

Cost Comparison of Solar Detoxification with Conventional Alternatives for the Destruction of Trichloroethylene

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COST COMPARISON OF SOLAR DETOXIFICATION WITH CONVENTIONAL ALTERNATIVES FOR THE DESTRUCTION OF TRICHLOROETHYLENE

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ABSTRACT

The purpose of this analysis is to compare the cost of solar waste detoxification processes with conventional alternatives for the treatment of trichloroethylene (TCE) in air. The solar processes that were evaluated are high flux photothermal oxidation (PHOTOX), high flux thermal catalytic reforming (SOLTOX), and low flux photocatalytic oxidation (PHOCAT). The high flux processes, PHOTOX and SOLTOX, were based on dish concentrator technology. The low flux photocatalytic process was based on parabolic trough concentrating technology. The conventional alternatives are thermal oxidation, thermal catalytic oxidation, off-site carbon regeneration, and on-site solvent recovery. Analysis of the seven processes showed PHOCAT to be the most economical treatment method. PHOTOX showed slightly better economics relative to SOLTOX. Both were competitive, with the best conventional destruction process, thermal oxidation. Off-site carbon regeneration was the most expensive treatment method.

INTRODUCTION

The occurrence of waste in the environment has increased sharply in recent years. In 1989, a total of 27,000 sites had been identified under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Environment Quality, 1989). Industry continues to release hazardous chemicals to the environment. In 1988, 2.4 billion lb of toxic chemicals were released to the air, and 310 million lb were released as water discharges (Citizens Fund, 1990).

Recent work has demonstrated that concentrated solar energy can destroy many hazardous chemicals that are of national concern, including dioxins, polychlorinated biphenyls (PCBs), and trichloroethylene (TCE). Field tests have shown that dioxins can be destroyed with an efficiency of 99.9999% (Glatzmaier et al., 1990). TCE has been destroyed with an efficiency of 99.99%. This work has shown that high destruction efficiencies can be obtained at temperatures (700 °C) significantly lower than that of thermal incineration (1,200 °C) due to photochemical reactions that result from the use of sunlight.

In certain cases, destruction can be achieved at ambient temperature (25 °C) due to photocatalytic reaction mechanisms.

In evaluating the potential of solar-based processes for waste treatment, the cost and the performance must be considered. The purpose of this analysis is to compare the cost of three solar waste detoxification processes to four conventional alternatives in the treatment of TCE in air. The intent is to determine which solar processes are competitive with conventional alternatives and to identify those conditions under which they can compete.

Solar-based processes provide a number of advantages that contribute to lower costs. Photo-enhanced destruction enables the reaction to operate at lower temperatures, which creates lower volumetric flow rates and smaller hardware size in both the reactor and scrubber. Solar thermal energy also displaces added fuel, which also decreases volumetric flow rates. Because TCE does not absorb sunlight, it is expected that a solar-based process that treats wastes that do absorb sunlight (PCBs, dioxin, TNT) will have even more favorable economics when compared to the conventional technologies.

BACKGROUND

A number of classes of chemicals have been considered as applications for solar detoxification processes. The classes include semivolatile organic contaminants, such as dioxins, PCBs, and trinitrotoluene (TNT), and volatile organic contaminants (VOCs), the most common being TCE.

Semivolatiles occur in contaminated soils and must be thermally desorbed from the soil at temperatures of 300 to 600 °C before they can be destroyed. VOCs also occur in contaminated soils and can be removed with a low-temperature soil vapor extraction process (Oster and Wenck, 1988). This process is less expensive than thermal desorption because it does not require soil excavation (in situ) and does not involve heating the soil. Use of solar energy for waste treatment would only involve the destruction step.

The occurrence of chlorinated VOCs in the environment is widespread, especially in the southwestern United States, an area of high solar insolation. A search of the National Priority List shows that 63% of the superfund sites in California, Arizona, and Nevada contain

chlorinated VOCs. The Environmental Protection Agency's (EPA) Toxic Chemical Release Inventory shows that 13 million lb of chlorinated VOCs are released annually to the atmosphere in the states of California, Arizona, Nevada, and Utah.

Because of its widespread occurrence, TCE (a VOC) in air was chosen as the waste for this analysis. A total of nine streams were analyzed for each process. Flow rates of 1,000, 2,000, and 5,000 standard cubic feet per minute (scfm) were considered. For each flow rate, TCE concentrations of 100, 500, and 1,000 parts per million by volume (ppmv) were analyzed for a total of nine streams for each process. These streams are assumed to be produced continuously and must be treated on a 24 hr/day basis. These flow rates and concentrations are typical for soil vapor extraction processes and industrial releases.

