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A Survey of Potential Low-Cost Concentrator Concepts for Use in Low-Temperature Water Detoxification

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A SURVEY OF POTENTIAL LOW-COST CONCENTRATOR CONCEPTS FOR USE IN LOW-TEMPERATURE WATER DETOXIFICATION

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ABSTRACT

Several different concentrator concepts have been considered for use in the detoxification of chemically contaminated water. The reactions of interest are predominantly photocatalytic in nature and are driven by low concentrations (between 1 and 50 suns) of UV radiation in the 300- to 385-nm wavelength range. Optical performance characteristics of these concentrators are thus somewhat different compared to concentrators developed for industrial process heat and electrical energy production. Relaxed optical tolerances might lead to reductions in concentrator cost that, when integrated into overall field system cost, could make the solar-driven process competitive with current UV lamp technology. Aspects of the concentrator system that might realize cost reductions include the concentrating element, the support structure, the tracking and drive system, the manufacturing processes, and the installation procedures. Several ideas have been resurrected from earlier research in the Solar Thermal Program where the need for more stringent optical performance requirements led to a decline or even an end to further investigation. In light of this new application, the most promising of these ideas are presented, including a description and a discussion of the cost and performance trade-offs. In addition, the results of recent investigative research on several of these concepts will be presented. The concepts include a low-cost parabolic trough, the inflatable line-focus concentrator, and the holographic concentrator.

INTRODUCTION

The U.S. Department of Energy (DOE) has directed the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (Sandia) to develop systems capable of detoxifying hazardous materials using concentrated solar energy. NREL and Sandia have shown that a variety of organic chemical contaminants in water can be destroyed to the limits of detection by exposure to concentrated sunlight in the presence of a nontoxic catalyst, titanium dioxide (Link and Turchi, 1991). The process produces hydroxyl radicals that are highly efficient oxidizing agents. The hydroxyl radicals attack organic chemicals and break them into nontoxic materials such as water, carbon dioxide, and dilute hydrochloric acid.

System analysis studies have shown that one of the requirements for the economic viability of solar photocatalytic water treatment systems is the availability of low-cost, durable, line-focus solar concentrators having low operation and maintenance (O&M) requirements and the capability to maximize collection of near-UV (300-385 nm) solar radiation (Turchi and Link, 1991). These studies, in combination with the previously mentioned experimental research, have established the optical concentration requirement to be less than 50 suns and have also established a subsystem cost goal of $\$50/m^2$. This value includes the concentrator subsystem capital cost (with tracking system and support hardware) and O&M costs at realistic production levels. It does not include costs associated with the photoreactor/receiver, piping, controls, buildings, or site preparation.

This paper discusses current efforts aimed at reducing cost to the $\$50/m^2$. Current thermal concentrator subsystem costs range from $70 to $\$120/m^2$ at relatively small manufacturing levels. A reduction of at least $\$20/m^2$ is needed to make the concept competitive with current lamp-driven processes. A significant design difference between a solar photoconcentrator and a solar thermal concentrator is that the necessary solar concentrations are much lower and that, being a purely a photocatalytic process, the generation of thermal energy is not a concern. In fact, heating of the receiver and its contents is undesirable because some contaminants may go into the gas phase at elevated temperatures and become untreatable. Therefore, the receiver size does not need to be minimized to reduce thermal losses. These characteristics might lead to relaxed optical accuracy requirements and thus open up this application to new lower-cost line-focus concentrator designs.

Several efforts were begun to explore this issue. First, a request for proposals was sent out in order to solicit ideas from industry concerning the development of a low-cost line-focus concentrator. This resulted in a subcontract aimed at identifying ways in which costs associated with a conventional parabolic trough system might be reduced for this photochemical application. Second, preliminary investigations were initiated in house to explore the low-cost potential of several other concentrator concepts. These include holographic optics and an inflatable line-focus concentrator design. In addition, a survey of potential low-cost UV reflecting materials was initiated and preliminary testing of some of these materials begun (Jorgensen and Govindarajan, 1991).

