THE USE OF OPTICAL SYSTEMS IN THE UTILIZATION OF SOLAR ENERGY

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Sunlight falls on the earth as a nearly parallel rain of photons, distributed in energy reasonably in accord with a Planck curve of 5700° K. The atmospheric blanket of the earth, however, exacts an appreciable toll of this photonic energy in the ultraviolet and in the infrared, but fortunately transmits all but about one-sixth of the energy in the richest part of the solar spectrum—the visible.

As in the case of ordinary rain, which can be used as it falls to promote the growth of crops or as a concentrated torrent to operate turbines, so can the rain of

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sunlight be used as it falls, or in mildy concentrated form, for certain purposes of energy transformation; and in a highly concentrated form for other purposes, notably those for which high temperatures are essential. In short, the transformation of solar to other forms of energy, depending on the particular method, can be characterized by the temperature differential at which the energy transformation is most efficiently effected. This temperature differential can vary from nearly zero in the case in which the energy transformation occurs say, by the drying out of chemical salts or the growth of *Chlorella* to those temperatures at which virtually all known substances vaporize. The laws of thermodynamics state that the maximum amount of work that can be obtained from the transformation of thermal to other forms of energy is given by the temperature drop in the process divided by the final temperature ($\Delta T/T$). This means that most schemes for the utilization of solar energy are grossly inefficient because they operate with small temperature differentials.

If the temperature differential for a given process is specified, this in turn specifies, within a relatively narrow range, the kind of optical system needed. That is to say, if our objective is simply to heat water for low grade energy transport, a quite different optical system will be called for from one whose purpose it is to produce high temperatures necessary to melt refractory substances.

Whichever optical system is used, however, it must conform to certain elementary optical principles. The kind of practical results these principles allow and the kind of limitations they impose on the physical structure of optical systems for these purposes follows directly from their application. These results and limitations may come as a surprise to many who have not had the occasion to think about these matters. And, of course, no matter how elaborate and fanciful the mirror-and-lens systems are made for the utilization of solar energy, these elementary optical principles cannot be circumvented.

We can start with perhaps the most basic of all physical principles—the second law of thermodynamics—which states, in effect, that no selfsustaining method can be devised for transferring heat from a cooler to a hotter body. This means, in our context, that no optical system whatever will enable us to produce higher temperatures than 5700° K—the surface temperature of the sun. To the uninitiated, it might appear that if a large enough collecting surface were used, enough sunlight might be collected and concentrated to produce a hot pit of incredibly high temperature. This, unfortunately, the second law of thermodynamics will not allow, but temperatures higher than any ordinarily sustained on earth can be produced as long as the sun shines. Furthermore, temperatures as high as 3000° and 4000° K. can be produced which give a pure uncontaminated heat, free of chemical byproducts which are present almost of necessity when the high temperatures are chemically or electrically produced. The production of such high temperatures in this pure form is particularly valuable when one wishes to study the behavior of substances at high temperatures without bringing these substances into contact with any others. Indeed, the rays of the sun can be directed into a vacuum chamber in which only the object to be treated is present. It is interesting to note that a black body heated to maximum temperature by sunlight in this manner will emit far more ultraviolet light than contained in sunlight at the surface of the earth.

The production of high temperatures is, however, a very special application and, in general, solar light need not be highly concentrated in order to do useful work. Since the limitations imposed by optical principles, however, apply to all cases, we proceed directly with their discussion.

Any optical system can be characterized by its effective aperture and its effective focal length, and by the ratio of these two. We say "effective" because in certain cases the optical system is no longer simple, that is, one in which the aperture is simply the physical opening of the system and the focal length the simple distance from the lens or mirror surface to the focal or image plane. Actually, when one looks at the matter more closely, one sees that we are not primarily dealing with image formation at all but rather with the position of the minimum cross section of the total bundle of rays. That this is not the same thing as the place of image formation can be seen by the simple experiment of projecting the image of the sun with a typical telescopic system. This is done by holding a sheet of paper several feet in back of the eyepiece of a telescope. By adjusting the eyepiece slightly, a large sharp image of the sun is obtained on the paper, of sufficiently good definition to show sunspots and even solar granulation. As one moves the sheet of paper toward the telescope, however, the image becomes indistinct and finally thoroughly blurred, but as the paper is moved still closer to the eyepiece it bursts into flame. The greatest concentration of energy does not, therefore, correspond necessarily to the place of image formation.

Rather, it might be put this way: the aim of optical systems for the utilization of solar energy is the production of a usable concentration of solar rays, not of a solar image suitable for photography. Thus, a rough spherical mirror of long focal length used with a mirror or lens of short focal length can be constructed at a very small fraction of the cost of a telescopic optical system, and yet can be made to produce a concentration of light for energy purposes that will essentially equal that of the more expensive telescopic system.

