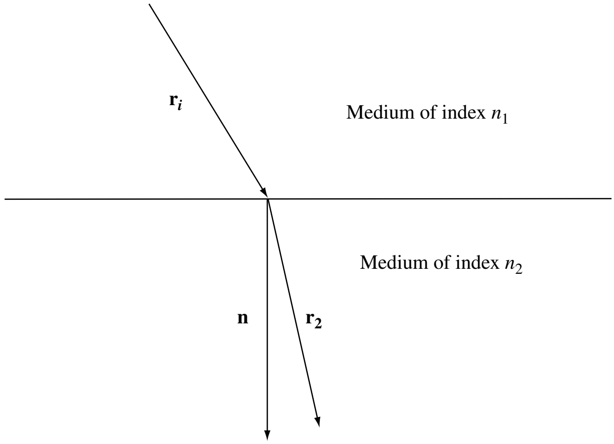

Figure 11.22 Vector relations during refraction

11.4.3 The Parabolic Concentrator

A basic concentrator configuration is the reflective parabolic concentrator shown in Figure 11.23. The two-dimensional cross section is shown, which could represent the cross section of either a two-dimensional linear parabolic trough or the cross section of a three-dimensional paraboloid of revolution.

The equation relating the x and y components of the parabolic surface is $y = 1/4Fx^2$, where F is the focal length of the parabola. It can be shown that all rays coming from straight up (i.e. with no x-component) will pass through the focus. If D is the diameter or width of the parabola, then this can be written in the normalized form

$$\frac{y}{D/2} = \frac{1}{8f}\left(\frac{x}{D/2}\right)^2$$

where $f = F/D$ is called the f-number of the parabola. Note that if $f = 1/4$, then when $x = D/2$, that is, at the rim of the parabola, $y = D/4 = F$. In other words, for an $f = 1/4$ parabola, the rim height is equal to the focal length. Obviously the slope at the rim is then 45°. Another useful relation that relates the distance from the focus to the parabolic surface, r, to the angle that the ray hits the receiver, θ_r, is

$$r = \frac{2F}{1 + \cos\theta_r}$$

and

$$x = r\sin\theta_r = \frac{2F\sin\theta_r}{1 + \cos\theta_r}$$

From this we can see that at the rim, when $x = D/2$ and the angle of rays at the receiver is maximum, we have

$$f = \frac{F}{D} = \frac{1}{4}\,\frac{1 + \cos\theta_{\max,r}}{\sin\theta_{\max,r}}$$

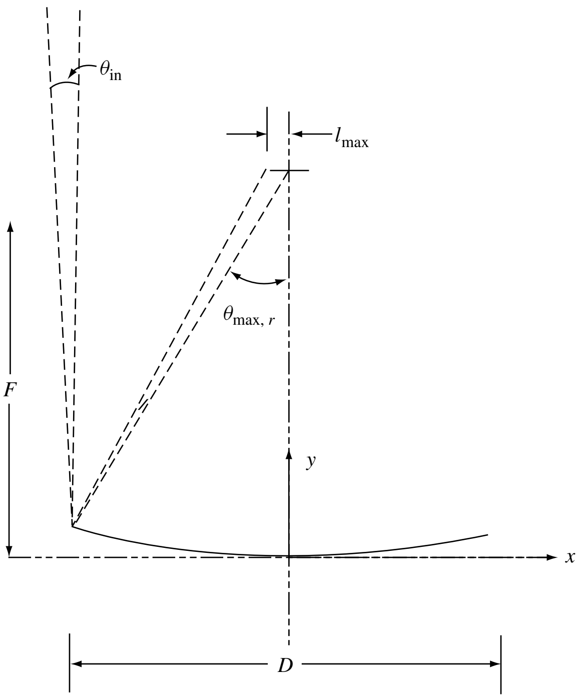

Figure 11.23 Cross section of a parabolic reflective concentrator

Now consider a ray that arrives at a small angle θ_{in} to the normal axis. It can be calculated that it will intercept the receiver at a distance s from the focus given by

$$s = \frac{r \sin\theta_{in}}{\cos\theta_r} = \frac{2F \sin\theta_{in}}{\cos\theta_r(1 + \cos\theta_r)}$$

This shows that s increases as one moves toward the rim, increasing θ_r. Clearly, the rays hitting the rim at $x = D/2$ will have the largest s. Noting that the total receiver size, S, required to capture all rays up to incident angles of $\pm\theta_{max,in}$ is $S = 2s_{max}$, gives

$$S = \frac{4F \sin\theta_{max,in}}{\cos\theta_{max,r}(1 + \cos\theta_{max,r})} = D\frac{\sin\theta_{max,in}}{\cos\theta_{max,r} \sin\theta_{max,r}}$$

For a two-dimensional parabolic trough, the concentration ratio is $C = D/S$, giving

$$C = \cos\theta_{max,r}\frac{\sin\theta_{max,r}}{\sin\theta_{max,in}}$$

It is interesting to note that the maximum concentration for a parabola without a secondary occurs at a rim angle of 45° (which corresponds to an f-number of 0.6) and is

$$C = \frac{1}{2}\frac{1}{\sin\theta_{max,in}}$$

When $\theta_{\text{max,in}}$ is 1/4°, as for the sun, this equation gives a maximum concentration ratio of 100. We see that the parabola is not an ideal concentrator, but at a rim angle of 45° it does achieve half of the maximum possible concentration. As the rim angle becomes small, it actually approaches an ideal concentrator because then $\cos\theta_r \approx 1$, but at small rim angles the concentration ratio is also lowered. A parabola can be used in conjunction with various secondary concentrators located at the receiver to boost the concentration toward the ideal. If we have an ideal secondary concentrator that transforms $\theta_{\text{max},r}$ into $\theta_{\text{max,out}}$, then it would have a concentration of $C_{\text{secondary}} = \sin\theta_{\text{max,out}}/\sin\theta_{\text{max},r}$. The combined concentration of the parabola and secondary is

$$C_{\text{tot}} = C_{\text{secondary}} C_{\text{parabola}} = \cos\theta_{\text{max},r} \frac{\sin\theta_{\text{max,out}}}{\sin\theta_{\text{max,in}}}$$

This differs from an ideal concentrator of maximum output angle and high concentration by the cosine of the rim angle and approaches an ideal for small rim angles. In practice, small rim angles result in a rather unwieldy shape and a compromise is sought. The f-numbers in the range of 0.7 to 1 are usually specified when using a secondary concentrator.

For three-dimensional paraboloidal concentrators, one squares the above ratios to get the concentration. Specifically,

$$C = \cos^2\theta_{\text{max},r} \left(\frac{\sin\theta_{\text{max},r}}{\sin\theta_{\text{max,in}}}\right)^2$$

and at a rim angle of 45°, we have

$$C = \frac{1}{4}\left(\frac{1}{\sin\theta_{\text{max,in}}}\right)^2$$

This gives a concentration ratio of 10 000 for a perfect paraboloid with $f = 0.6$.