Because TCE does not absorb sunlight, this analysis assumed no photoeffect for TCE destruction using PHOTOX (defined below). TCE can be destroyed by photochemical mechanisms if other components in the gas stream absorb sunlight. These components may be other wastes or by-products of the destruction reaction. In these cases (or for cases where the contamination does absorb sunlight), the economics for the photothermal process (PHOTOX), defined below, will be more favorable.

PROCESS DESCRIPTIONS

Previous work (Glatzmaier, 1991) compared TCE destruction using a generic solar process with thermal catalytic oxidation. That work was limited because only one waste stream was considered, other conventional treatment options were not considered, and the solar process was not specified in terms of reaction conditions (residence time, solar flux, temperature, feed gas, catalytic or noncatalytic). The current work (Figure 1) includes all these features. A total of nine TCE gas streams of varying flow rates and concentrations were analyzed, and four conventional processes and three solar processes were analyzed for each waste stream. The three solar processes were characterized in terms of the reaction conditions that are required for TCE destruction, i.e., temperature, flux, and residence time.

The solar processes are photothermal oxidation (PHOTOX), thermal catalytic steam reforming (SOLTOX), and photocatalytic oxidation (PHOCAT) (Figure 2). PHOTOX and SOLTOX are high flux processes requiring point focus concentrators. For this analysis, it was assumed that both processes are based on a 25-kW parabolic dish. Cases that required high TCE processing rates utilize multiple dish/reactors. PHOCAT operates at low flux levels and, therefore, was based on a parabolic trough concentrator.

All the solar processes require activated carbon storage to handle a waste stream that is produced continuously. Each carbon storage vessel contains a 3-day capacity of carbon. The waste was assumed to be processed over an average period of 4-hr/day. Therefore, the flow rate of TCE exiting the carbon vessel is an average of six (24/4) times the rate it enters the carbon storage vessel. For the SOLTOX process, the concentration of TCE in steam coming off the carbon and going to the solar reactor was 5% by volume (50,000 ppmv). This concentration is the highest that has been tested in the laboratory. The concentration of TCE in air coming off the carbon and going to the solar reactor was 1.5% by volume (15,000 ppmv) in the PHOTOX process and 0.1% by volume (1,000 ppmv) in the PHOCAT process. Again, these are the highest concentrations that have been tested in laboratory and field experiments.

Reaction rates for each solar process were based on laboratory rate data. Rate data were available for TCE destruction for the PHOTOX and PHOCAT processes. Rate data for the SOLTOX process were available only for trichloroethane (TCA). For that case, it was assumed that rate

data for TCE would be comparable to those of TCA. Reaction rate data, as a function of solar flux and temperature, for the three solar processes were used to determine residence times for the TCE in the reactors. Residence time and volumetric flow rate are the two critical factors in determining reactor size and cost. Once the reactor size is determined, solar flux is the critical factor in determining solar concentrator area and cost.

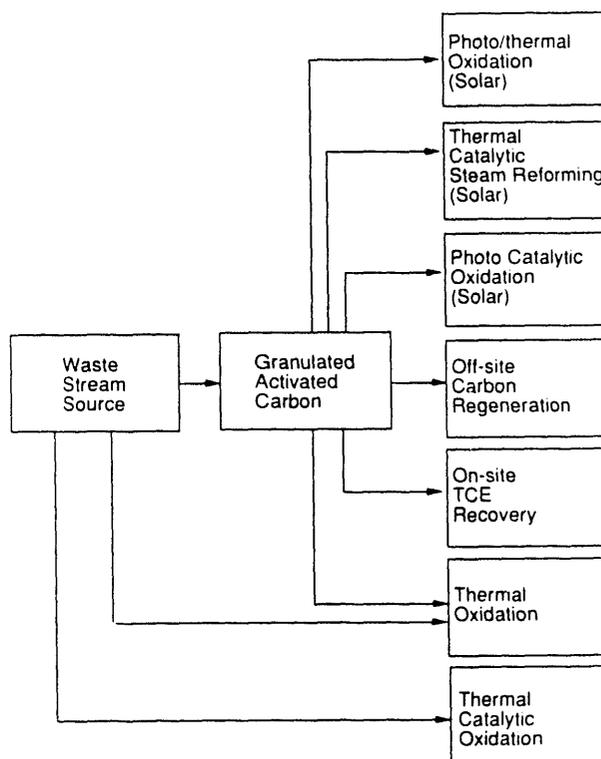


Figure 1. Treatment Options of TCE in Air.

All the solar processes require a scrubber to remove hydrogen chloride (HCl) from the reactor exit stream. For the SOLTOX and PHOCAT processes, it was assumed that all chlorine in the feed stream forms HCl rather than chlorine gas. For the PHOTOX process, methane was added to the TCE gas stream to ensure that the chlorine forms HCl rather than chlorine gas. Chlorine gas is extremely corrosive and cannot be scrubbed easily from the exit gas stream.

