Design and Cost of Solar Photocatalytic Systems for Groundwater Remediation

C. S. Turchi

M. S. Mehos

H. F. Link

◀◆▶ NR⊒L

On September 16, 1991 the Solar Energy Institute was designated a national laboratory, and its name was changed to the National Renewable Energy Laboratory

NOTICE

Design and Cost of Solar Photocatalytic Systems for Groundwater Remediation

Craig S. Turchi, Mark S. Mehos, and Harold F. Link
National Renewable Energy Laboratory
Golden, Colorado

ABSTRACT

Laboratory and small-scale field experiments have shown that sunlight in conjunction with a simple catalyst can be used to detoxify water contaminated with a variety of hazardous chemicals. This study builds on previous analyses and recent field test data to predict the cost and performance of a representative commercial water detoxification system. Three different solar operating configurations are explored for the treatment of 100,000 gal/day of groundwater contaminated with trichloroethylene. Current costs for solar water detoxification systems are projected to be comparable to those for conventional treatment technologies such as carbon adsorption and electric lamp-powered, ultraviolet light/hydrogen peroxide systems.

INTRODUCTION

The feasibility of using sunlight in conjunction with a photocatalyst to destroy organic water pollutants was demonstrated by researchers in the mid-1980s [1,2,3]. By directing the ultraviolet (UV) portion of sunlight onto a catalyst immersed in contaminated water, solar detoxification systems break down toxic organic chemicals into nontoxic compounds. The UV fraction of the solar spectrum activates the semiconductor catalyst in a process that produces hydroxyl radicals, OH•, as depicted in Figure 1. The oxidation chemistry and potency of the photocatalytic process are similar to other chemical oxidation methods that generate hydroxyl radicals, e.g., UV/hydrogen peroxide and UV/ozone. Given sufficient exposure to hydroxyl radicals, most organic pollutants will oxidize into nontoxic materials, such as carbon dioxide and water. In the case of the commonly found chlorinated solvents, dilute hydrochloric acid is also formed. The solar detoxification process holds the potential for inexpensive, on-site destruction of hazardous chemicals. As such, the National Renewable Energy Laboratory (NREL), and Sandia National Laboratories are heading the U.S. Department of Energy effort to develop solar detoxification technology for commercial application.
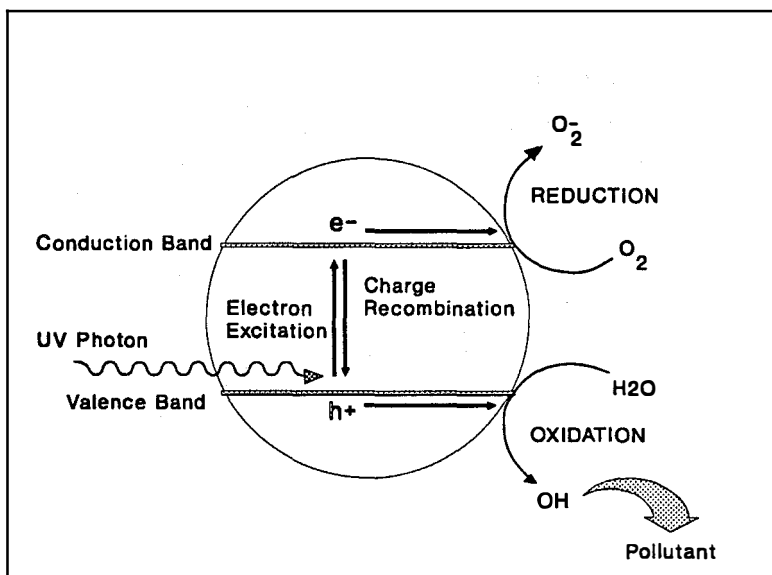
Figure 1:   Oxidation and reduction reactions occurring on a UV-illuminated TiO$_2$ particle.

Solar Resource

To estimate the performance of a solar water detoxification system, one must determine the amount of UV sunlight (wavelength < 385 nm) available at the treatment site. For preliminary site evaluation and comparison, results from a computer simulation of available sunlight are employed. The BRITE model [4] code calculates the terrestrial insolation as a function of atmospheric conditions. BRITE model simulations of available UV light in a cloudless sky can be expressed as a simple exponential function of the amount of atmosphere that sunlight must penetrate to reach Earth's surface. Because the air mass that sunlight must penetrate is a known function of geographic position and time, this formulation is a convenient means to assess geographic influence on system performance.

