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UNIFORM FLUX DISH CONCENTRATORS FOR PHOTOVOLTAIC APPLICATION

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ABSTRACT

Researchers at the National Renewable Energy Laboratory (NREL) have designed a unique and innovative molded dish concentrator capable of producing a uniform flux profile on a flat target plane. Concentration levels of 100-200 suns, which are uniform over an area of several square inches, can be directly achieved for collection apertures of a reasonable size (~1.5-m diameter). Such performance would be immediately applicable to photovoltaic (PV) use. Economic concerns have shown that the proposed approach would be less expensive than Fresnel lens concepts or other dish concentrator designs that require complicated and costly receivers to mix the flux to obtain a uniform distribution.

1. INTRODUCTION

An important reason for using concentrated sunlight for photovoltaic (PV) solar cell applications is that the efficiency of such cells increases logarithmically with the level of solar irradiance up to the point at which resistive losses dominate (1). The concentrated light should ideally provide a uniform flux profile over the area containing the cell array. The reason for this is that concentrator modules are comprised of a number of cells connected in series. Because the output current from each cell varies with the level of incident flux, the maximum output current from a module will be limited by the cell receiving the lowest flux (2). Several ranges of applicable concentration levels have recently been suggested for PV concentrator use (3). These are generally tied to the current state of PV cell technology and include low (10-30 suns), intermediate (200-400 suns) and high (70-1000 suns) concentration.

One approach to attaining uniform flux has been the use of refractive Fresnel lens concentrators. Several drawbacks of this concept include transmission losses through the lense, sensitivity to tracking errors, and high cost. A secondary concentrator has been proposed (4) as a way of achieving 200-500 suns and increasing the uniformity of the flux profile. However, for applications that do not require such high levels of concentration, the addition of a secondary concentrator adds cost and complexity.

An alternative novel approach makes use of a molded/stamped reflective dish concentrator comprised of multistep sections whose shapes are tailored to provide the desired flux level and profile. Simulations of performance using an existing in-house computer code, ODMF (5), at the National Renewable Energy Laboratory (NREL) indicate an attractive potential for this concept. Based upon these results, a patent application entitled "Method and Apparatus for Uniformly Concentrating Solar Flux for Photovoltaic Applications" has been filed.

2. PERFORMANCE ANALYSIS

An existing in-house computer code, ODMF, (5) was used to model the performance of a number of multistep dish concentrator designs. ODMF is based on a three-dimensional ray-trace procedure. Solar rays are traced to their intersection with a multi-faceted dish concentrator array. Optical errors are incorporated into the reflected ray directions. The target plane is divided into a two-dimensional grid and a tally is kept of the number of rays that intersect each grid area. Based upon the density of rays within each grid area, the concentration ratio in the target plane can be calculated.

One simplified dish configuration that was modeled is shown in Figure 1. Five concentric annular regions were arranged so that each annulus represents one fifth of the total aperture area. Each step section was offset along the optical axis by a z-displacement given in Table 1.

