Approaching the irradiance of the sun through nonimaging optics

By Philip Gleckman, Joseph O'Gallagher, and Roland Winston

In designing a concentrator as an image-forming system, unnecessarily high standards are being set since high light collection rather than imaging is desired. Nonimaging designs exceed the concentration attainable with focusing techniques by factors of four or more and approach the thermodynamic limit. These methods have been applied to concentrate terrestrial sunlight by 56,000 fold and are capable of approaching or even exceeding the surface irradiance of the sun.

It is well-known that the thermodynamic limits for optical concentration place an upper limit on the solar flux density achievable on Earth.[1] This limiting concentration ratio is related to the sun's angular size (2Θ by

$$C_{max} = 1/\sin^2\Theta \qquad (1)$$

$$\approx 1/\Theta_2 \text{ (small angle approximation)}$$

Since $\Theta = 0.27°$ or 4.67 milliradians when the sun is viewed from Earth, this flux limit corresponds to approximately 46,000 times the natural terrestrial intensity of sunlight (typically between 700 and 1,000 Watts/M^2).

This concentration limit can be derived, for example, from the requirement that the temperature of the target of the concentrated flux cannot, even in principle, exceed that of the surface of the sun itself. Similar considerations show that, in the case where the target is immersed in a medium of refractive index n, this limit is increased by a factor n^2. Thus, in the most general case, the thermodynam-

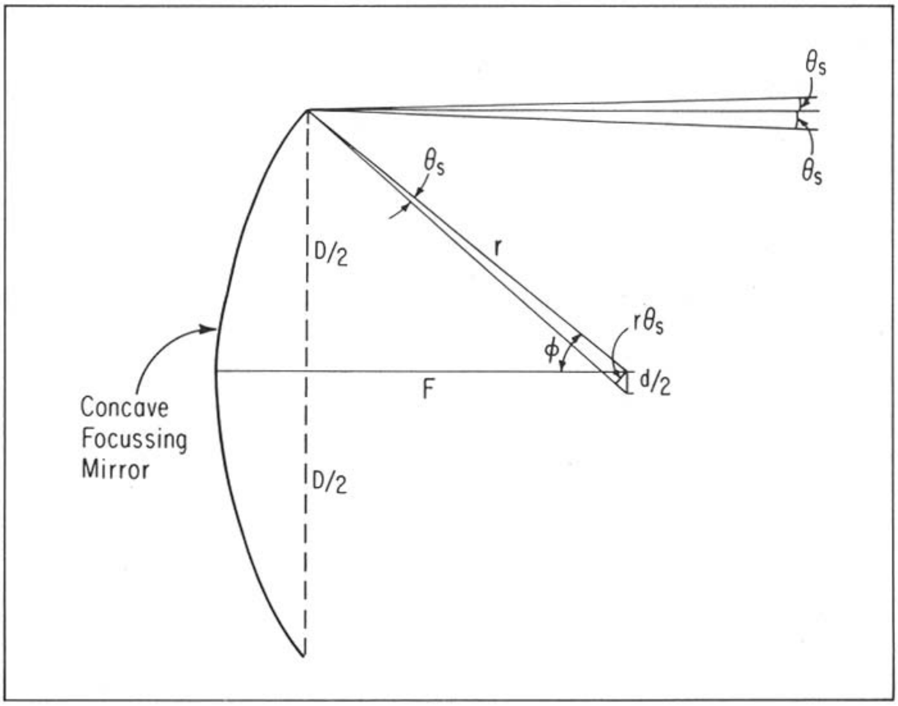

FIGURE 1. Geometry of a focusing mirror concentrator. The angular size of the source (Θ_s) determines the diameter of the image (d).

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ic or “ideal” limit of Eq. 1 becomes

$$C_{max} = n^2/\sin^2\Theta \qquad (2)$$

This means that concentration of about 100,000 will be the upper limit for ordinary ($n \approx 1.5$) refractive materials.