Parabolic dishes are thus capable of quite high-concentration ratios. In practice, slope errors, or waviness in the reflective surface, degrade the performance. This can be analyzed to first approximation by realizing that a slope error of value θ_s will cause the reflected ray to deviate from the intended path by $2\theta_s$, and this will add to the angle of arrival $\theta_{\text{in,max}}$. A high-quality paraboloid for solar concentration use might have $\theta_s = 1/8°$, thus doubling the divergence of light from the sun from 1/4° to 1/2°. This has the effect of decreasing the concentration by one-fourth, to 2500 for a three-dimensional concentrator, or one-half, to 50, for a two-dimensional trough. Detailed designs should be conducted with actual ray-tracing programs, but this gives an idea of the results that can be achieved.

Parabolic concentrators are more highly developed for solar thermal applications in which high temperature is desired and flux uniformity is not so big an issue as with PV receivers. The successful Luz trough concentrators generate heat for steam turbines and have a combined output of over 300 MW [48]. A comprehensive review of parabolic dishes for solar thermal applications is given in [49].

In practice, reflective dishes can achieve higher concentration than desired for PV receivers. There is no need for SOEs to increase concentration, so the concentration ratio is usually sacrificed to achieve flux uniformity and pointing tolerance. One method of doing this is the kaleidoscope flux homogenizer. This is simply a box in front of the receiver having internal reflecting walls. When properly designed, the incoming rays are scrambled by reflecting several times and are distributed relatively uniformly over the receiver, independently of where they arrived at the entrance aperture [32, 50].

11.4.4 The Compound Parabolic Concentrator

We have seen that the parabolic concentrator is not an ideal concentrator. The first realization of an ideal concentrator was the compound parabolic concentrator (CPC). As seen in Figure 11.24, this actually comprises two parabolic surfaces; however, the axis of each is tilted by $\pm\theta_{\max,\mathrm{in}}$ and their foci are at opposite edges of the receiver. The parabolas are extended upwards until the surface is vertical, at which point the entrance aperture is as large as possible. When light is incident at the maximum angle, it is clear that all the light hits one parabolic surface and ends up focused at the receiver edge. As the light moves toward the normal, all the rays are directed more downward and continue to hit the receiver. Using the geometry of parabolic surfaces, it is straightforward, if a little tedious, to show that $C = 1/\sin\theta_{\max,\mathrm{in}}$. So the CPC concentrator is ideal. If the CPC is

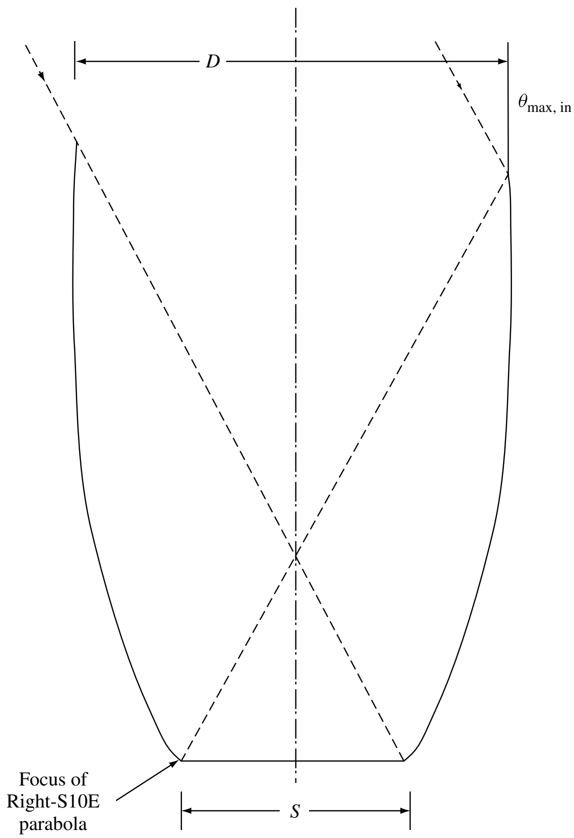

Figure 11.24 Geometry of the compound parabolic concentrator, in this case for $\theta'_{\max,\mathrm{in}} = 30°$

filled with a dielectric of index n, the incoming ray is refracted downward according to Snell's law so that the ray enters the CPC at angle $\theta'_{\text{max,in}}$, giving $C = 1/\sin\theta'_{\text{max,in}}$. Now $n \sin\theta'_{\text{max,in}} = \sin\theta_{\text{max,in}}$, which gives $C = n/\sin\theta_{\text{max,in}}$, and so the CPC is still ideal.

Three-dimensional CPC concentrators can be made by revolving the two-dimensional cross section about the central axis. It turns out that, while the three-dimensional CPC has near-ideal concentration, it is not strictly ideal. Some rays (those that come near the edge with a large skew component) are rejected.

A problem with CPC concentrators is that they are rather long and narrow for high concentration. For dielectric-filled CPCs, this problem can be somewhat ameliorated by doming the top surface to get some initial concentration from the resulting lens. Figure 11.25 shows how doming the top affects CPC shape [2] in concentrators operating by total internal reflection (called DTIR for Direct Total Internal Reflection), which are also ideal in two dimensions.

CPCs are often used as secondary concentrators at the focus of a primary concentrator, particularly for Fresnel lens systems, because then they have a rather large acceptance angle and the resulting design is rather compact.

At the time of writing this, there were no known ideal three-dimensional concentrators that image onto a flat surface (unless with graded index of refraction, not treated here). The author knows of only one ideal three-dimensional concentrator, and it is shown in Figure 11.26. This images all rays striking a sphere onto a smaller sphere imbedded in a dielectric. If the radius of the outer sphere is r_1 and the inner sphere is r_2, where $r_2 = r_1/n$, then the concentration ratio is n^2, referenced to the surface areas of the spheres. Unfortunately, solar cells are generally not spherical.

11.4.5 The V-trough Concentrator

The CPC, while admittedly ideal, has some drawbacks. One is that the intensity pattern at the exit aperture is quite nonuniform under typical illumination conditions. It can be

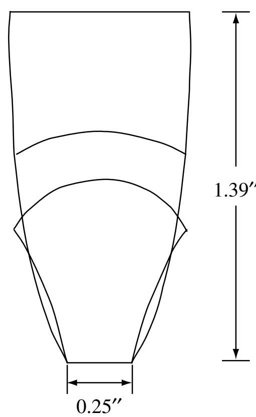

Figure 11.25 A series of dielectric-filled CPCs with flat and domed tops [2], all having the same concentration and a 10° acceptance angle. Adapted from Luque A, *Solar Cells and Optics for Photovoltaic Concentration*, 1989, Adam Hilger, © 2002 with permission by IOP Publishing Limited