In addition to the research being done on concentrator design, work is also ongoing in the area of receiver/reactor design. This receiver/reactor work is beyond the scope of this paper. Ultimately, the design of a complete photocatalytic water treatment system depends on the interrelations between each of the subsystems.

As mentioned previously, the photocatalytic process is most efficient at low concentrations of UV radiation. Some recent work suggests that a one-sun photoreactor might deliver better overall photochemical performance than a concentrating system. Certainly, there is more UV energy available when one takes advantage of the diffuse radiation in addition to the direct normal component. Based on these preliminary findings, significant research efforts on one-sun photoreactors have recently begun. In one-sun systems with large aperture areas, receiver flow velocities are typically smaller than in line-focus concentrating systems. These smaller velocities result in lower destruction rates. Thus for one-sun systems, mass transfer is an issue that needs to be addressed. Also, increased aperture area requires more catalyst, leading to questions concerning cost. These issues will be examined extensively in the one-sun photoreactor research effort. Line-focus concentrator technology, by comparison, is relatively mature and well established. The performance capabilities and cost goals for concentrators are reasonably well known. Therefore it is important to continue the development of both one-sun and concentrating systems for this application in order to arrive at a cost-effective design that industry might manufacture and market within the next five years.

What follows is a discussion of each concentrator concept mentioned previously. A summary of the research done to date is also presented. Finally, potential follow-on work and future research plans are discussed.

CONCENTRATOR CONCEPT DESCRIPTIONS

Low-Cost Parabolic Trough

One approach NREL is taking in developing a low-cost concentrator for detoxification applications begins with established line-focus concentrator technology. By re-examining all aspects of the design, cost reductions may be realized in many areas by taking advantage of the relaxed optical requirements. Large cost reductions would not be expected, but the potential exists for a number of smaller cost reductions to be made that when added together result in a significant lowering of the overall cost. The best example of existing line-focus technology would be the conventional solar thermal parabolic trough. Several companies currently manufacture and market such systems.

Because this approach establishes a relatively clear and low-risk path to achieving hardware capable of performing at the desired level, it represents a significant part of the low-cost concentrator development effort at NREL. Under contract to NREL, Industrial Solar Technology (IST) is exploring potential modifications to its existing solar thermal parabolic trough design with the aim of reducing installed concentrator costs (including concentrator and support structure, drive system, and foundation) to $\$50/m^2$ or less at realistic production levels. The concentrator system aspects that are being investigated include the concentrator rim angle, optical accuracy requirements of certain reflector components, receiver fixtures, the drive/tracking system, installation procedures, and UV reflective materials. Each one of these areas will be visited to determine the potential for cost reductions given the different optical requirements for this application.

Inflatable Line-Focus Concentrator

NREL is also approaching the development process from a more innovative perspective. One concept being considered is the inflatable line-focus concentrator or inflatable cylindrical concentrator. This concept is not new. Researchers at Lawrence Livermore National Laboratories did an extensive amount of work on this design for solar thermal applications (Gerich, 1977). Figure 1 is a photograph of a prototype inflated cylindrical concentrator that was fabricated by the Lawrence Livermore research group. In short, the inflatable line-focus concentrator consists of a large-diameter plastic sleeve that is inflated with a blower. Part of the circumference of the resulting cylinder is reflective and concentrates light onto a receiver supported at half the radius of curvature of the cylinder (i.e., the focus). The reflective material can be seen at the bottom of the inflated tube with the receiver suspended directly above it. The inflated structure serves to support itself and the receiver, simultaneously providing a relatively accurate optical shape. At the time this work was done, the end use envisioned for the inflated trough was providing mid- to high-temperature industrial process heat. This, unfortunately, required higher-accuracy trough systems, and research on the inflated cylindrical concentrator was discontinued. However, for this application, the optical performance of the inflatable concentrator may be better matched with the requirements; this, coupled with the potential low cost of the concept, has justified further investigation.