When dealing with any solar system, seasonal and diurnal variations in solar flux must be taken into account. These variations in solar resource are incorporated by sizing the treatment unit to handle the desired average daily flow on the day of the year with the least sunlight (i.e., winter solstice). To account for weather patterns, measured data on solar flux are compared to clear-sky BRITE model predictions to determine what fraction of the incoming light is attenuated by weather conditions. This fraction is used to project how much larger a solar unit must be to account for *average* weather conditions. This procedure typically leads to a doubling of the solar system size. However, more detailed site information is required to determine specific temporal fluctuations in weather. Finally, as a test, computer simulations of the various solar units are run using measured solar radiation values. During this simulation the solar-UV is artificially set to zero for one entire day. If insufficiently treated water is discharged because of this "dark" day, the solar system size is adjusted to prevent that occurrence.

2

REPRESENTATIVE CASE

The case presented here is for a site at Lawrence Livermore National Laboratory in northern California. This site is typical for groundwater remediation, in that contaminated water is pumped to the surface, treated, and then reinjected into the aquifer. The facility is designed to treat 100,000 gal/day (0.1 MGD) at a constant flow rate of 70 gal/min. Groundwater conditions are given in Table 1.

Table 1: Groundwater Conditions from Extraction Wells

Constituent	Range
Trichloroethylene (TCE)	400 ppb
Other volatile organic compounds	<10 ppb
Bicarbonate ion	200 - 500 ppm
pH	6.5 - 8.0
Flow rate	70 GPM

The Livermore site has good solar resources and is typical for the western one-third of the contiguous United States. Solar resources are even better at sites with less cloud cover and haze (e.g., the desert regions of California, Arizona, and New Mexico).

Reaction Kinetics

During the summer of 1991, detailed field experiments with a pilot-scale solar treatment unit were carried out at the Livermore site [5]. Based on these experiments, it was determined that a first order rate expression in the form of equation (1) adequately described the destruction of TCE for the conditions of that site.

$$r = \frac{A}{V} \left(\frac{I}{I_{ref}} \right)^{0.5} K_1 C \tag{1}$$

The reaction rate for any pollutant depends on a variety of factors including reactant species, UV intensity, oxidant type and concentration, and catalyst type and configuration. In general it is believed that compounds that exhibit high reactivity with hydroxyl radicals will be suitable candidates for solar detoxification (see, for example, reference [6]). Candidate chemicals include chlorinated olefins (such as TCE), benzene and derivatives, phenol and derivatives, and pesticides.

Cost Analysis Background

In late 1990, prior to the Livermore field tests, NREL completed a preliminary solar water detoxification cost study [7]. At that time, few cost studies had been attempted for photocatalytic water treatment [8], and costs for a full-scale commercial system were based on laboratory and limited outdoor tests. The 1990 study compared the projected performance and cost of a solar detoxification system to two other technologies: granular activated carbon (GAC) adsorption and

UV-lamp, hydrogen peroxide oxidation (UV/H_2O_2). The configuration of the solar system consisted of an inlet flow-buffering tank and an array of concentrating, parabolic trough solar photoreactors. The facility was based on the specifications of the Livermore site given above.

Since the publication of that study, a great deal of new information has been obtained, including data from the field experiments run at the Livermore site [5]. Updated equipment costs were obtained from various vendors, and a detailed assessment of the costs involved in constructing a solar treatment facility (at a different site) was completed by an independent consultant [9]. An important finding of laboratory and field test data was the indication that the photodestruction reaction operates more efficiently at lower light intensities. This has led to investigation and testing of nonconcentrating or "one-sun" photoreactors. The current study provides conceptual designs and preliminary cost estimates for nonconcentrating solar photoreactors at the Livermore, California, site.