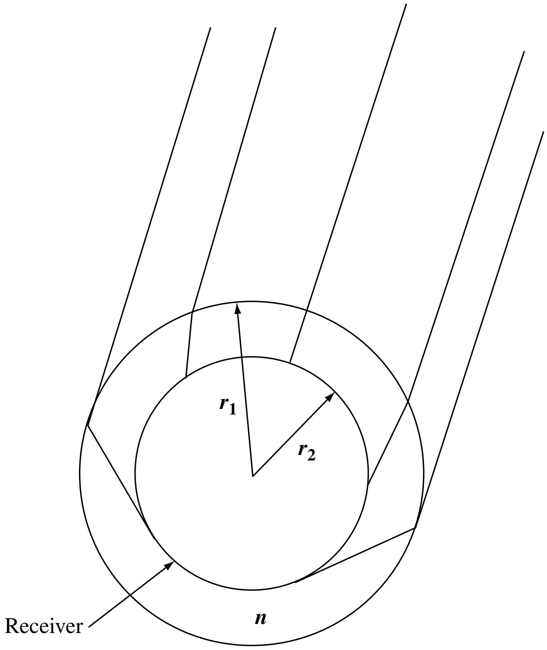

Figure 11.26 The ideal spherical concentrator of concentration ratio n^2

shown that the output intensity is uniform when the illumination is uniform over all directions within the acceptance angle. Such is not the case in practice, however, because the sun provides a localized region of the sky that is much brighter than the surrounding acceptance region (assuming that the acceptance angle is greater than the sun's half angle). A simplified version shown in Figure 11.27 uses planar reflectors and is often called a v-trough. The v-trough concentrator has a maximum intensity concentration of 3, thereby avoiding the hot spots of the CPC.

Referring to the symbols in Figure 11.27, some rather tedious but straightforward calculations indicate that the concentration ratio of the v-trough concentrator is (hint: use the law of signs on the triangle inside the trough)

$$C = 1 + \frac{2\sin\theta_m\cos(\theta_i + 2\theta_m)}{\sin(\theta_i + \theta_m)}$$

When $\theta_i = 0$, one obtains $C = 1 + 2\cos(2\theta_m)$, so the concentrator is clearly not ideal. In fact, it reaches a maximum concentration of 3 for small θ_m, that is, steep mirrors.

It should not be thought that the v-trough is necessarily inferior to the CPC concentrator. Besides the reduction in hot spots, it can be easier to manufacture, especially with flat glass mirrors. For wide acceptance angles and reasonable maximum exit angles such as 60°, v-troughs closely approach ideal concentrators. For example, when $\theta_i = 30°$ and $\theta_m = 15°$, then $\theta_{\text{out}} = 60°$ and $C = 1.37$. This is 79% of the ideal concentration.

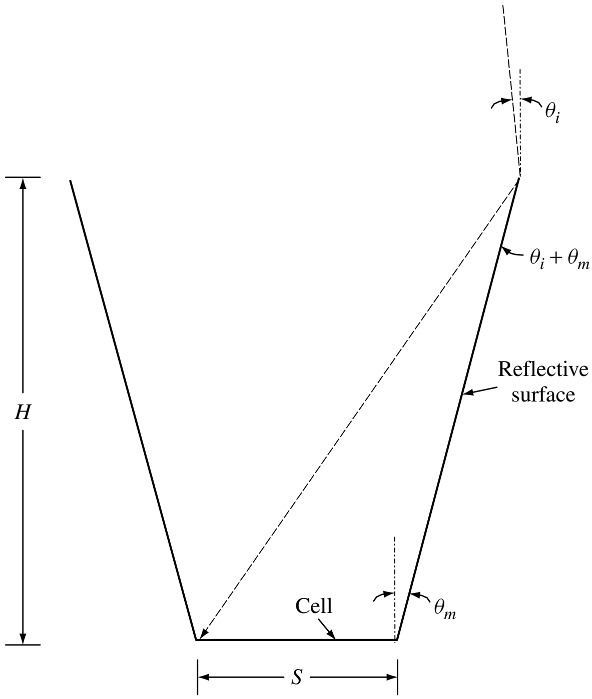

Figure 11.27 Geometry of a v-trough concentrator

Interestingly, if one allows for multiple reflections, then the v-trough approaches an ideal concentrator for small θ_m [51]. This results, however, in a very tall, narrow structure with many reflections. In contrast, the CPC has a maximum of one reflection.

Two-axis v-trough concentrators are made either by rotating the v-trough about its central vertical axis, forming an inverted truncated cone, or by combining two v-troughs at right angles, forming an inverted truncated pyramid. The resulting two-axis concentration approaches the square of the above numbers; however, as in the two-axis CPC, some of the rays within θ_i will not strike the receiver. The rotational version produces some regions of high intensity under certain illumination conditions as the light is focused off the cylindrical surface, whereas the square version does not suffer from this effect. Two-axis v-troughs are often used as secondary concentrators in conjunction with point-focus Fresnel lenses. With proper design, they can also smooth the flux profile over that obtained with the Fresnel alone.

11.4.6 Refractive Lenses

Refractive lenses are a common alternative to reflective lenses. Such a lens is shown in Figure 11.28.

The lens can be analyzed by ray-tracing using Snell's law. In the case we have shown, a plano-convex lens with the flat surface facing upwards, the analysis can be expedited using Fermat's principle, which states that rays at the focus all travel the same

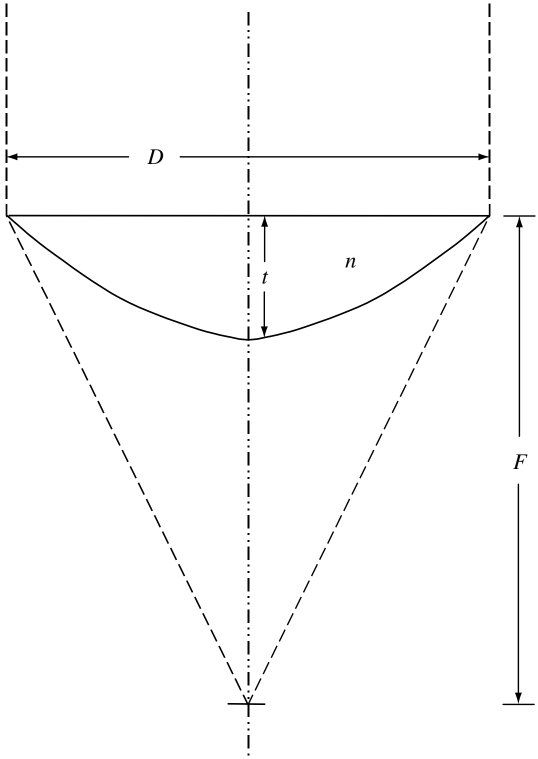

Figure 11.28 Refractive lens geometry

optical path length. (And hence, if they leave the source at the same time, they will arrive at the focus at the same time, regardless of where they strike the lens.) By equating the optical path length of the two rays shown in Figure 11.28, one obtains

$$F + (n - 1)t = \sqrt{(F - y)^2 + x^2} + ny$$

This is the equation of a hyperbola. Such a lens is called *aspheric* to differentiate it from the common spherical lens that is an approximation of the above for large F and small x. The thickness of the lens can be related to the f-number by setting $x = D/2$, the edge of the lens, giving

$$\frac{t}{D} = \frac{\sqrt{F^2/D^2 + 1/4} - F/D}{n - 1}$$

A serious problem with such a lens is that it becomes rather thick for short f-numbers. For example, for $F/D = 1$ and $n = 1.5$, one obtains $t/D = 0.24$. If the lens has a diameter of 10 cm, then the thickness will be 2.4 cm, resulting in a rather heavy, material-intensive structure. For small lenses on the order of several centimeters in diameter, the thickness is quite acceptable. Such "microlenses," accompanied by small cells at the focus, are an interesting avenue for possible development. This approach was explored by Wattsun [52].