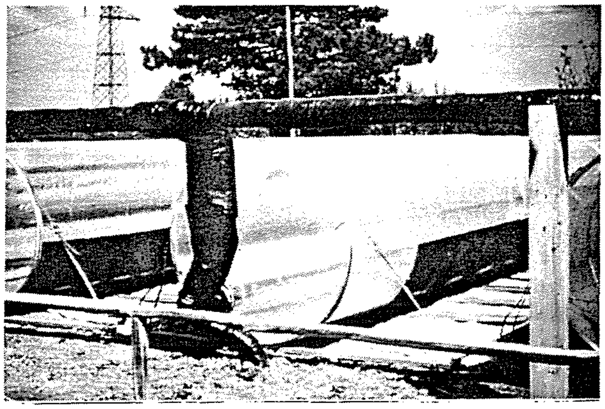
Figure 1. Photograph of an inflatable line focus concentrator prototype

Inflated structures exhibit excellent structural properties, as typified by the construction of inflatable buildings and domed roofs. The inflated cylindrical concentrator is a purely tensioned structure, and thus material is used to the best advantage. It exhibits excellent structural stiffness for its weight and could be almost entirely self-supporting. It is this characteristic that could translate into lower costs. There all also other potential benefits regarding system maintenance. It is conceivable that the replacement of a reflective or transmissive surface might be a relatively simple and inexpensive process. The protected interior environment that the reflective surface sees might also enhance the lifetime of that material.

The development of the inflated concentrator also presents some interesting challenges. The most significant is the identification of UV transmissive and reflective materials that can stand up to the outdoor environment, perform well, and have reasonable lifetimes. In addition, inflated structures require pressurizing systems using fans, blowers, or compressors. These all tax the system economics somewhat and present certain O&M issues. The Lawrence Livermore research emphasized the technical design and performance of the concept. Other than alluding to the low-cost potential of the inflatable concentrator, little has been done to actually estimate manufacturing costs. A cost/performance analysis should be a necessary element of future research. NREL researchers are just beginning to work with industry to answer some of these questions concerning the inflatable line-focus concentrator.

Holographic Concentrators

Another innovative idea being explored is the holographic concentrator. This concept has also seen some extensive development work in the solar thermal program and more recently in the area of concentrators for photovoltaic systems. Developing holographic surfaces (which are highly wavelength selective) for solar thermal applications requiring the full solar spectrum proved to be a very difficult task, and eventually research for this application also ended. However, work on holographics and other diffractive technologies has continued for narrow-wavelength band processes such as photovoltaics and photochemistry. Because the water detoxification process is purely photocatalytic in nature (needing photons in the 300- to 385-nm range), the holographic concentrator could be a good candidate for supplying these photons while essentially filtering out those that are unnecessary and/or those photons that might adversely affect the process. The most significant unknowns concerning the holographic concentrator are cost and large-scale manufacturing issues. NREL researchers have been studying the literature pertaining to holographic optical elements (HOEs) for both solar and non-solar applications. This information has been used to identify the important performance and cost issues for further study.

SUMMARY OF WORK DONE TO DATE

Low-Cost Parabolic Trough

This work has been carried out by IST under subcontract to NREL. The first task analyzed the effect of photoconcentrator rim angle on cost and performance. For those reasons mentioned earlier, there may be optical design differences compared to a thermal concentrator. The rim angle has a direct bearing on the optical performance and the use of materials in a trough design. The performance of a thermal concentrator is very sensitive to slope and specularity errors in the mirror surface. High intercept factor and concentration are needed to generate the temperatures for industrial process heat and electricity applications. Large rim angles (i.e., short focal lengths) are favored for the thermal concentrator because the adverse effects of optical errors are less pronounced than at longer focal lengths. However, longer focal lengths appear to have some benefits with regard to more efficient use of materials in that the concentrator surface area decreases as the rim angle decreases.