SOLAR WATER DETOXIFICATION SYSTEMS

Three different configurations were investigated for the solar facility. All are designed to pump water from the ground and discharge clean water 24 h/day. This mode of operation is common for current treatment systems and was adopted for the solar units for consistency. (As will be discussed later, this requirement affects the cost of the buffer tank/PFR unit.) Pumping 24 h/day is accomplished by building several days of retention time into the solar systems. Although all the solar systems are designed to accommodate several days of poor weather, if the period of low UV sunlight exceeds this design time, the well pumps must be stopped. All three systems also require similar pre- and posttreatment equipment for the Livermore site. Field tests determined that lowering the groundwater pH was necessary to eliminate bicarbonate inhibition of the process. This simple step was accomplished by HCl addition to drop the pH to 5. Prior to discharge of the treated water, the pH was returned to 7 by addition of small amounts of NaOH. These two pH adjustment steps comprise the major pre- and posttreatment operations. A strainer and 5 micron filter are used to screen particulates from the incoming water.

The method of catalyst deployment was also assumed to be similar for the three solar units. For a commercial system it is assumed that the photocatalyst is supported on a small buoyant pellet, roughly 1/8 in. in diameter. The catalyst is removed from the treated water by a simple screen, and recycled to the photoreactor inlet. This catalyst configuration differs from that used in most tests run to date. The majority of tests, including the field experiments, were run with a catalyst slurry. A key consideration in this cost analysis is that the pellet-supported catalyst achieves the same activity as the slurry form and has a useful life of 3 months. NREL is investigating the effectiveness of a variety of different catalyst supports through subcontracted work at four research laboratories.

Finally, a common concern with solar systems is the required land area. Although the three solar facilities described below will occupy more area than the conventional treatment units, they are not overly large. On the conservative basis of requiring three times the nominal aperture area of the photoreactors, the required land usage ranges from 0.7 to 1.5 acres for these 100,000 gal/day systems.

Buffer Tank/Plug Flow Photoreactor (PFR)

The buffer tank/PFR configuration consists of two large flow buffering tanks and a set of single-pass photoreactors. The inlet tank is constantly fed by the well pumps and holds the pretreated water. During daylight hours, solar sensors detect the available amount of UV light and adjust the flow rate through the photoreactors to allow for sufficient residence time for complete destruction of the TCE. The unit is sized to account for weather and diurnal and seasonal variations in insolation. Maximum flow through the photoreactors is 560 GPM (compared to the 24 h average of 70 GPM).

One possible photoreactor configuration uses parallel paths of sealed fluoropolymer liners (Figure 2). Relatively few, long paths are shown in Figure 2, however the actual configuration can vary depending on land area and topography and desired piping and flow characteristics. The use of thin-walled fluoropolymer provides good UV transmission, excellent chemical resistance, and sufficient mechanical strength and durability. Other designs, such as ganged flat-plate or falling film collectors, are possible for the PFR. Because a PFR system has a high surface area to volume ratio in the photoreactors, it can treat the water quickly and efficiently. However, additional controls are required to allow the system to adjust for variations in sunlight. Flow buffering tanks are necessary so that the well pumps and the pre- and posttreatment unit can operate at a constant flow rate.
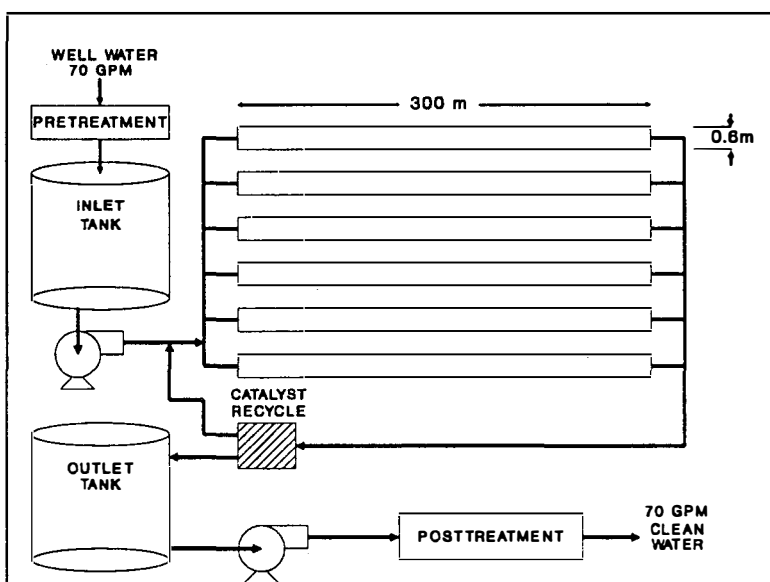
Figure 2:   Conceptual design for solar buffer tank/plug flow reactor configuration