For larger lenses it is usual to collapse the lens back to zero thickness at a number of points, forming the Fresnel lens of Figure 11.29. Because of the need for very high optical quality surfaces on the curved facets, it has proved difficult to manufacture such lenses with high transmission [53] because the mold tool is manufactured using diamond point turning. This leaves microscopic grooves, which are difficult to polish out because of the presence of the vertical region between facets.[14] If the facets are made small compared to the size of the cell, then flat facets can be used with little loss of concentration. In this case, the mold can be manufactured using a flat diamond turning tool, which gives very good optical surfaces.

Fresnel lenses do not transmit all the light they intercept to the focus. Losses come from several sources. First, Fresnel reflection from the optical interfaces causes about 8% loss (more for a short focal length lens because of the steep angle of the exit ray to the facet surface). This can potentially be reduced by the use of antireflection coatings. Second, the vertical regions between facets cannot be completely vertical or the lens cannot be removed from the mold. The angle of this portion is called the draft angle, and is in the neighborhood of 2°. Light striking this wall is deflected out of the focus. Finally, the tips and valleys have nonzero radius. Clearly, the smaller the facets, the more important

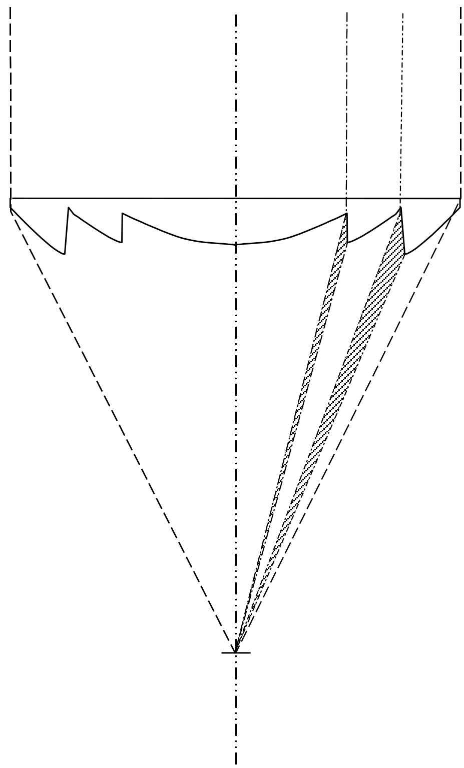

Figure 11.29 Cross section of a Fresnel lens

[14] This work was performed in the 1980s. It is very likely that the modern tool making machines can produce a very high-quality mold.

this loss is. Modern flat-facet, compression-molded lenses have an optical transmission of typically about 85%.

To date, the highest performance point-focus Fresnel lenses have been made only by compression molding. This results in a rather expensive product because of the long cycle times in the molding machine. Attempts at injection molding, which has a much shorter cycle time, have been disappointing. To the author's knowledge, little effort has been expended on Fresnel-lens development using recent plastic molding technology such as compression-injection molding. Significant improvements in performance and cost are likely possibilities with a concerted effort.

Entech has developed an innovative domed linear Fresnel lens illustrated in Figure 11.30. Because of the dome, the light is refracted upon entering the lens, and refracted again upon exiting. Many benefits are obtained by making the angle of the rays to the lens surface approximately the same as they enter and exit the lens. It can be shown that this condition minimizes reflection loss, minimizes chromatic aberration (spreading of the image for different wavelengths due to dispersion in the index of refraction), minimizes the effect of deflection in the lens, and minimizes the size of the focus. In addition, the draft region and tip radius can be outside the ray path, as seen in Figure 11.30. The transmission of a domed Fresnel lens can exceed 90%, close to the loss for a flat acrylic sheet alone [54].

One cost-effective method of producing Fresnel lenses has been 3M, and is called Lensfilm. In his method, a thin acrylic plastic sheet is molded by an embossed roller

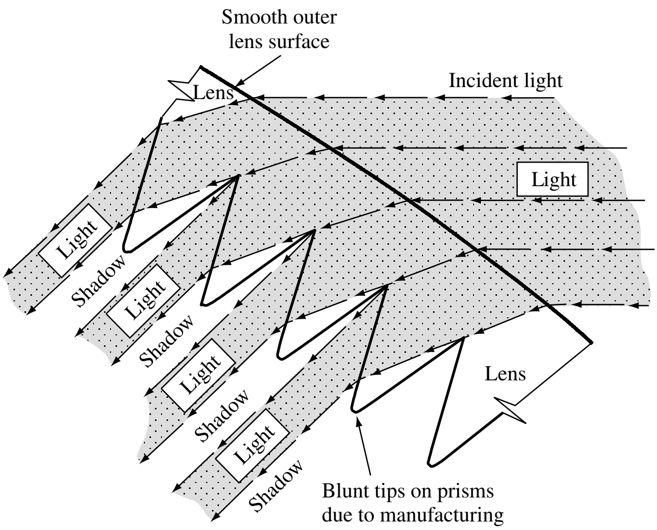

Figure 11.30 Cross section of the Entech domed Fresnel lens showing how the angle of incidence is nearly equal to the angle of exit, as well as how rays are shielded from the draft and the tip radius regions. Reproduced from O'Neill M, "Acrylic Extrusion/Embossing Process Development for the Low-Cost Production of Linear Fresnel Lenses", Presented at *Photovoltaic Concentrator Technology Development Project, Sixth Project Integration Meeting* (Albuquerque, NM, 1980) with permission by Sandia National Laboratories

on a continuous basis. The sheet is later bonded to an acrylic superstrate for mechanical strength. This method yields larger draft angles than compression molding and results in slightly lower transmission for flat, point-focus lenses. In contrast, it is particularly suited to the domed linear Fresnel approach of Entech, because when the lens is warped into the domed shape, the facets are deflected to an angle where the draft is out of the ray path.

The reader interested in the details of Fresnel lens design is referred to textbooks on the subject [2]. Modern design usually involves numerical ray-tracing analysis coupled with electronic design transfer to numerically controlled machining for tool making. Commercial programs, such as those available from James and Associates, are available for implementing this procedure.

11.4.7 Secondary Optics

Secondary optical elements are often used to increase concentration, or alternatively to increase acceptance angle. They are applicable with either reflective or refractive systems; however, they are most often used with point-focus Fresnel lenses in which concentration ratios in the range of 200 to 1000 are typical. Three types of secondaries are common: v-troughs, refractive CPCs, and refractive silos. These are described below.