In this short treatment, it would carry us too far afield to examine anything but the simpler optical systems. In these the aperture can be defined as the total light-gathering area and the focal length can be defined in the usual way. Using the word "image" rather loosely, the size of the image will depend, of course, only on the focal length. A handy "thumb rule" for the size of the sun's image, for any optical system, is to divide the focal length by one hundred and eleven (f/111). A reading glass of, say, six inches aperture and a focal length of one foot will give an image of the sun about a tenth of an inch in diameter; a telescope typical of those used on college campuses, having a focal length of, say, 175 inches, will yield an image of the sun about an inch and a half in diameter. The great Yerkes refractor of focal length 63 ft. gives an image of the sun that is nearly 7 in. in diameter, and, if the large reflector of the Perkins Observatory, of focal length 104 ft. were used on the sun (which, of course, it never is) we should have an image at the Cassegrain focus of nearly a foot in diameter.

One is reminded of the war-scare stories of the Germans' intention to launch an artificial satellite some hundreds of miles in space equipped with a lens or mirror system to focus the sun's rays and thereby wipe out entire cities. We need have little fear of this since the size of the sun's image would increase in diameter by approximately one mile for every one hundred or so miles the lens was farther out in space. It would take a huge mirror to collect enough light so that, when spread over an area of many square miles, the energy density would be sufficient to vaporize cities. However, it would still be possible for an enemy with an artificial satellite-lens of imaginable proportions to raise the temperature in a city sufficiently to make living in that city very uncomfortable.

Elementary calculation shows that a mile-diameter mirror or lens at 222 miles above the earth's surface would yield an "image" of the sun having approximately four times the area of the light gatherer. Even if occultation effects were absent, the sunlight on the target area would be increased by one-fourth its normal value. Applying simple black-body considerations, the momentary increase in temperature amounts to not more than 30°F. We say "momentary" since the optical system would be in rapid revolution about the earth, completing a round trip in about two hours.

The aperture of a lens system determines the total amount of energy that can be gathered. The focal length determines over how wide an area this energy is distributed. Consequently, the f/number, or the ratio of the focal length to the aperture, alone determines the energy density in the image. If one assumes black body conditions for the receiver, the temperature of the receiver can be determined from Stefan's law, and is likewise solely a function of the f/number. A small hand magnifier is thus capable of concentrating as much solar energy per unit area as a large telescope of the same f/number, if the optical excellence of the two systems is the same. As an example, let us take the world's largest refracting telescope—the Yerkes refractor—and a reading glass 4 in. in diameter and of 8 in. focal length. The Yerkes refractor has an objective 40 in. in diameter and a focal length of 63 ft. The telescope gathers, therefore, 100 times as much flux as the reading glass but spreads it into an area that is nearly 9,000 times as great as the area covered by the image formed by the reading class. Its ability to produce heat-at-a-point is, therefore, some 90 times less than that of a simple reading glass. The reading glass, however, gives a solar image less than 0.1 in. in diameter while the Yerkes refractor produces an image nearly 7 in. in diameter.

As a further example, take the world's largest telescope, the 200-inch reflector at Palomar. A precise reflector of this kind is never directed toward the sun because of the distortion of the figure that would result by this procedure. Nonetheless, if it were used on the sun, all the sunlight falling on the mirror area of more than 200,000 sq. cm. would be concentrated in an image 177 sq. cm. in area. Now, although the solar constant is generally stated as 1.94 cal./min./sq. cm., this refers to energy received outside the earth's atmosphere. Measures made at Mt. Wilson with the sun near the zenith show that only 1.54 cal./min./sq. cm. are received, representing a loss of about one-fifth of the total. Thus the total energy received by the 200-inch telescope would be 2.18×10^{11} ergs/sec. Assuming no losses in the optical system, the image receives 1.23×10 ergs/cm. which, under black body conditions, corresponds to a temperature of 2,150° K. The 200-inch telescope has a focal length of 660 in. and therefore an f/number of 3.3. A similar calculation carried out for a 6-inch aperture, 12-inch focal length reading glass shows that although the image has an area of but 0.06 sq. cm. the image receives energy at the rate of 3.26×10 ergs/sec./sq. cm. The black body temperature is therefore 2,750° K.—some 600° higher than that given by the world's largest telescope.

These illustrations are, of course, simple and do not take into consideration the temperature of the surroundings, the conduction of heat away from the receiver, and other factors. They serve merely to illustrate that while large telescopes collect a great deal of energy, it is less concentrated than in the case of a simple hand magnifier.