Batch Tank Farm

The batch tank farm (Figure 3) represents a facility that incorporates photoreactor and tankage in the same vessels. This system consists of a set of shallow, well-mixed tanks that hold the water for several days to allow for complete destruction of the pollutant. The tanks are sized and controlled such that one of the tanks is being filled while the next in line is being drained. This sequence cycles through the tanks so that each tank holds water for the same residence time. In

this fashion, a constant flow rate is maintained from the wells and through the pre- and posttreatment systems. Because two tanks are always in a fill or drain step, the batch tank farm is slightly less efficient in use of area than the tank/PFR system. The efficiency drawback is traded against a much simpler control scheme.
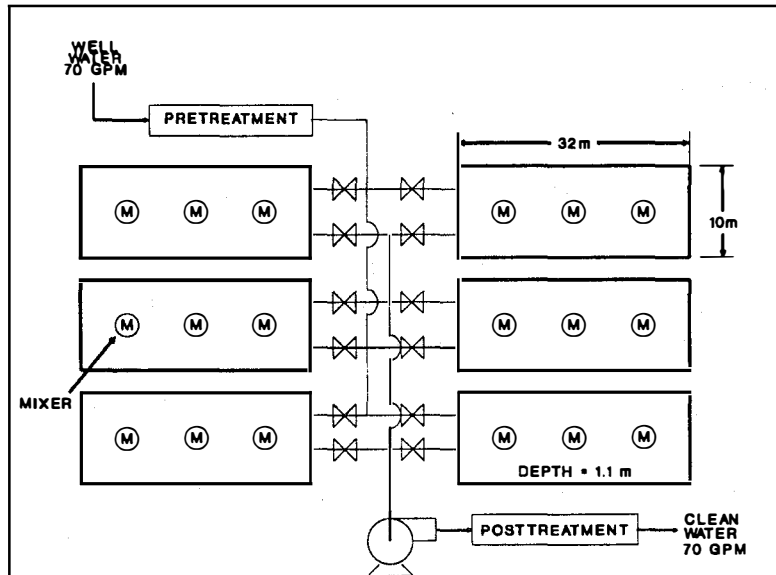

Figure 3:   Conceptual design for solar batch tank farm configuration

For this fairly small unit, above ground tanks with plastic liners are assumed. Larger systems could use lined earthen ponds. The tanks are covered by a UV transparent glazing (e.g., thin film fluoropolymer) to prevent escape of the volatile pollutant. The area to volume ratio of the tanks is set so that sufficient UV sunlight will be captured to completely destroy the pollutant, even under cloudy skies. A solar radiometer monitors the total UV captured to guarantee that the water has had enough exposure before a tank is drained.

Lazy River
The Lazy River concept incorporates attributes of both of the above designs. In this scheme, flow continuously enters and exits a long, serpentine channel (Figure 4). The channel, which serves as a photoreactor and holding tank, is dimensioned so that by the time the fluid exits the system it has had sufficient exposure to sunlight to completely destroy the TCE. Residence time in the current design is approximately three days. The Lazy River concept benefits from both an efficient use of area and a simple control scheme. All flows are constant, thus simplifying pretreatment, posttreatment, piping, and photoreactor control.
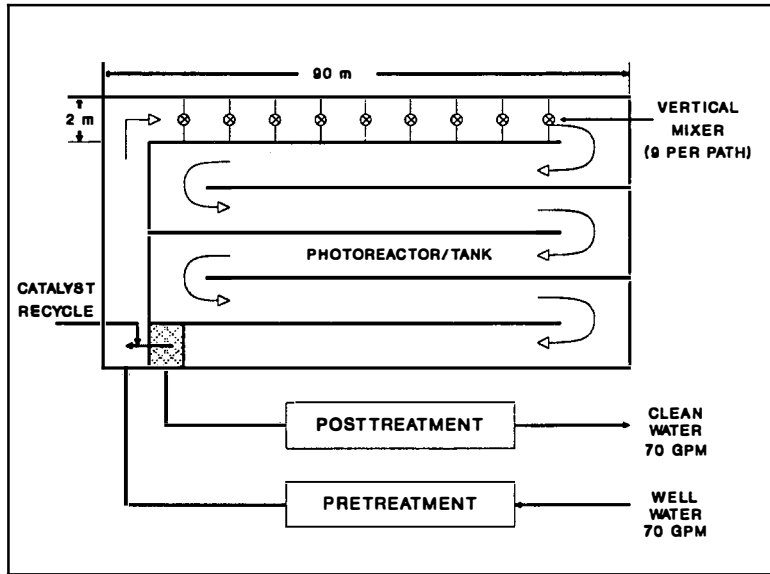
Figure 4: Conceptual design for solar lazy river configuration