Figure 11.31 shows the case of a Fresnel lens coupled with a v-trough. This design was for a 500X Fresnel module [30]. In this case the lens was designed with multiple

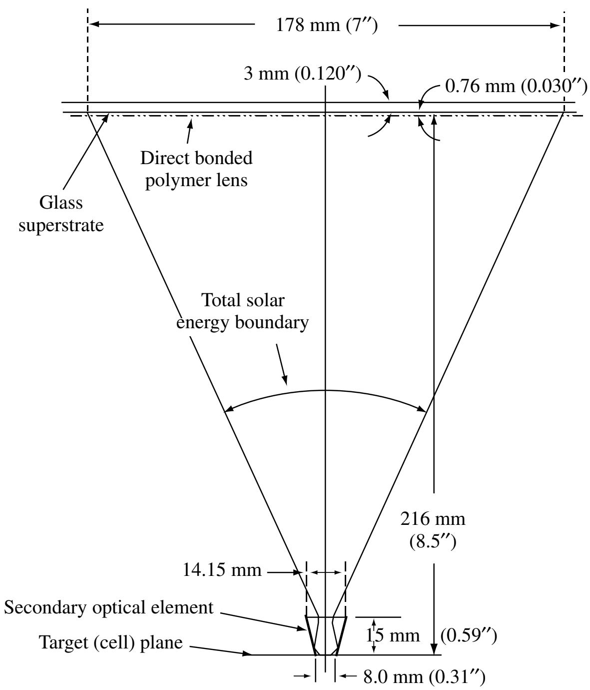

Figure 11.31 Lens cell configuration for a Fresnel lens with v-trough secondary [30]. Copyright © 1984. Electric Power Research Institute. *AP-3263. Conceptual Design for a High-Concentration (500X) Photovoltaic Array*. Reprinted with permission

zones of different focal lengths in order to smooth the flux profile. The secondary provides additional smoothing while providing 3X concentration. Generally, such secondaries are made with reflective aluminum sheet.

Dielectric-filled CPCs have also been used as secondary optical elements. In one case a concentration of 1000X was achieved on GaAs cells with an acceptance angle of $\pm 0.8^\circ$ [55].

As mentioned above, CPCs can have a rather nonuniform output. There is another type of secondary that gives almost uniform illumination intensity. The basic idea is to image the primary lens onto the cell [56]. Thus, if light strikes the primary uniformly, the illumination on the cell will be uniform. The principle is illustrated in Figure 11.32. The top surface of the secondary is an aspheric surface that images the lens on the cell. The definition of this surface can be found by using the same methodology as for the plano-convex lens mentioned above. In practice, however, it is usual to use ray tracing to optimize the shape of the lens in order to minimize the effect of edge ray distortion.

It is seen that the center of the primary lens is imaged on the center of the cell and the edge is imaged on the edge of the cell. If the lens is uniformly bright, then so will be the cell illumination. Some understanding of the operation of a silo secondary can be

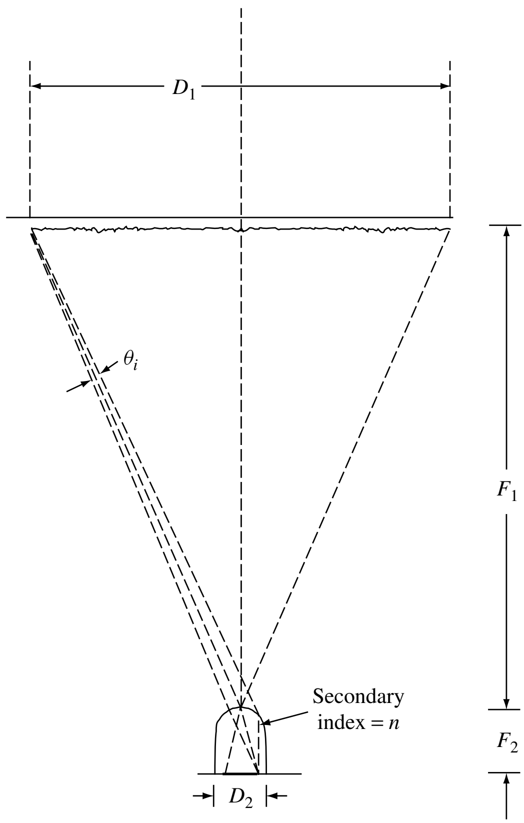

Figure 11.32 Geometry of a silo secondary

gleaned by a simple analysis using the above rays where it is found that for large primary lens f-numbers, the concentration is

$$C = \frac{nF_1}{F_2} = \frac{n}{2(F_2/D_2)\sin\theta_i}$$

For two-axis concentration, this relation is squared. The combination of Fresnel primary and silo secondary is seen to be ideal if the f-number of the secondary is 1/2. Note that it can be shown that a lens with f-number less than 1/2 cannot be realized, preventing the above from violating the maximum concentration law.[15] Nevertheless, concentration ratios of around one-fourth the maximum are readily obtained. Despite the loss of some acceptance angle, the uniform output provides significant advantages to this approach.

11.4.8 Static Concentrators

The necessity of tracking concentrators has long been considered a disadvantage. While there is little doubt that tracking systems can be made cost-effectively when manufactured in very large volumes and installed in large "energy parks" with 50-MW or more capacity [57], the existing markets for PV systems are for smaller installations. This has lead to considerable research to find a nontracking or static concentrator. Most of the early work was for solar thermal concentrators in which the basic principles were established [58].

Static concentrators rely on three factors to generate concentration greater than unity. First, the region of the sky where most of the energy falls within a band $\pm 24^\circ$ of a plane normal to the Earth's axis of rotation. Figure 11.33 shows a typical yearly average distribution of light falling on a plane tilted at the latitude angle, for a latitude of 34° south [59]. This is representative of what is found at most locations, where the bulk of the energy falls in a band of angles around the normal to a plane that is tilted at the latitude angle. An ideal one-axis concentrator with an acceptance angle of 24° has a concentration of 2.5. When the details of such concentrators are examined, it is found that they do not receive all the light early in the morning or late in the evening when the sun is near the solstices, but most of the energy can be harvested if the acceptance angle is opened slightly [2].

The second reason that the concentration can be increased is that the cell can be immersed in a dielectric with index of refraction greater than unity. This can typically provide another factor of 1.5X for one-axis and 2.25X for two-axis concentrators.[16] Unfortunately, such dielectric-filled concentrators are rather heavy and expensive if the cells are large. One possibility is to make very small cells coupled with small dielectric concentrators [60]. The practicality of this "microconcentrator" approach depends on the ability to highly automate the assembly of many small cells into the module. Finally, solar cells can be made bifacial, that is, sensitive to light from both sides. This provides

[15] More correctly, this should be thought of as proof that it is impossible to make a lens shorter than $f/0.5$.

[16] Sometimes it is also overlooked that immersing a cell in a dielectric medium that is not a thin planar surface (such as in a glass module) will increase the escape probability of rays reaching the cell's top surface from within and, hence, reducing the impact of light trapping. This type of effect also happens in dielectric secondaries, and results in the loss of several percent in current for silicon cells that rely on light trapping.