In order to investigate these cost/performance trade-offs, a model developed by Bendt and Rabl (Bendt et al., 1979) was used to predict trough intercept factor as a function of concentration, rim angle, receiver size, and optical error. Intercept factor was used as the definition of optical performance. This was then combined with a cost analysis, including detailed cost estimates for those components that are rim angle dependent. These include concentrator surface and receiver materials. Manufacturing and installation costs, as well as the drive/tracking system and foundation, were not included in the analysis because they would essentially be unchanged for all rim angles. The analysis also incorporated photoreactor cost estimates for two-, three- and four-inch-diameter receiver sizes using the most current glass tubing and catalyst cost data. A simple supported catalyst-in-tube design was assumed for the photoreactor.

Because a final photoreactor/receiver design (including the optimum concentration ratio) and its associated cost have not been established in detail, it should be noted that this was not an absolute analysis but one that looked at cost changes relative to the current IST trough as the baseline optical design. It is thus useful for continuing the concentrator design.

Another important factor considered in this study was the change in concentrator structural properties with rim angle. In IST's baseline design, the stiffness of the concentrator decreased with decreasing rim angle. Structural calculations were done by computer to assess the structural stiffness as a function of rim angle. If the stiffness fell below the beam strength requirement, then the concentrator had to be "beefed up" in other areas to meet this requirement. These additional material costs were taken into account in the cost analysis. The resulting cost changes as a function of rim angle were found to be relatively small. However, this represents just one aspect of the overall system. When combined with other subsystem cost savings, a significant overall cost reduction may be realized.

The last system parameter included was the optical error budget. The analysis was done for two different error budgets: a conservative estimate of 13.1 mrad and an optimistic estimate of 10.3 mrad. These values represent the total optical error in the system, including slope, tracking, and specularity, and are half angle root-mean-square values. The optimistic value is representative of the thermal trough design. Again, the goal of the study was to determine the optimum rim angle for a reasonable range of receiver diameters and a reasonable range of optical error budgets.

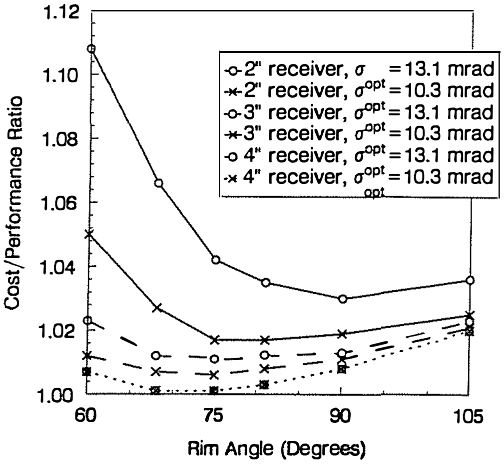

Figure 2. Rim angle optimization for three photoreactor sizes and two optical error budgets

The results are shown in Figure 2. The ratio of cost in dollars to performance (i.e., intercept factor) is plotted as a function of rim angle for the range of receiver sizes investigated and the best- and worst-case optical error budgets. A broad optimum exists for all cases. The 2-in. receiver diameter and the optical error budget of 13.1 mrad is not considered to be a realistic combination due to unacceptable performance. The other cases have minimum cost/performance ratios with rim angles ranging from 72 to 84 deg. The change in cost/performance ratio over this range is less than 0.5% for both receiver sizes and optical error budgets. This illustrates that decreasing the rim angle has little effect on the cost/performance. Based on this result, it was decided to continue with the 72-deg rim angle for the photoconcentrator trough design. This insensitivity results in large part from the structural stiffening that must be done in order to maintain stiffness at the lower rim angles. Because the rim angle is unchanged from the baseline design, no cost savings were realized for this system parameter.

The drive/control system was investigated next. IST's current design employs a pulley system that allows one motor to drive multiple concentrator rows. The tracking errors increase with additional rows and eventually become prohibitive. For the thermal concentrator, the maximum number of rows that can be ganged together is four. However, consistent with the idea that a larger error budget exists for the photoconcentrator, a study was done to determine if the number of rows could be increased for this application. This could have a significant impact on the system cost because it increases the amount of aperture area that can be driven with one drive/control system and thereby lowers the per-unit aperture area costs.