As with the batch tanks, the small-scale unit described here is based on plastic lined, above ground tanks. Larger units would likely use lined earthen channels. The channel is covered by UV-transparent glazing. For the Livermore site the channel is assumed to be 1 m deep. Periodically, the flow is vertically mixed to ensure that all water comes in contact with the buoyant illuminated catalyst. This mixing can be accomplished by circulating water from the channel bottom to the surface with small pumps or aerators. If aeration is used the sparge gas must be recirculated to prevent loss of the TCE.

RESULTS OF COST ANALYSES

Cost information for the three nonconcentrating solar systems, the granular activated carbon (GAC) unit, and the lamp-powered, UV/hydrogen peroxide system unit are shown in Table 2. Also included for comparison are the cost estimates for a *concentrating* solar system based on the information known in late 1991. Costs for the GAC adsorption and ultraviolet-lamp, hydrogen peroxide oxidation units were derived from a feasibility study undertaken by Lawrence Livermore [10]. The variation in treatment cost between the three nonconcentrating solar units listed in Table 2 is likely within the range of uncertainty in the cost numbers. Similarly, the solar unit costs are roughly the same as the more established technologies. Some readers may note that costs for the GAC system are somewhat higher than those obtained using other cost models [11,12]. This is attributed to the relatively small size of the system and the costing assumptions common to all the systems. UV/H_2O_2 cost estimates given in Table 2 are consistent with recently published costs for these systems [13].

Table 2: Comparative costs of different treatment systems for a 100,000 gal/day facility at Livermore, California. Values are in thousands of dollars except where specified.

CAPITAL COSTS	1991 Field Test Design	Solar Buffer Tank & PFR	Solar Batch Tank Farm	Solar Lazy River	GAC	UV/H_2O_2
Photoreactor	732	49	144	106	na	86
Tank Glazing	0	0	42	23	na	na
Tanks (flow buffering)	136	136	0	0	na	na
GAC Unit	na	na	na	na	120	1
Pumps, Piping, Mixers	64	64	54	26	55	42
Catalyst & Recovery	35	35	11	8	na	na
Controls	25	25	7	5	14	11
Pre & Posttreatment	24	24	24	24	0	4
Major Pur. Equip. (MPE)	1,016	333	282	192	190	143
Install. Labor (35% MPE)	356	116	99	67	66	50
Site Preparation	25	25	25	25	20	20
Contractor Fee	150	46	36	27	28	22
Design & Permitting	60	60	60	60	60	60
Subtotal	1,606	580	505	371	364	294
Contingency (20%)	321	116	101	74	73	59
Total Capital Req. (TCR)	1,927	696	606	445	437	353
ANNUAL COSTS						
Annual Cap. (TCR*13.4%)	257	93	81	59	58	47
Labor & Maintenance	74	49	47	44	44	51
Electricity ($0.07/Kwh)	1	1	6	4	1	37
Chemicals (acid/base,H_2O_2)	31	31	31	31	0	13
Catalyst Replacement	25	25	43	32	na	na
Carbon Replacement	na	na	na	na	114	0
Water/VOC Analysis	11	11	11	11	11	11
Total Annual Cost ($K/yr)	399	210	219	181	228	159
Treatment Cost ($/1000gal)	10.90	5.80	6.00	5.00	6.20	4.40

Cost Analysis Method

The costing method is designed to obtain an annual treatment cost in terms of dollars per 1000 gallons treated. Capital costs are converted to an annual cost with a fixed charge rate (FCR) of 13.4% based on an assumed plant life of 20 years. The annual levelized cost and treatment cost were calculated as:

Annual Cost = (Total Capital) x FCR + Operating Costs.