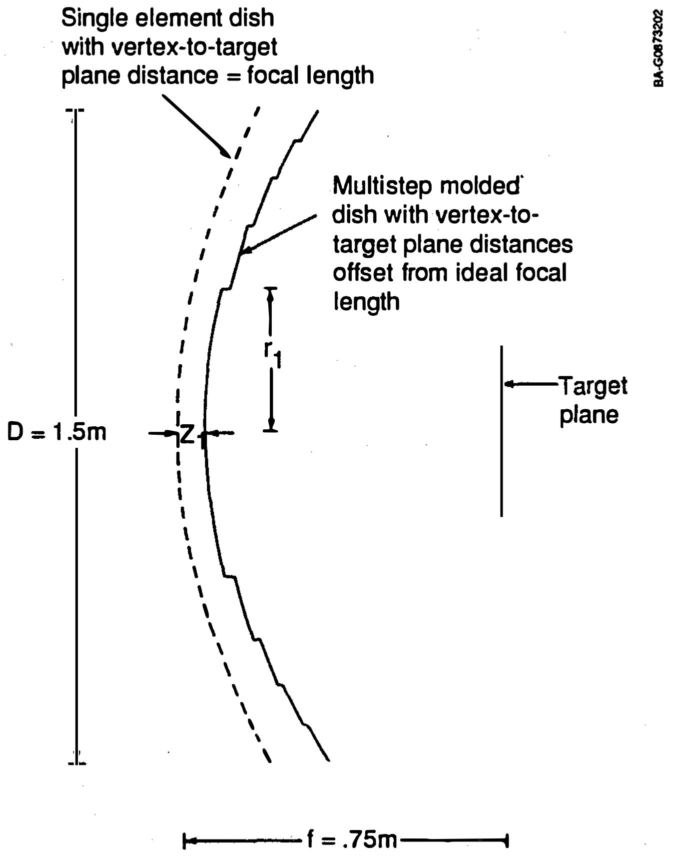

Fig. 1. Cross section geometry of 5-element molded dish

TABLE 1. PARAMETERS USED TO MODEL MULTISTEP (N=5) MOLDED DISH CONCENTRATOR.

z-Displacement (m)	Radius (m)	Curvature (m^{-1})
0.07	0.335410	0.6666667
0.09	0.474342	0.6666667
0.10	0.580948	0.6666667
0.11	0.670820	0.6666667
0.12	0.750000	0.6666667

For the arrangement shown in Figure 1, each step was specified to be a spherical element whose curvature was 1/2f (f = focal length). Spherical conic sections were chosen because the aberrations associated with such shapes tend to spread out the image at the focal plane, resulting in a larger useable area. For a D = 1.5-meter diameter overall aperture and a f/D = 0.5 system, rays were traced off the multistep dish to the target plane. The resulting flux profile as a function of radial position in the target plane is shown in Figure 2.

The radial position of each ray as it intersects the target plane is tallied into concentric annular bins. The concentration ratio (in suns) is then the number of rays per annular bin divided by the total number of rays per dish aperture area, multiplied by the assumed reflectance of the dish (0.90). For the geometry discussed above, this results in a frequency histogram (Figure 2) having a fairly flat concentration (of roughly 175 suns) out to 4.5 cm. In practice, the central peak would be somewhat less due to blockage of incident sunlight by the PV module. The data

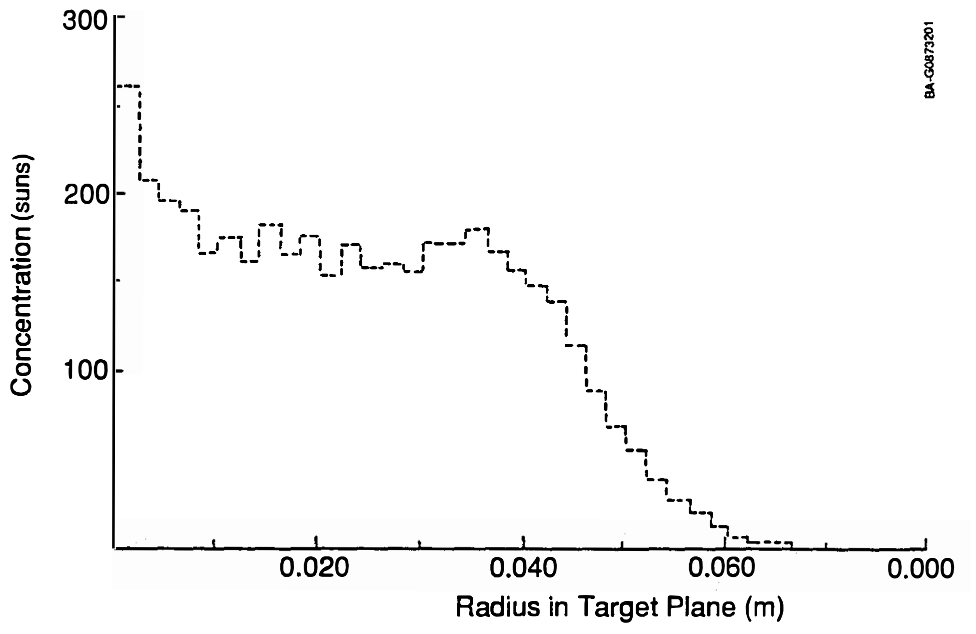

Fig. 2. Frequency histogram of concentration ratio for 5.0 mrad specularity

shown in Figure 2 are for a slope error of 3.0 mrad, a Gaussian sun shape with $\sigma = 2.73$ mrad, and a specularity of 5.0 mrad. The first two error terms are reasonable; the specularity has been purposely degraded (1.5-3.0 mrad specularity is easily achieved) to spread out the flux profile. An attempt to further improve the flux profile by using a 10.0 mrad specularity resulted in decreased performance.