It is amusing to consider what would happen if the 6-inch image given by the world's largest telescope were further concentrated by the simple reading glass of 6-inch aperture and focal length of 12 in. If the full 6-inch image were allowed to fall directly on this reading glass, a concentration of energy would occur in an area 3.7 in. in diameter, slightly more than one foot beyond the normal focal plane of the 200-inch telescope. The energy density would be increased by a factor of 2.6 and the black body temperature to 2,730° K. so that the temperatures are essentially equal; the area of the image has been increased from 0.1 in. to 3.7 in. and thus far more energy is available for work at that higher temperature. The fact that the secondary lens would become quite warm is merely a practical difficulty and does not destroy the value of the illustration.

Now let us consider briefly the relative merits of paraboloidal and spherical mirror systems. We are accustomed to thinking of a parabolic surface as the ideal light gathering medium. The formula for a parabola, $y^2 = 4fx$, where f is the focal length of the parabola, indicates that simply by constructing increasingly "cigar-shaped" light collectors, very small f/numbers and thus extremely high temperatures could be obtained. One needs here, however, to reckon with the fact that the sun is not a point source. Conn (1951) has recently described a parabolic receiver of aperture 120 in. and a focal length of 34 in. This implies an f/number of 0.3. If one traces rays for the system one finds, however, that the image size corresponds to a focal length of 7 ft. and hence an f/number of 0.7. This is merely to illustrate that short focus parabolas are extremely sensitive to off-axis rays, and even the half degree subtended by the sun produces a notable distortion. Preliminary calculations indicate that it would be better, and probably cheaper, to construct a large-aperture spherical mirror of say, f/20 ratio in which, therefore, the spherical aberration is not serious, and to further collect and concentrate the beam by a small auxiliary lens or mirror on to the receiver. The secondary mirror would, of course, have to be constructed of a highly refractory substance.

If we get away from high energy densities and speak rather of high total energies at lower densities, we are much more likely to be dealing with examples which will be useful. Let us suppose a hypothetical example of this sort, an industrial plant located in an open, semi-arid region, or at least in a region having cheap land nearby. A black hemisphere to act as an energy collector is mounted atop a tall tower, giving the appearance of a tall water-storage tank. At the base and extending out for several acres we shall have an array of plane mirrors, or perhaps slightly spherical mirrors of very long focal length. These shall be directed to deflect the sun's rays to the black receiver atop the tower. Modest power needs could be supplied by such an arrangement at a relatively small cost.

Let us imagine, however, a solar installation on a much larger scale. Since we are not limited in our imagination, let us choose a valley surrounded by a ring of mountains. If the valley had a radius of one mile, 10,000 plane mirrors, each of one square yard area mounted so as to form the elements of a large spherical reflector would produce, applying the simple rule-of-thumb, an image of the sun, a mile away, some fifty feet in diameter. If a 50-foot diameter black sphere were placed in the center of the valley, simple calculation shows, even making generous allowance for losses in transmission and general inefficiency of the system, that more than one hundred gallons of water could be brought to boil per minute and more than ten gallons could be converted into steam per minute. Even so, 10,000 mirrors would cover but a few acres and if much larger parts of the mountain-ringed valleys were employed, enough solar energy could be transformed to supply a good-sized community with power. One needs only to remember that each mirror receives the equivalent of better than one horsepower and that even a small-sized valley could accomodate several million mirrors. Even allowing for 10 percent efficiency of the entire system, it can be seen that a solar energy project on this scale would develop many hundreds of thousands of horsepower for industrial purposes. If power were not the object but instead merely the heating of great quantities of water to, say 150° F, a large community could be heated by a relatively modest solar energy plant. The entire storage system, of course, would have to have sufficient heat capacity to act as a reserve for cloudy periods.

Numerous schemes for low temperature solar engines have been proposed from time to time (Conference on the Sun in the Service of Man, 1951) and some small installations are now in operation.

As far-fetched as some of these optical schemes may seem, it seems clear that eventually solar energy must be used more directly for human needs. The astronomical time-scale for the earth is rated in the billions of years; and if present theories of the source of solar energy are correct, the climate of the earth will not change sensibly for the next 10,000,000,000 years. In this period nature would have time to start the entire process of evolution from amoeba to man several times over, should man destroy himself and other forms of life. Ordinary natural resources will most probably be exhausted long, long before this. Over long periods of time, atomic energy likewise is not the final solution since it, itself, permanently destroys supplies of the critical heavier elements. The only apparent eventual answer seems to be the use of solar energy.

The eventual answer must also make better use of the high energy potential (low entropy) of solar photons, characteristic of radiation at 6,000°C, rather than of their utilization after degradation to thermal motion by black body absorption—that is, advantage should be taken of the "ability to do work" of the individual photon, rather than to attempt to put solar energy to work after the entropy of the system has been increased and the same total energy reduced to a less useful form. In both types of usage, however, the optical principles enumerated above must be obeyed.

In the words of the advertiser, "Eventually, why not now?": Experiments on a sufficiently large scale might well be made now so that the human race might gain some experience on the application of an energy supply which, sooner or later, it must use universally.

REFERENCES

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