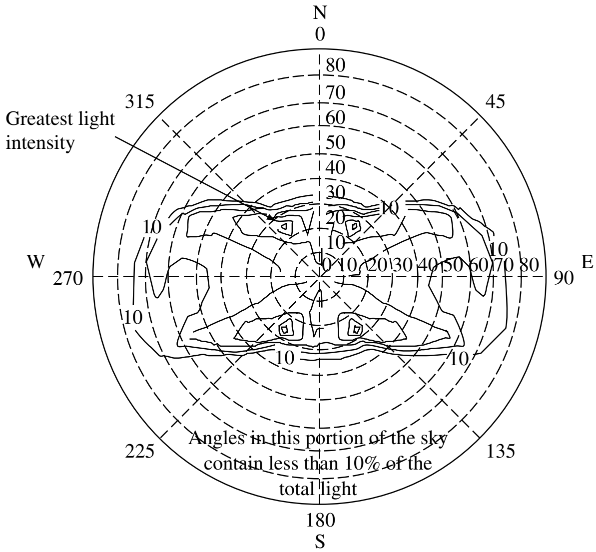

Figure 11.33 Yearly average distribution of incident light as seen by a module with tilt angle equal to the latitude of 34° south. Reproduced from Bowden S, Wenham S, Green M, "High Efficiency Photovoltaic Roof Tiles with Static Concentrators", *Proc. 12th European Photovoltaic Solar Energy Conference*, 1893–1896 (1994) with permission by WIP

potentially another factor of 2X concentration. Bifaciality alone can yield a concentration of 2X by providing for cusps that direct light to the cell [61]. Goetzberger reviewed various static concentrator options and proposed a combination of all of the above that attains a concentration of 12X [62]. Figure 11.34 illustrates the possibilities.

Another approach to static concentrators is the dielectric prism, which relies on total internal reflection. This concept has been refined by incorporating grooves on the back surface, which improves the light trapping [63]. Concentration ratios of around 4X are achieved. Figure 11.35 illustrates the concept.

To date, no firm has succeeded in commercializing static concentrators. Apparently, no concept examined so far appears to offer compelling advantages over a standard flat-plate module. It is a fruitful line of research to see if a cost-effective design can be found. The concentrator must have wide acceptance angle (over 30° in one direction and near 90° in the perpendicular direction) and have reasonable concentration (say, over 2X). Both of these are clearly possible. In addition, however, the device must not cost more to implement than the cell area replaced, and must not significantly degrade the module performance compared to a flat-plate. Therein lies the challenge. Until it is clear that such a device is impossible, the payoff is sufficient to warrant continued search.

11.4.9 Innovative Concentrators

The methodology of nonimaging optics has been extended to a large variety of new and innovative designs. Many of these are covered in the text *Solar Cells and Optics for Photovoltaic Concentration* [2]. One recent and particularly interesting case is the RXI

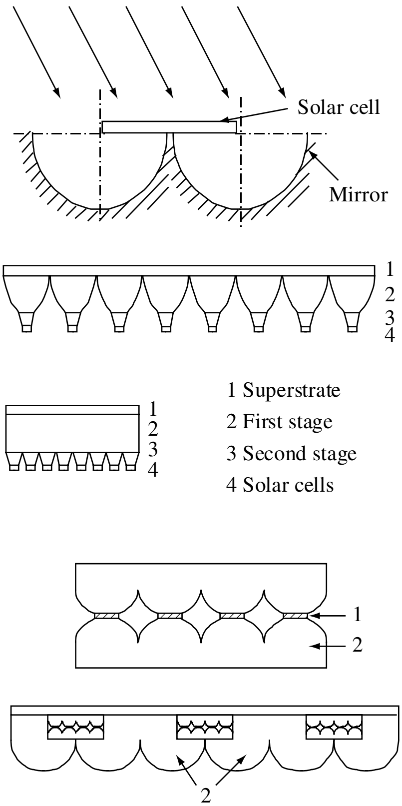

Figure 11.34 A combination of concentrators achieving 12X concentration. (a) 2X trough; (b) dielectric CPC; and (c) the combination. Goetzberger A, Static Concentration Systems with Enhance Light Concentration, *20th IEEE Photovoltaic Specialists Conference* © 1988 IEEE

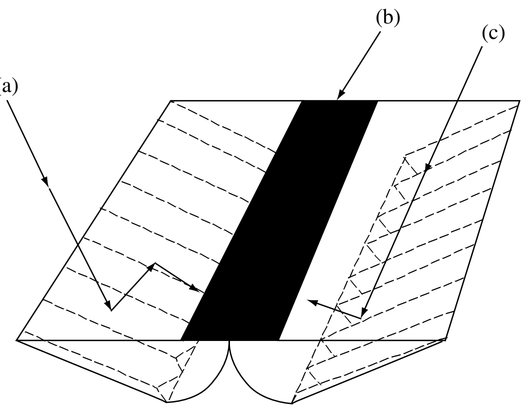

Figure 11.35 Static concentrator using bifacial cells with dielectric prisms. Bowden S, High Efficiency Photovoltaic Roof Tiles with Static Concentrators, *First World Conference on Photovoltaic Energy Conversion* © 1994 IEEE

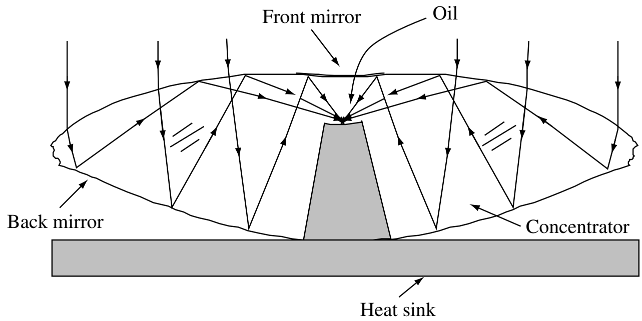

Figure 11.36 The RXI concentrator cross section. This version has an acceptance angle of 2.7° and a concentration of 1000X, and is close to ideal. Minano J, Gonzalez J, Zanesco I, Flat High Concentration Devices, *First World Conference on Photovoltaic Energy Conversion* © 1994 IEEE

concentrator shown in Figure 11.36 [64]. The name RXI comes from the fact that the lens uses refraction, reflection (denoted by X), followed by internal reflection. This device can be thought of as a two-axis version of the prism concentrator that relies on total internal reflection and that has been fine-tuned for optimum performance. The result is a very shallow device using a minimum of dielectric material. It is most suited for small apertures, and hence very small cells, so that the overall thickness and volume of material is minimized.

Other innovative concentrators include the D-SMTS (Dielectric-Single Mirror Two Stage) trough, which incorporates refractive secondaries into a reflective trough primary lens [65]. This device, whose cross section is shown in Figure 11.37, achieves one-axis concentration of 30X with a high acceptance angle of 2.44°. This is close to an ideal concentrator, which would give 2.87° acceptance angle at 30X and $n = 1.5$.