Treatment Cost ($/1000 gal) = (Annual Cost)/(Annual Treatment Capacity).

Three main sources were used to determine capital and operating costs: the cost of equipment for the 1991 field experiment, the Lawrence Livermore Feasibility report [10], and a Bechtel report [9] concerning the cost of a full-scale solar treatment facility. Costs for the photoreactors were based on 1992 vendor price quotes for shallow modular tanks and thin fluoropolymer films.

Pre- and posttreatment equipment costs were obtained by estimating 70 GPM units from the cost of the 30 GPM units used for the field test. Piping, controls, and catalyst recovery equipment costs were based on engineering estimates. Costs from the Livermore study [10] were used to predict installation, contractor fee (10% of MPE, installation, and site preparation), and design costs. For certain items costs were taken to be equal for all the technologies. Examples are design cost, water analysis, and operating labor. Maintenance cost was set at 2% of the total capital (the UV/H_2O_2 system had an additional cost for lamp replacement).

IMPROVEMENTS TO SOLAR WATER DETOXIFICATION SYSTEMS

This current analysis of solar water detoxification projects that costs for the solar technology are similar to those for the currently accepted treatment methods of carbon adsorption and UV-lamp/H_2O_2 oxidation. In addition, the solar systems have an added advantage of on-site pollutant destruction (compared to GAC) and low power consumption (compared to UV/H_2O_2). Yet as a new technology, solar detoxification must demonstrate reliability and clear cost advantages before it will gain acceptance in the remediation market. Research and testing are needed to accurately assess catalyst life and activity. With this in mind, continuing research is needed to obtain field test data and to further improve the efficiency and durability of the process. Several such potential process improvements are outlined here.

Enhancing Catalyst Activity or Life

As is apparent from Table 2, the major cost components of the solar units are the total capital cost and costs for pH adjustment and catalyst replacement. (Annual labor and maintenance are assumed to be a fixed cost plus a percentage of the total capital required.) All of these costs can be lowered by improving the effectiveness of the photocatalyst. A more active catalyst would reduce reactor size and cost, and if a great enough increase in activity is obtained, it may be possible to avoid pH adjustment by compensating for the slower rates (because of bicarbonate inhibition) with a relatively larger reactor. Of course, if the alkalinity is low at a different site, pH adjustment may not be necessary.

Catalyst activity is measured by its quantum efficiency, defined here as the number of contaminant molecules destroyed per incident UV photon. Quantum efficiency is not only a function of catalyst but also depends on contaminant and oxidant concentrations and light intensity. The calculated quantum efficiency for the current slurry catalyst at the 400-ppb TCE concentration level is on the order of 0.2%. Several methods to boost the quantum efficiency of the catalyst are being investigated; some of the most promising include thermal pretreatments and surface doping with metals. Activity increases by factors of 2 to 10 have been witnessed in laboratory tests. Work is ongoing to substantiate these findings and demonstrate the activity enhancement under outdoor conditions.

The active lifetime of the catalyst continues to be a major uncertainty. Limited tests have shown that the life of the catalyst depends on the constituents (organic and inorganic) in the water. In some cases, it is possible to regenerate a poisoned catalyst by a simple treatment such as an acid wash. The assumed life of three months leads to a substantial annual cost for catalyst (Table 2). Clearly there is room for improvement in this area by either increasing the catalyst life or reducing its cost; however, with the limited information currently available, it is difficult to

accurately project catalyst life. To date, laboratory tests have been run for 100 h of illumination or less (i.e., 8-10 days of outdoor use). Long-term field testing is necessary to firmly establish catalyst longevity under field conditions.