Cost estimates of adding additional rows were made, including the re-engineering of the drive pedestals and support pedestals for larger row numbers. Overall, total cost savings were shown to increase moderately as the number of ganged rows increased. As a fraction of the total installed concentrator cost, the savings are even smaller, but again this represents one aspect of the total system.

Root-mean-square tracking errors were calculated based on the structural behavior of the drive/system as a function of the number of rows. This information was input to the previously mentioned optical model, and the intercept factor (i.e., optical performance) was calculated as a function of the number of ganged rows, again for the three receiver sizes and the optical error range discussed previously. Dividing the cost by the performance resulted in the curves shown in Figure 3. This analysis suggests that for the range of receiver sizes investigated, the

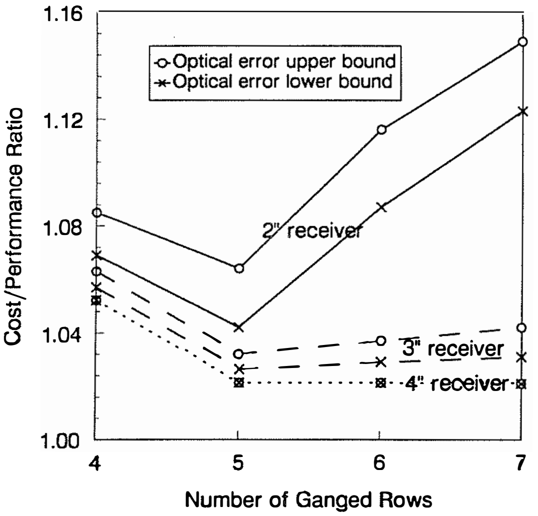

Figure 3. Ganged row optimization for three photoreactor sizes and two optical error budgets

optimum number of rows that can be ganged together and driven by one drive/control system is five. This is an addition of only one row to the current conventional design.

Because this system component has the potential for significant cost impact, IST decided to check the analytical result by building a six-row drive string, simulating the actual concentrator rows (mass and wind loads) with weights and measuring actual tracking errors between the master row and the other five rows. Preliminary results indicate that the material properties of certain drive system components may have been underestimated in the analysis because the measured tracking errors are roughly half that predicted. With the use of the tracking errors measured in the experiment and with their extrapolation out to larger row numbers, the optimum row number appears to be closer to seven. This, together with cost savings associated with reduced machining tolerances for the drive system, would reduce system costs by approximately \$2.27/m^2.

Other cost savings attributed to the relaxed concentrator accuracy requirements include the use of fewer parabolic support ribs, less accurate ribs, fewer construction rivets, and coiled aluminum instead of levelled aluminum sheets. Together, these components result in a savings of approximately \$2.47/m^2. IST has also looked at installation costs as an area where savings might be made. One savings already identified is in the concentrator layout. Previously, this involved painstaking surveying techniques that were time consuming and expensive. IST has developed a lightweight portable layout jig for determining the location of foundation holes. This has proven to be very effective and has resulted in a procedure that is simple and less expensive by about \$0.37/m^2.

The cost savings discussed here total approximately \$5.00/m^2. The starting cost of the concentrator portion of the IST baseline thermal trough system is estimated to be \$70.00/m^2. This includes the concentrator structure, the reflective film, drive/control system, support pylons, and foundation and is representative of the tenth installation of a 2,700-m^2 system. A \$5.00/m^2 cost reduction is equivalent to a 7% savings and brings the concentrator system cost within \$15.00/m^2 of the \$50.00/m^2 goal. Several areas are yet to be investigated. These include the reflective surface film; the concentration installation costs; photoreactor support hardware; and, most importantly, economies of scale. The potential savings of these additional system components may provide the potential to achieve the \$50.00/m^2 goal.

Holographic Concentrators

To date, the work done on holographic concentrators consists of an extensive literature search covering both solar thermal electric, photovoltaic, and industrial applications. This includes work done by universities and research groups in both the United States and Europe.