A fact that is perhaps somewhat less appreciated is that conventional means for concentrating sunlight will fall substantially short of this limit, not for any fundamental reason, but because conventional imaging optical design is quite inefficient for delivering maximum concentration. This can be illustrated by a simple example. Consider the use of a paraboloidal mirror to concentrate sunlight at its focus. From the simple geometry shown in Fig. 1, the diameter (d) of the solar image produced by an element of mirror at the rim is

$$d = 2r\Theta/(\cos\psi), \qquad (3)$$

where r is the distance from the focus of the paraboloid to its rim, ψ is its rim angle, and Θ is the angular subtense of the sun and we have used the small angle approximation for Θ. The diameter of the paraboloid (D) is given by

$$D = 2r\sin\psi \qquad (4)$$

Therefore the corresponding geometric concentration is $C_{para}=(D/d)^2$ or

$$C_{para} = (\sin\varphi\cos\psi/\Theta = (1/4)\sin^2 2\psi/\Theta^2 \qquad (5)$$

Equation (5) yields a maximum for a rim angle $\psi=\pi/4$, or

$$C_{para,\ max} = 1/(4\Theta^2) = (1/4)\ C_{max}. \quad (6)$$

Notice that this argument does not depend on the detailed shape of the paraboloid and would hold for any focusing mirror.

One fares no better (and probably worse) with a lens, since the 45° rim angle paraboloid in the above example is equivalent in concentrating performance to a lens with focal ratio $f = 1$ that has been corrected for spherical aberration and coma. Such high aperture lenses are typically complex structures with many components. In fact, the limit given by Eq. 1 would require a lens with focal ratio $f = 0.5$ which, as every optical designer knows, is unattainable.

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The reason for the large short-fall in Eq. 6 is not hard to find. The paraboloid images perfectly on-axis, but has severe off-axis aberration (coma), which produces substantial image blurring and broadening. The essential point is that requiring an image is unnecessarily restrictive when only concentration is desired. Recognition of this restriction and relaxation of the associated constraints led to the development of nonimaging optics[2].

Nonimaging optics is non-traditional

Nonimaging optics departs from the methods of traditional optical design to develop, instead, techniques for maximizing the collection power of concentrating elements and systems. Designs that exceed the concentration attainable with focusing techniques by factors of four or more and approach the theoretical limit (ideal concentrators) are possible. This is accomplished by applying the methods of phase space conservation (Liouville’s theorem) and radiative transfer methods.

The traditional approaches of aberration theory are replaced by a few key ideas. In the “edge ray” method,[2] maximum concentration is achieved by ensuring that rays collected at the extreme angle for which the concentrator is designed are redirected, after at most one reflection, to form a caustic on the absorber. This principle proved sufficiently elastic to accommodate most boundary conditions in two dimensions (i.e., linear geometry). Alternatively, in the flow-line method[3] reflective surfaces that follow the lines of net flux, combined with refractive surfaces, can lead to “ideal” concentrating elements and systems in three dimensions.[4]

Our group at the University of Chicago has been developing this new discipline since the 1970s. Last year, we began to employ the techniques of nonimaging optics to attain the highest possible irradiance from the sun. In this note, we describe an experimental test of a new concentrator that has already produced a solar flux equal to 56,000 “suns”, (56,000 times the ambient level of sunlight). Experiments now in progress are expected to exceed 70,000 suns. At such levels, one attains an irradiance comparable to that of the surface of the sun itself (even after taking atmospheric losses into account).

The high flux experiment

Optical design

In principle, a single nonimaging optical element could be designed that would attain the theoretical limit of concentration C_{max} given by Eqs. (1) and (2). However, when C_{max} is very large, as is the goal here, such an element also becomes large and unwieldy. A more practical design is to employ a nonimaging concentrator at the focal plane of an imaging element, e.g., a paraboloid. This nonimaging "secondary concentrator" can provide an additional concentration factor approaching the "ideal" limit for an acceptance angle ψ replacing Θ in equations (1) or (2). Then, combining the concentration of the paraboloid (Eq. 4) with that of the secondary concentrator ($n^2/\sin^2\psi$), one obtains an overall concentration.

$$C = n^2\cos^2\psi/\Theta^2 \qquad (7)$$

In the limit of small ψ, which corresponds to large focal ratio, such two-stage concentrators can come quite close to the theoretical limit. For our experiment, we chose $\psi \approx 11°$ corresponding to a focal ratio $f = 2.5$ parabolic mirror. Moreover, we filled the secondary with a transparent oil having index of refraction $n = 1.5.3$. Hence, from Eq. 7, our geometrical concentration, before taking absorption and blocking into account was

$$C = [1.53^*\cos(11°)/(4.67^* \, 10^{-3}\text{rad})]^2 \approx 104{,}000. \qquad (8)$$

The design of the secondary element followed the edge-ray principle. Rays incident on the secondary from the rim of the primary are redirected to the edge of the exit aperture after refraction by the curved entrance aperture and reflection by the side wall, as shown in Fig. 2. Strictly speaking, this "one reflection" design is an ideal two-dimensional solution. As a three-dimensional figure of revolution, some out-of-plane or skew rays are turned back. However, such skew ray losses are very small (about 28%), much smaller than absorption in the refractive medium. Truly "ideal" three-dimensional solutions could be constructed from the flow-line method[4], but these designs are longer and hence have more absorption. Therefore we chose the more compact edge-ray design.