Increasing the Usable Portion of the Solar Spectrum
The present catalyst, anatase TiO_2, uses only 2%-4% of the energy in the solar spectrum because photons with wavelengths longer than about 385 nm are not absorbed. Although limited by thermodynamic considerations (the appropriate redox reactions must be energetically feasible), it may be possible to extend the usable portion of the solar spectrum. Possibilities for achieving this include the use of non-anatase catalysts or addition of cocatalysts. Extending the usable spectrum out to 415 nm would more than double the usable flux of solar photons.

Adjusting Process Conditions
Laboratory studies have shown that simple treatments such as increasing oxygen concentration or adding other mild oxidizing agents often enhance observed destruction rates. The field experiment demonstrated that adjustment of solution pH can provide substantial rate increases. Naturally, potential gains in reaction rate must be weighed against the cost of adding reagents. The value of these adjustments is highly dependent on the conditions of the particular site and are difficult to generalize.

These systems have assumed that 24 h/day pumping of the well is required. This stipulation particularly impacts the tank/PFR design because the holding tanks are a significant fraction of the total cost. An important benefit of 24 h/day pumping is that pre- and posttreatment units can be sized to handle the 24 h average flow rate. However, if an application is found where 24h/day pumping is not required and pH adjustment is unnecessary, cost for the tank/PFR concept would drop. For the Livermore site under those conditions the cost would drop by 30%.

Locally Concentrating the Pollutant
It has been established that catalyst quantum efficiency and photocatalytic reaction rate are faster at higher pollutant concentrations. One way to take advantage of this effect is to concentrate the pollutant near the surface of the catalyst. In a process analogous to GAC supported biological treatment, hydrophobic coatings or supports can be used to sorb dissolved organic pollutants and oxygen, thereby increasing the local concentration of these species near the catalyst. This same hydrophobic layer will repel charged species, thus keeping bicarbonate and other potentially inhibitory ions away from the catalyst. Preliminary tests have demonstrated the feasibility of this concept; however, practical configurations are still forthcoming.

Summary of Anticipated Improvements
Figure 5 shows how the solar water detoxification costs are likely to drop over the next few years through a combination of the factors described above. Key to the 1995 solar costs are the assumptions that the need for pH adjustment is eliminated by enhanced system performance through the methods discussed above. Annual replacement costs for the catalyst are also reduced. Costs for the mature technology of carbon adsorption are not expected to drop. Likely process improvements for UV-lamp systems involve more durable and UV-efficient lamps. Typical low-pressure mercury lamp efficiencies range from 20%-30% and any increase in this number would significantly help UV-lamp system cost. To address possible UV/H_2O_2 improvements, the 1995 costs for the UV/H_2O_2 system assumes lamp replacement and electrical usage costs drop in half

due to improvements in lamp efficiency and life. However, one should remember that electricity costs can be expected to rise with time.
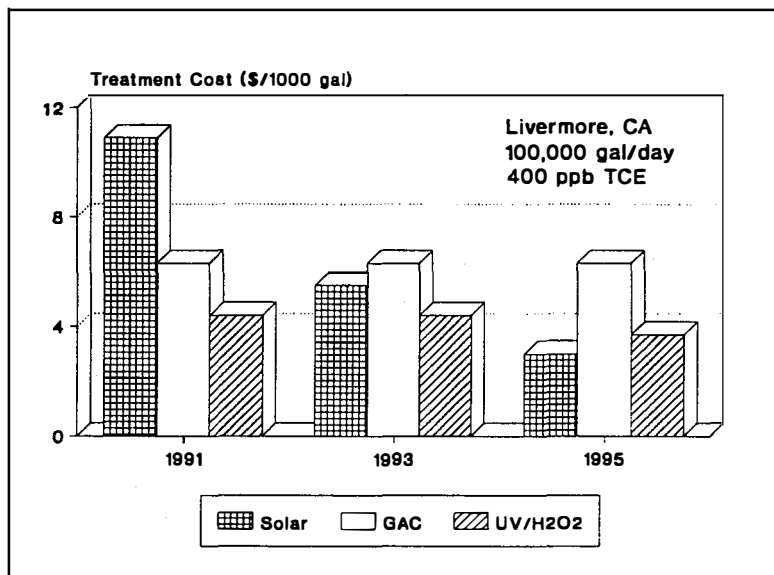

Figure 5:   Current and projected costs of solar detoxification relative to conventional technologies