Earlier NREL-sponsored work on HOEs for solar thermal applications was done by the Acurex Company (Hull, 1987). The thrust behind the effort in HOEs at this time was that a concentrating structure could presumably be made flat and avoid the complexities associated with the curved support structures of conventional reflecting concentrators such as glass/metal troughs and dishes. In addition, there was an idea proposed earlier by Magarinos (1981) that holographic concentrators might achieve high concentrations with minimal or no tracking. The idea was that this could translate into lower cost.

Many references discuss and explain the theory behind holographic optics (Collier et al., 1971; Francon, 1974; and Cathey, 1974), so the theory will not be described in any detail here. Essentially, an HOE is made by recording the interference pattern between a reference beam of highly coherent monochromatic light and an object beam using the same light source. In the case of a solar HOE, the object beam would be that emanating from the focal region of a point-focus or line-focus concentrator; the reference beam would be analogous to the virtual image of the sun as a source. A schematic of a solar HOE fabrication setup is shown in Figure 4. Once fabricated, sunlight striking the hologram will focus back to the focal region by either transmission or reflection depending on whether the reference beam used to create the hologram impinges on the film from the same or opposite direction as the object beam. Acurex determined that for solar thermal applications, the reflection hologram is the better choice because of its ability to perform more efficiently with a non-monochromatic light source such as the sun.

Most HOEs designed for these applications use dichromate gelatin as the recording media. It is relatively inexpensive, readily available, and easy to use. Most HOEs are made with highly coherent monochromatic laser light. This results in an HOE that is most efficient at that wavelength. In order to yield good diffraction efficiency (or optical efficiency) over a wider-wavelength band, certain aspects of the film developing and curing process are adjusted. These include the humidity and temperature of the processing environment. By swelling or shrinking the dichromate gelatin, the bandwidth can be adjusted. The maximum usable bandwidth attained by researchers (Windeln and Stojanoff, 1985; Quintana et al. 1989; and Coleman and Magarinos, 1981) has been on the order of 100 nm. From this, it is obvious that one HOE will not suffice for coverage of the solar spectrum. In order to cover the solar spectrum, several holograms had to be made, each responsive to a different wavelength band. These bands could not overlap significantly; otherwise, crosstalk between the different layers would adversely affect the optical efficiency. This turned out to be a formidable task. In addition, it was shown by Welford and Winston (1982) that a passive optical device such as a hologram could not possibly track the sun without moving. This violates a basic optical law known as the brightness theorem. Figure 5 illustrates this relatively simple proof, which is discussed in more detail in by Welford and Winston (1982). By the principle of reversality, it is seen that a ray traced backward from a stationary image through a stationary passive optical device (such as a hologram) cannot possibly have more than one initial source (i.e., one sun position). It is physically impossible for the light to take one path at time t_1 and another path at time t_2. These developments ultimately led to the end of holographic research for solar thermal applications.

The detoxification process differs from the thermal process in that only a narrow-wavelength band of light is desired. If the UV band can be utilized and the remainder of the solar spectrum is filtered in some way, then thermal heating of the photoreactor can be minimized. This