Flux measurement

The overall conceptual approach is shown schematically in Fig. 3 and the experimental arrangement is illustrated in Fig. 4. The detailed description of the experiment is published elsewhere.[5] The principal sources of loss were absorption in the oil and blocking by the calorimeter used to measure the flux. We measured the flux calorimetrically because our irradiance levels were substantially beyond the range of conventional radiometry.

In fact, reliably measuring the flux proved to be the most demanding part of the experiment. This was accomplished by filling the vacuum dewar calorimeter with the same oil used in the secondary and measuring the rate of temperature rise of the oil produced by the solar flux emerging through the secondary exit aperture. The absolute power level was determined by comparing the rate of solar flux induced temperature rise with that produced by a calibrated electrical heater. In a series of experimental runs conducted in February 1988 on the rooftop of one of our campus buildings, we achieved an irradiance value of 4.4 kW/cm² at an insolation (direct solar component) of 800W/m.² This corresponds to 56,000 suns.

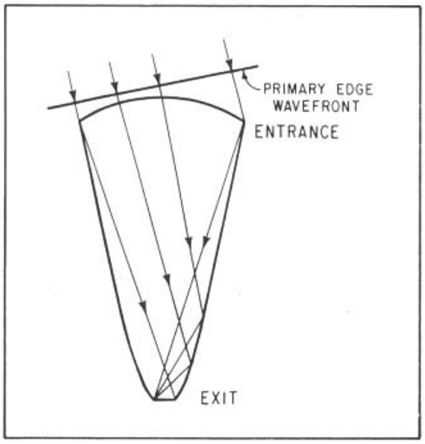

FIGURE 2. Edge ray principle. The secondary wall profile is designed in the meridional plane to image the rays from the primary edge to the secondary exit rim. Designed in this way, the secondary concentrates all rays from the primary interior to the secondary exit aperture in the meridional plane.

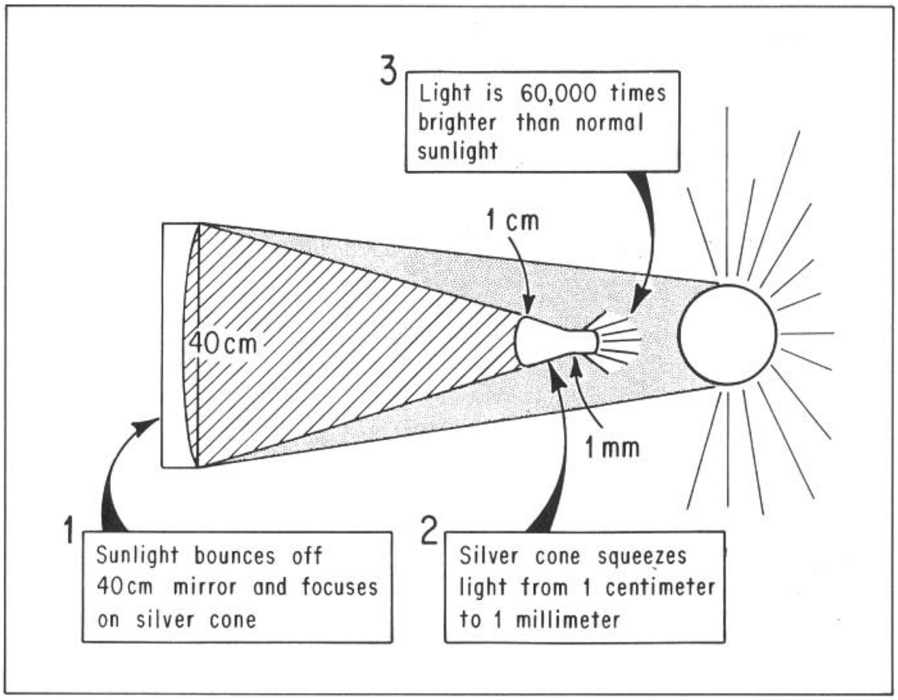

FIGURE 3. Conceptual overview of the high flux solar concentrator.