CONCLUSIONS

It is now well documented that sunlight can be used to photocatalytically destroy organic water contaminants. In addition to its effectiveness, solar water detoxification contains environmental benefits compared to other treatment technologies, notably low power consumption and on-site contaminant destruction. Based on reaction rates obtained in the first field experiments, the present analysis projects that costs for nonconcentrating solar systems are similar to those for conventional carbon adsorption and UV-lamp/hydrogen peroxide systems for the destruction of trichloroethylene in groundwater. Continued field tests will evaluate the performance for other pollutants and the effective lifetime of the photocatalyst. In addition, laboratory research into increased catalyst efficiency are expected to lead to further cost reductions over the next few years.

The National Renewable Energy Laboratory and Sandia National Laboratory are endeavoring to expand and demonstrate the technology through industrial interactions and field testing. In addition to the first field tests on contaminated groundwater, research and testing are underway with industrial wastewater and gas-phase decontamination. More work is yet to be done, but encouraging field results and attractive economics pave the way for planned future demonstrations and eventual commercialization of the solar detoxification technology.

NOMENCLATURE

A/V Ratio of illuminated reactor area to system volume, m^{-1}.
C Contaminant concentration, ppm
I Intensity < 385 nm, photon/m^2-s
I_{ref} Reference intensity value, photon/m^2-s
K_1 Kinetic rate constant, m/min
r Rate of contaminant destruction, ppm/min

REFERENCES

1. Ahmed, S., and D.F. Ollis, "Solar Photoassisted Catalytic Decomposition of the Chlorinated Hydrocarbons Trichloroethylene and Trichloromethane," *Solar Energy*, **32**, 597 (1984).
2. Matthews, R., "Photo-oxidation of Organic Material in Aqueous Suspensions of Titanium Dioxide," *Water Res.*, **20**, 569 (1986).
3. Barbeni, M., M. Morello, E. Pramauro, E. Pelizzetti, M. Vincenti, E. Borgarello, and N. Serpone, "Sunlight Photodegradation of 2,4,5-Trichlorophenoxy-acetic acid and 2,4,5-Trichlorophenol on TiO_2," *Chemosphere*, **16**, 1165 (1987).
4. Hulstrom, R., R. Bird, and C. Riordan, "Spectral Solar irradiance Data Sets for Selected Terrestrial Conditions," *Solar Cells*, **15**, 365 (1985).
5. Mehos, M.S., et al., "Solar Photocatalytic Detoxification of Groundwater: Field Test Results," National Renewable Energy Laboratory, Golden, CO, paper in preparation, 1992.
6. Buxton, G.V., C.L. Greenstock, W.P. Helman, and A.B. Ross, "Critical Review of Rate Constants for Reactions of Hydrated Electrons, Hydrogen Atoms, and Hydroxyl Radicals in Aqueous Solutions," *J. Phys. Chem. Ref. Data*, **17**, No. 2, 513 (1988).
7. Link, H.F., and C.S. Turchi, "Cost and Performance Projections for Solar Water Detoxification Systems." ASME International Solar Energy Conference, Reno, Nevada, March 1991.
8. Ollis, D.F., "Process Economics for Water Purification: A Comparative Assessment," in Photocatalysis and Environment, M. Schiavello, Ed., Kluwer Academic Pub., Dordrecht, 1987.
9. *Conceptual Design of a Photocatalytic Wastewater Treatment Plant*, Bechtel Corp., Sandia National Laboratory Report SAND91-7005, 1991.
10. Isherwood, W.F., C.H. Hall, and M.D. Dresen, *CERCLA Feasibility Study for the LLNL-Livermore Site*, Lawrence Livermore National Laboratory Report UCRL-AR-104040, December 1990.
11. Adams, J.Q., and R.M. Clark, "Development of Cost Equations for GAC Treatment Systems," *J. Environ. Eng.*, **114** (1988).
12. *Organics Removal by Granular Activated Carbon*, American Water Works Association, Denver, CO, 1989.
13. Cheuvront, D.A., C.L. Giggy, C.G. Loven, and G.H. Swett, "Groundwater Treatment with Zero Air Emissions," *Environ. Prog.*, **9**, No. 3, 143 (1990).