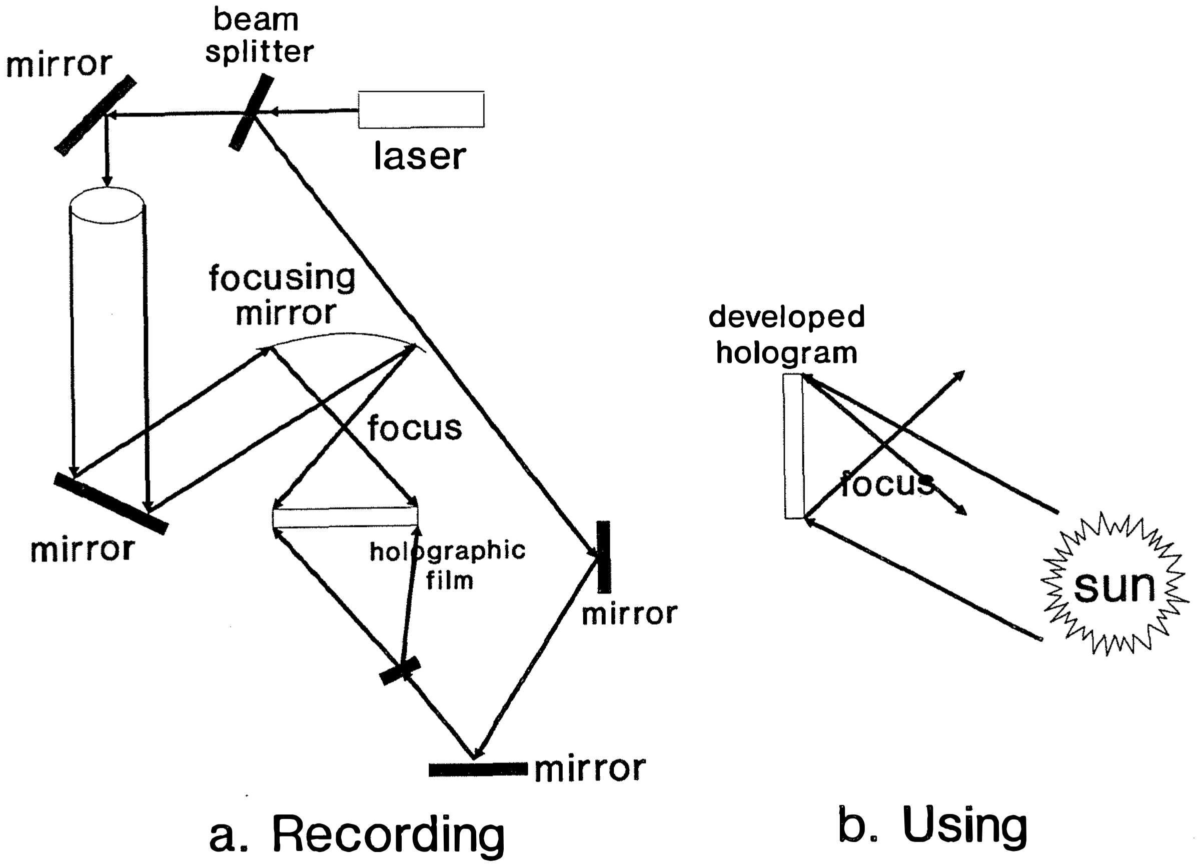

Figure 4. Recording and using a focusing reflection hologram

band spans roughly 300 to 385 nm and suggests that the problems encountered with the thermal HOE might be avoided in a photochemical HOE. Diffractive devices, including HOEs, have been and continue to be investigated for such wavelength-dependent processes as radiation input to photovoltaic cells (Bloss et al., 1982). Indeed, diffraction efficiencies of up to 90% have been achieved for wavelength bands on the order of 100 nm. Because the necessary wavelength range for the photoconcentrator is on the order of 100 nm, it is conceivable that one HOE layer will suffice and that the losses associated with multilayer devices might therefore be avoided. There are other questions concerning the use of HOEs in solar industrial processes that must be addressed, however. The most significant is whether the size of HOEs developed in research programs can be expanded to realistic sizes for cost-effective collection of solar energy. A related issue is the identification of other materials for recording holographic information that are inexpensive and are able to stand up to the outdoor environment without the protection of expensive materials such as glass. Some work has been done with the goal of developing photopolymers for HOEs (Hay and Guenther, 1988). However, the performance of these materials has so far been lacking, and questions exist regarding the effectiveness of these materials in the UV wavelength region and their ability to survive the outdoor environment.