11.4.10 Issues in Concentrator Optics

The preceding sections discuss the theoretical aspects of designing PV concentrating optics. The designer is also faced with difficult materials and manufacturing issues.

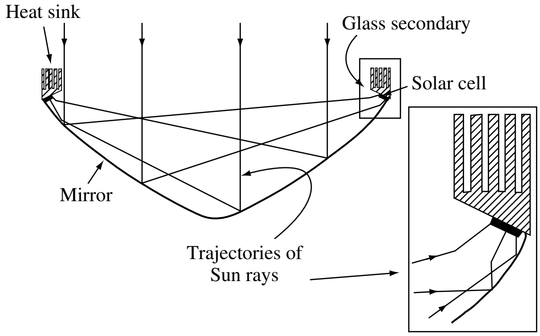

Figure 11.37 Cross section of the D-SMTS reflective trough concentrator. Reproduced from Mohedano R, Benitez P, Perez F, Minano J, "Design of a Simple Structure for the D-SMTS Concentrator", Presented at *16th European Photovoltaic Solar Energy Conference* (Glasgow, UK, 2000) by permission of WIP [65]

The optical concentrator must withstand at least 20 years of outdoor weathering. It must also be cleanable in order to remove accumulated dust and grime. On top of this, it must meet cost targets and have good optical performance. These are difficult requirements.

For reflective surfaces, the only suitable material found to date is back-surface-silvered, low-iron glass. Glass is very durable and protects the silver surface from corrosion and damage. This has been well proven in the large LUZ solar thermal plants [66]. If the radius of curvature for the surface is less than about 10 m, then the glass must be sagged at high temperature to the desired shape (much as automobile windshields are manufactured), which adds to the cost. Many attempts at making reflectors of polymer film with deposited silver have been tried; however, to date none has had sufficient weatherability for commercial concentrator use. Anodized aluminum sheet is another option, but it has lower reflectance than silvered glass and questionable weatherability. Anodized aluminum can be used in the interior of modules, such as for SOEs, where it is protected from the weather.

The most common material for refractive lenses is acrylic plastic (PMMA).[17] When combined with UV stabilizers, acrylic has shown very good weatherability [67]. It has some disadvantages, however, which must be worked around. Chief among these is its large thermal expansion coefficient, low strength and stiffness, water absorption expansion, and susceptibility to scratches when cleaning with any method other than spray rinsing. Considerable effort has been expended on ways to bond thin acrylic lenses behind glass [68], but the large difference in expansion coefficients has stymied any solution. Another approach to realize the advantage of a glass front surface has involved the lamination of alternative materials to acrylic, particularly those with a low Young's modulus [30]. Recently, the idea of molding silicone rubber to glass has been revived [69]. This may be the ultimate solution for long-lasting Fresnel lenses that can be integrated into practical modules.

For point-focus SOEs, acrylic is unsuitable because the small amount of residual absorption causes the lens to overheat and melt. In this case, optical glass is needed. Quartz has been successfully used, but is expensive. Pyrex is cost-effective, but has too high an absorptance and overheats. Schott BK7 optical glass works well initially, but tends to solarize (turn purple) with exposure to the intense, concentrated light in a secondary [70]. Groups developing glass secondaries must work closely with glass suppliers to select the best glass with the best combination of cost, moldabiltiy, and resistance to solarizing.

11.5 CURRENT CONCENTRATOR ACTIVITIES

There are a number of groups working on concentrator PV systems around the world. This section outlines the diversity of this global effort. Only the larger, more well-funded activities are included. There are a number of small-scale, exploratory activities in addition to those discussed. The promise, quality, and vitality of research on concentrators will become apparent when reviewing the diversity and scope of this work.

[17] The only common optical plastics that are sufficiently stable under UV radiation in sunlight are acrylic plastic, Teflon, Tedlar, Tefzel, and silicone. Silicone cannot be used on an exterior surface.

11.5.1 Amonix

Amonix, Inc. and SunPower Corporation are the two companies that licensed the high-efficiency point-contact solar cell from EPRI. This cell was developed at Stanford University under EPRI funding. Amonix has developed a 20-kW point-focus Fresnel lens array intended for the utility market. It has an innovative integral-backplane module design that greatly reduces the number of parts by incorporating the wiring and cell package as a part of the module back [34]. Systems have been installed at PVUSA and the Arizona Public Service's STAR facility. They recently announced that five more systems are under order. Figure 11.38 shows a recent Amonix array.

11.5.2 Australian National University

Australian National University (ANU) is developing a linear trough concentrator system. They are also developing a novel, rather simple silicon concentrator cell, which is expected to have 22 to 23% efficiency with only one nonaligned photolithography step. The cells are designed for operation at 30X concentration. Work is under way on a 2-kW demonstration at Spring Valley, Australia. They expect the system to have a 15% overall efficiency [71].

11.5.3 BP Solar and the Polytechnical University of Madrid

A 480-kW concentrator project (the largest ever) has been built recently in Tenerife, Canary Islands [50]. It is called the Euclides Project and is part of the European Joule program. Euclides is composed of 14 one-axis tracking reflective parabolic troughs, each 84 m long, with specially designed PV receiver modules built by BP Solar using buried contact solar cells operating at 38X geometric concentration. The reflector is a very lightweight and innovative space-frame design developed at the Polytechnical University of Madrid. The system uses passive cooling, accomplished with another innovative concept – heat sinks built of compression-bonded, thin aluminum fins. The system has approximately 13% overall efficiency and is projected to produce power at 23 cents per kWh, half the cost of power from a crystalline flat-plate plant. This cost is projected to

Figure 11.38 Amonix 100-kW high-concentration Fresnel lens array at the Glendale, California Airport

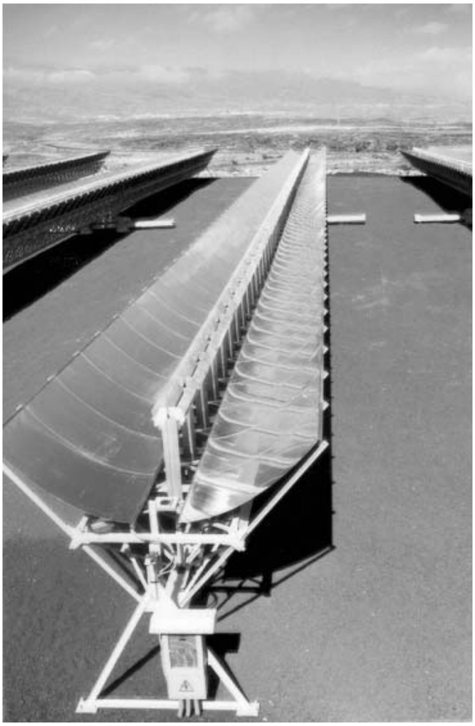

Figure 11.39 Picture of the Euclides linear trough system

drop to 13 cents per kWh at a production volume of 15 MW/year. Figure 11.39 shows a picture of the Euclides system.