The level of flux, the flatness of the flux profile, and the size over which such a distribution is obtained can be optimized by varying a number of controllable simulation parameters. To achieve a (physically realistic) desired performance, the number and relative size (% of total aperture area) of each step element can be varied. The type of conic section (spherical, parabolic, other conic sections, or other user-specified shapes) and the magnitude of the vertex curvature can also be changed. Each section can likewise be shifted varying amounts along the optical axis (z-displacement). The optical errors (slope and specularity) of each section can also be tailored to obtain a level of uniform flux.

3. COST PERFORMANCE TRADE-OFF ISSUES

The cost of a PV array energy system depends on a wide range of parameters such as cell cost, cell efficiency, concentration ratio, orientation of the array (and/or tracking costs), insolation, etc. A number of cost/performance analyses have shown that concentrating systems have the potential to dramatically reduce the cost of delivered energy. Compared to non-concentrating systems, the concentration approach has been shown to be more favorable for cell costs as low as $50/m^2 (6) and for systems using more expensive, higher efficiency cells (7).

There are two primary reasons for the cost/performance benefits of concentrating systems. First, conversion efficiency increases logarithmically with the level of solar irradiance up to the point at which resistive losses dominate. Second, and perhaps more important for the present argument, the area of solar cells needed to produce a specified amount of electricity decreases relative to the level of concentration. Thus a significant cost advantage is obtained because solar cells typically are several orders of magnitude more expensive (per unit area) than reflector materials (8). In particular, the cost (at moderate production levels) for cells which operate at an intermediate range of concentration, has recently been estimated (3) as \$1.5-4.0 x 10^4 / m^2. State-of-the-art reflector materials (glass or silvered polymer films) cost roughly \$20-30 / m^2. Silvered polymer reflectors could be readily adapted for use with this application.

Both line and point focus concentration have been proposed for PV electricity generation. Emphasis has been placed on achieving such concentration either by Fresnel refractor lenses or by parabolic reflectors. A major problem with traditional designs has been the lack of uniformity of the flux profile in the target plane. Typically, attempts have been made to defocus the concentrated light by moving the target plane to obtain a more uniform distribution. Unfortunately, such an approach does not provide adequate uniformity. Kurzweg investigated several axicon concentrators that delivered uniform flux (8-10) but nonflat target geometries are required.

From a performance perspective (11) a parabolic mirror can achieve a higher optical gain than a flat or roof Fresnel lens arrangement. Although a curved Fresnel lens can outperform a reflector, such a lens is more costly and more susceptible to thermal/mechanical failure than are flat designs.

An excellent comparison of Fresnel lens designs versus reflector technology is provided by Swanson (12). Several problem areas with the Fresnel lens approach in terms of meeting manufacturing cost goals are addressed. Most compelling, it is claimed that conventional compression molded acrylic Fresnel lenses simply will not be capable of meeting the DOE cost and longevity goals associated with PV concentrator systems. The feasibility and performance of alternative Fresnel lens designs has still to be demonstrated.

Swanson's solution to this dilemma is to rely on "well developed, low-cost mirror technology in a dish configuration." He proposes a proprietary parabolic reflective dish comprised of 16 2' by 44' parabolic mirrors that are curved in the long direction and are flat in the short direction. These slats are arranged to deliver sunlight to a cavity receiver that is designed to convert the nonuniform entering flux into a uniform flux at the cell array plane. This concept is claimed to be capable of achieving DOE's goal of $0.06 per kilowatt hour by the year 2000. Projections for another approach (2) which uses a conventional molded parabolic dish and a receiver (again designed to mix the captured sunlight in order to obtain a uniform flux distribution at the PV module) suggest this goal can be attained for production levels of 5000-10000 units per year. For low production levels, the cost of the receiver is 1/3-1/2 of the total system cost.