The Acurex Company performed a preliminary cost analysis for the holographic concentrator and compared this with a parabolic trough (Hull, 1987). This analysis suggested that the capital and O&M costs of a holographic concentrator compared well with that of a conventional parabolic trough and in fact might be lower. The reason given for this was the elimination of the complex support structure needed for a parabolic trough and the associated labor and installation costs. Although the study was preliminary and several uncertainties have been identified,

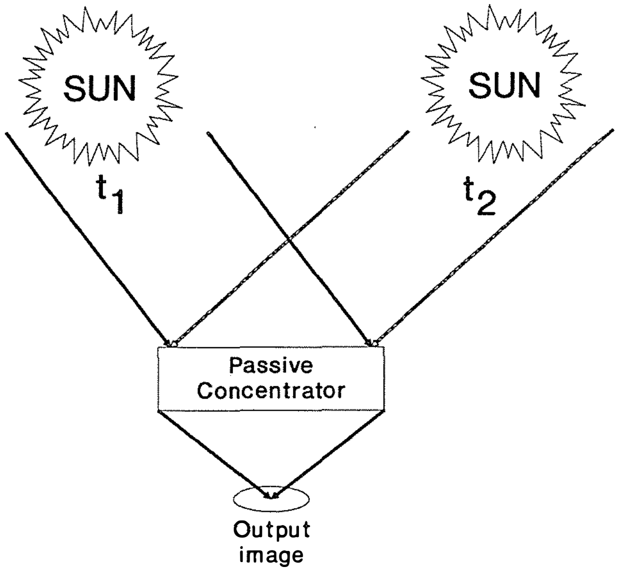

Figure 5. Illustration of a violation of the Brightness Theorem

this result, combined with the benefits associated with the desired narrow-wavelength band, make the concept for this application worth further investigation.

FUTURE WORK

Future efforts will concentrate on the completion of the low-cost parabolic trough project. Several design and cost issues remain to be investigated, including the photoreactor support system, alternate reflective materials, and the economies of scale. Once the cost study is completed, a final design will be determined and a manufacturing process plan developed. In addition, a prototype of the low-cost design will be built and tested at NREL. O&M documentation will also be supplied with the prototype. The photoreactor prototypes to be delivered as part of the photoreactor research effort may also be tested with the low-cost concentrator prototype.

In order to further examine the potential of holographic optics, the literature survey will be completed, and industrial candidates will be identified who have both technical and manufacturing experience in this area. This experience will aid tremendously in determining the manufacturing issues and associated costs so that a more in-depth analysis can be done regarding the feasibility of this technology for this application. Based on the literature survey, in-house efforts may be initiated to investigate standard materials, such as dichromate gelatin, and newer materials, such as photopolymers, for their UV sensitivity and durability.

The inflatable trough also has potential for low cost but has seen little research toward this end. As mentioned previously, the most significant issue to be explored is the identification of materials that have the necessary structural and optical requirements and are low cost. In order to evaluate the concept in these areas, industrial candidates will be sought who have experience with this type of structure and who can identify potential materials that meet these requirements. A preliminary cost analysis of a prototype will be done to better understand the potential of this concept for needed performance and low cost.

As mentioned previously, the diffuse component of solar radiation provides considerably more UV energy than the direct normal component. This important fact has led to a significant part of NREL's research being devoted to developing one sun-photoreactors. This work is already under way.

CONCLUSIONS

The work done to date on the development of low-cost concentrators for low-temperature aqueous detoxification has significantly advanced our knowledge of the design, manufacturing, and cost issues of line-focus concentrator technology in general. Two approaches were taken in this development effort: a conservative approach investigating modifications to existing technology and a more innovative and less proven approach looking at such concepts as holographics and inflatable structures. These approaches are representative of the variety of concepts that have been proposed for this application and have provided two very different and effective paths for arriving at a design that will, hopefully, perform well and be affordable. The \$50/m^2 cost goal is an ambitious one but one that is very close and, in fact, may be within our reach at the present time. The low-cost trough development effort has demonstrated realizable concentrator subsystem costs of \$65/m^2 with several system aspects yet to be evaluated. The performance and costs associated with holographic and inflatable concentrators are less understood at this point in time, but the potential of these concepts has been demonstrated and with appropriate research may lead to alternative methods for providing cost-effective concentrated sunlight.

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