11.5.4 Entech

Entech, Inc. has been pursuing line-focus Fresnel concentrators since the start of the Federal PV program. They hold a fundamental patent on curved Fresnel lenses that have very high transmission (90%). These systems have improved over the years through demonstration projects at PVUSA, the 300-kW Austin 3M system, a 100-kW system at the Solar Park in Ft. Davis, Texas, being developed by Central and South West Utilities, and a 100-kW system at the Energy Park near Dallas, Texas, being developed by TU Electric. Entech was also part of the DOE PVMaT program to improve PV manufacturing processes. Entech systems use modified one-sun cells operating at 20X. Their newest, fourth-generation modules have an efficiency of about 15% at standard operating conditions. Entech projects a levelized electricity cost of 7 to 15 cents/kWh at an annual production rate of 30 MW/year [72]. A picture of an Entech system appears in Figure 11.12.

11.5.5 Fraunhofer-Institut fur Solare Energiesysteme

The Fraunhofer Institute has been researching both concentrator cells and systems. GaAs cell efficiencies in the 24% range have been demonstrated. Fresnel module efficiencies of 19% were achieved [73]. Concentrator silicon cells are also being researched. An innovative one-axis reflective tracking concentrator design was demonstrated that achieves 300X concentration through a refractive CPC-type secondary concentrator [41].

11.5.6 Ioffe Physical-Technical Institute

The Ioffe Physical-Technical Institute has a long history with compound semiconductor solar cell development, particularly for concentrator cells. Recently, they have been developing GaSb and AlGaAs cells for multijunction applications. As part of a European consortium, they have developed a unique, all-glass concentrator module that uses GaAs cells and a thin silicone Fresnel lens, molded to the inside of the top glass sheet. This approach appears very promising [69].

11.5.7 National Renewable Energy Laboratory

National Renewable Energy Laboratory (NREL) conducts leading-edge research on high-efficiency, multijunction solar cells. They have achieved a record 30% efficient GaInP/GaAs two-junction monolithic concentrator cell operating at 150X [74], and even higher efficiency in collaboration with Spectrolab, as seen below. Interestingly, the pioneering research on compound semiconductor solar cells conducted at NREL has found widespread application in high-efficiency space solar cells. It is curious to contemplate that when the concentrating PV industry is ready to accept high-efficiency multijunction cells, the lowest cost route to securing their supply could be through the space solar cell industry, which would have had considerable manufacturing experience with multijunction cells by then.

11.5.8 Polytechnical University of Madrid

The Polytechnical University of Madrid has had a long-term program on concentrators, of which the Euclides project mentioned above is only a part. This includes pioneering work in the optics of concentrators, as well as GaAs concentrator cells. Their work, particularly that on static concentrators, is well described in the textbook, *Solar Cells and Optics for Photovoltaic Concentration* [2]. Recently, a new type of concentrator has been invented and researched, called the RXI concentrator discussed in Section 11.4 [64]. It is designed to use small GaAs cells that are only 1 mm on a side and manufactured and packaged similarly to LEDs. Modules built using this approach will resemble flat-plate modules, yet potentially exhibit very high performance and low cost. Additionally, the large acceptance angle reduces the cost of tracking structure. Such modules could be applicable for certain markets currently served by flat-plate modules. A consortium has been formed to further develop the RXI concentrator including the University of Madrid, the Ioffe Physico-Technical Institute (Russia), Energies Nouvelles et Environment (Belgium), Vishay Semiconductors (Germany), and Progressive Technologies (Russia). The system is called Hercules [75]. The team calculates that it could deploy systems that produce electric power at 0.104 euros/kWh using present performance and ultimately 0.033 euros/kWh at a production volume of 1000 MW. This is the lowest cost of energy projection reported for a PV system, and would be very remarkable if it holds up in practice. SunPower is also working on a similar concept in partnership with the Polytechnical University of Madrid, except that they are using silicon cells [76].

11.5.9 Solar Research Corporation

Solar Research Corporation, Pty. Ltd., is developing reflective dish concentrators and water-cooled close-packed PV arrays for use at the focus [77]. A single close-packed silicon array produced more than 200 W with a reported efficiency (not independently confirmed) of 22% at 239 suns and a GaAs module produced 85 W with an efficiency of 18% at 381 suns. These systems will be deployed first in the Australian outback by an affiliated company, Solar Systems, Pty. The design has progressed to the point where full-sized prototype dishes have been tested and Solar Research Corporation is preparing for a larger system test. Figure 11.40 shows the Solar Systems dish in operation.

11.5.10 Spectrolab

Spectrolab, a major manufacturer of multijunction solar cells for space application, has initiated a concentrator cell and module development effort utilizing their high-efficiency cells. They recently announced a 34% conversion efficiency cell, a remarkable result, especially considering that the high efficiency was obtained at sufficiently high concentration for practical, low-cost module use.[18]

11.5.11 SunPower Corporation

SunPower Corporation manufactures a variety of high-efficiency silicon concentrator solar cells. These include cells designed for point-focus Fresnel lens applications as well as cells designed for closely spaced arrays for use with large dishes and central receivers. Design concentration ratios vary from 250X to 400X. Peak efficiency is around 27% at 100X, dropping to 26% at 250X. SunPower has built complete water-cooled dense

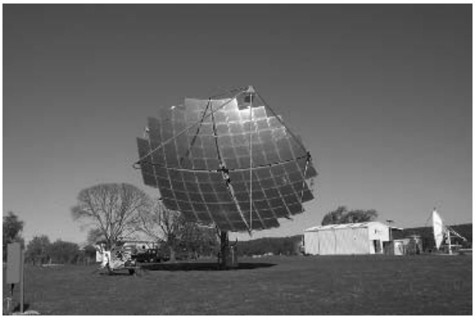

Figure 11.40 Solar Systems 24-kW dish concentrator-PV system in operation

[18] Spectrolab press release.

arrays for dish and TPV applications. These cells are supplied to companies developing concentrating systems.

11.5.12 University of Reading

The University of Reading, United Kingdom, is researching a variety of concentrating approaches including point-focus Fresnel modules [78] and novel reflective trough modules [79].

11.5.13 Tokyo A&T University

Tokyo A&T University has been researching two and three-dimensional refractive static concentrators. These are designed to accept most of the diffuse light and, hence, are suitable for cloudy climates [80]. The two-dimensional lens has a concentration of 1.65X and the three-dimensional lens has a concentration of around 2X. While it might be concluded that this modest concentration is hardly worth the effort, it must be remembered that these systems use standard one-sun cells and the cell cost, which dominates module cost, is correspondingly reduced by these factors.

11.5.14 Zentrum fur Sonnenenergie und Wasserstoff Forschung Baden Wurttenberg (ZSW)

Zentrum fur Sonnenenergie und Wasserstoff Forschung Baden Wurttenberg (ZSW), in conjunction with a European consortium consisting of BP Solar, the Instituto de Energias Renovables (Spain) and the University of Crete, is developing a promising low-concentration system based on a 2X v-trough concentrator. The system uses polar-axis tracking that is driven by a passive, thermo-hydraulic system. This results in a simple, maintenance-free system that is projected to offer a 40% cost advantage over fixed, flat-plate modules [81].

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