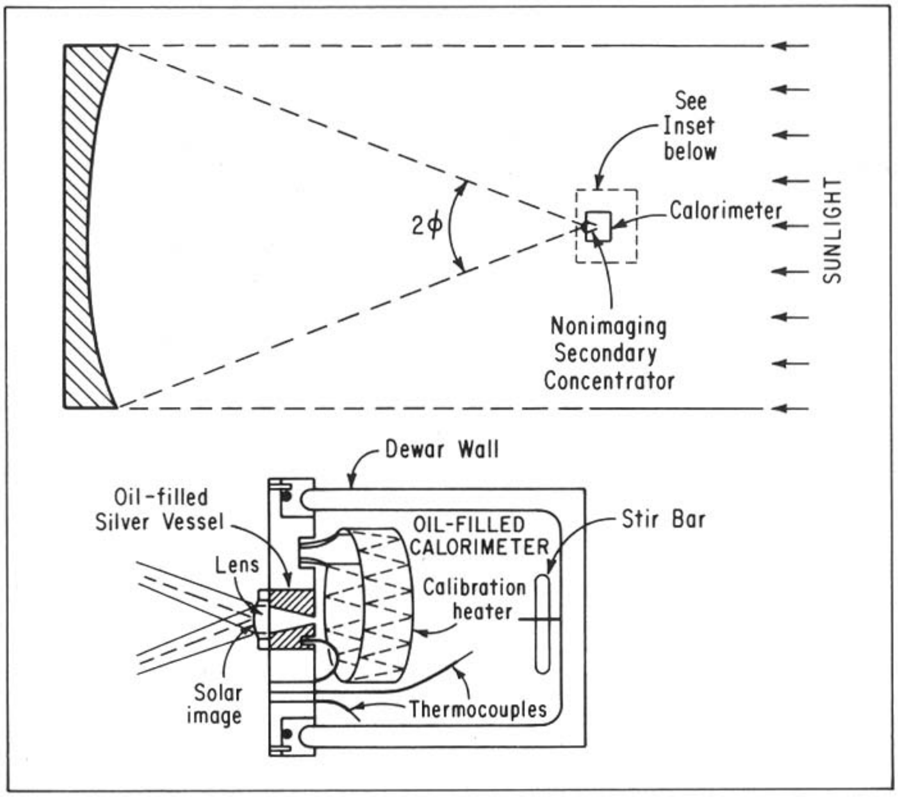

FIGURE 4. Two-stage concentrator with refracting nonimaging secondary. Oil-filled Dewar calorimeter (insert) measures the flux by comparison with a calibrated electrical heater.

Applications and outlook

Our present two-stage concentrator would, if deployed above the Earth's atmosphere, already give an irradiance in excess of that on the sun's surface. That is, the flux level at the sun's surface corresponds to about 46,000 times the local interplanetary solar constant of 137 milliwatts/cm^2 or to about 6.3kW/cm^2, whereas our flux enhancement factor of 56,000 would yield an irradiance of about 7.7 kW/cm.^{2}

Certain straightforward improvements can increase the flux significantly above that already achieved. For instance, replacing the metallic oil-filled secondary with an all-dielectric secondary, which operates by total internal reflection[6] is very effective. This is because (a) absorption is substantially eliminated by proper choice of material, (say sapphire), (b) imperfect specular reflection is replaced by total internal reflection, and (c) one gains as n^2 with a higher index material (for sapphire, $n \approx 1.8$). Thus, one might expect to be able to achieve at least 80,000 suns. Even on the Earth's surface, this would correspond to an irradiance substantially in excess of that on the surface of the sun and would be far in excess of the most intense artificial broadband continuous light sources that have been devised.[7] These are, at best, ≈ 2 kW/cm^2.

One application of such very high flux is to solar pumped lasers. Previous researchers have achieved lasing with solar pumping of Nd:YAG crystals, but the efficiency was low—< 1%. Higher flux increases efficiency since the optical energy can be delivered to the end of a cylindrical laser rod where most of it can be trapped inside by reflection so that absorption takes place along the entire length of the rod.

Perhaps an even more important benefit of high flux levels for laser pumping is that they may have special advantages for pumping alternative lasants. Some examples are alexandrite, which is tunable, dye lasers that lase in the visible, and glass lasers, which are low-cost. Other applications of high radiant flux might be in providing new techniques for the destruction of hazardous waste or the processing of specialized materials. For example, the production or certain fibers of very great tensile strength requires very high temperatures.[8] These temperatures (in the 3000°K range) are readily available when the fiber is grown in a high radiation flux environment. Other applications are likely to be found once the availability of ultra-high flux, comparable to the surface irradiance of the sun, becomes generally recognized.

Acknowledgments

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