The manufacturing costs of the dish design proposed in this paper would be comparable to that estimated by (2). However, significant cost and complexity would be saved because the presently proposed design delivers a uniform flux profile on a flat target plane without requiring a receiver to mix the input flux to achieve a uniformly distributed profile.

4. CONCLUSIONS

The design of an innovative molded dish concentrator capable of producing a uniform flux profile on a flat target plane has been carried out at NREL. The performance of this design would allow concentration levels of 100-200 suns, which are uniform over an area of several square inches, to be readily and economically achieved. Such performance would be directly applicable for use with PV cells designed for intermediate levels of concentrated sunlight. A system level economic analysis will be performed to quantify the merits of the proposed approach relative to other concentrator concepts as well as to non-concentrating designs.

5. ACKNOWLEDGMENT

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6. REFERENCES

(1) Rios, M., Jr., and E.C. Boes, "Photovoltaic Concentrator Technology," *Progress in Solar Energy, The Renewable Challenge*, Vol. 5, Part 3 of 3, Reviews and Indexes, 1982 Annual Meeting, American Solar Energy Society, Houston, TX, Franta, G.E., et al., eds., (1982), pp. 1563-1576.

(2) Beninga, K., and M. Thomas, "Parabolic Dish Photovoltaic Concentrator Development," *1989 DOE/Sandia Crystalline Photovoltaic Technology Project Review Meeting*, Basore, P.A., ed., SAND89-1543, Sandia National Laboratory, Albuquerque, NM, (July 1989), pp. 134-138.

(3) Chamberlin, J.L., and D.L. King, "The Photovoltaic Concentrator Initiative," *Conference Record of the Twenty First IEEE Photovoltaic Specialists Conference - 1990, Volume II*, (1990), pp. 870-875.

(4) Winston, R., and J. O'Gallagher, "Performance of a Two-Stage 500X Nonimaging Concentrator Designed for New High Efficiency, High Concentration Photovoltaic Cells," *Solar '88, Proceedings of the 1988 Annual Meeting*, American Solar Energy Society, Inc., Cambridge, MA, June 20-24, 1988, Coleman, M.J., ed.,pp. 393-395.

(5) Jorgensen, G., "Comparison of Predicted Optical Performance with Measured Results for Dish Concentrators," *1991 Solar World Congress, Vol. 2, Part II*, M.E. Arden, S.M.A. Burley, and M. Coleman, eds, Pergamon Press, Oxford, England, (1991), pp. 2031-2036.

(6) Evans, D.L., and L.W. Florschuetz, "Cost Studies on Terrestrial Photovoltaic Power Systems with Sunlight Concentration," *Solar Energy*, Vol. 19, (1977), pp. 255-262.

(7) Roy, A.S., "Economic Analysis of Concentrators for Solar Cells," *Solar Energy*, Vol. 21, (1978), pp. 371-375.

(8) Kurzweg, U.H., "Characteristics of Axicon Concentrators for Use in Photovoltaic Energy Conversion," *Solar Energy*, Vol. 24, (1980), pp. 411-412.

(9) Kurzweg, U.H., "On a Class of Axisymmetric Concentrators with Uniform Flux Concentration for Photovoltaic Applications," *Solar Energy*, Vol. 24, (1980), pp. 507-509.

(10) Kurzweg, U.H., "Class of Axisymmetric Mirrors with Uniform Flux Concentration Properties along their Axes," *J. Opt. Soc. Am.*, Vol. 70, No. 6, (1980), pp. 750-752.

(11) Lorenzo, E., and A. Luque, "Comparison of Fresnel Lenses and Parabolic Mirrors as Solar Energy Concentrators," *Applied Optics*, Vol. 21, No. 10, (May 15, 1982), pp. 1851-1853.

(12) Swanson, R.M., "Photovoltaic Dish Solar-Electric Generator," *Proceedings of the Joint Crystalline Cell Research and Concentrating Collector Projects Review*, SAND88-0522, Sandia National Laboratories, Albuquerque, NM, (July 1988), pp. 109-119.