The conventional processes are thermal oxidation, thermal catalytic oxidation, off-site carbon regeneration, and on-site TCE recovery (Figures 3 and 4). The first three processes destroy TCE, but the last process recovers TCE.

Thermal oxidation operates at 1200 °C while thermal catalytic oxidation operates at 800 °C. Both processes run 24 hr/day and require a 2-sec residence time. The processes utilize a heat exchanger that recovers thermal energy from the reactor exit stream and uses it to heat the inlet stream. This feature reduces the requirement for methane. Enough methane is added to the inlet stream to ensure that there is sufficient hydrogen to allow HCl to form in the outlet stream, instead of chlorine gas. A scrubber is used to remove HCl.

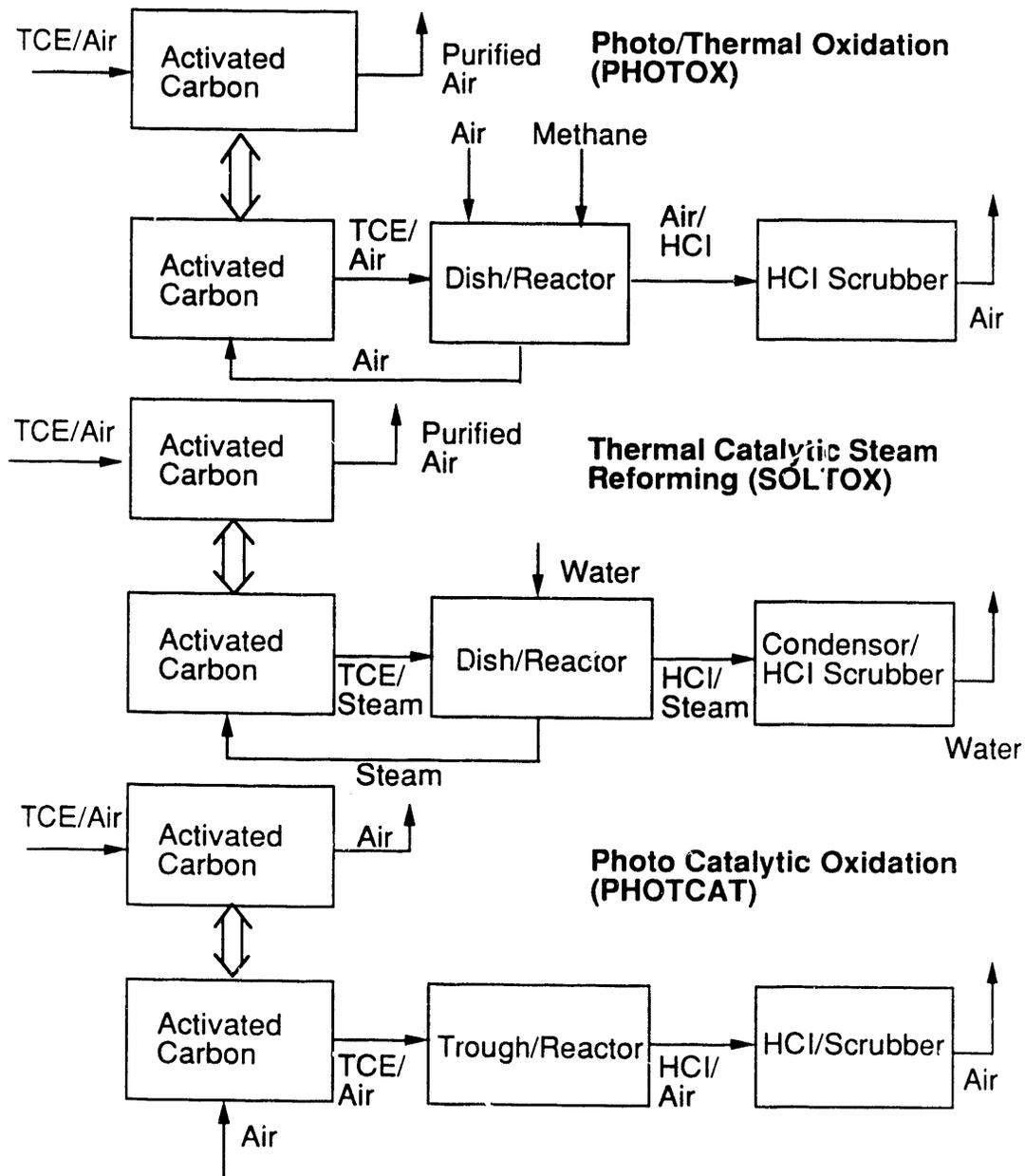


Figure 2. Solar Processes: PHOTOX, SOLTOX, and PHOCAT.

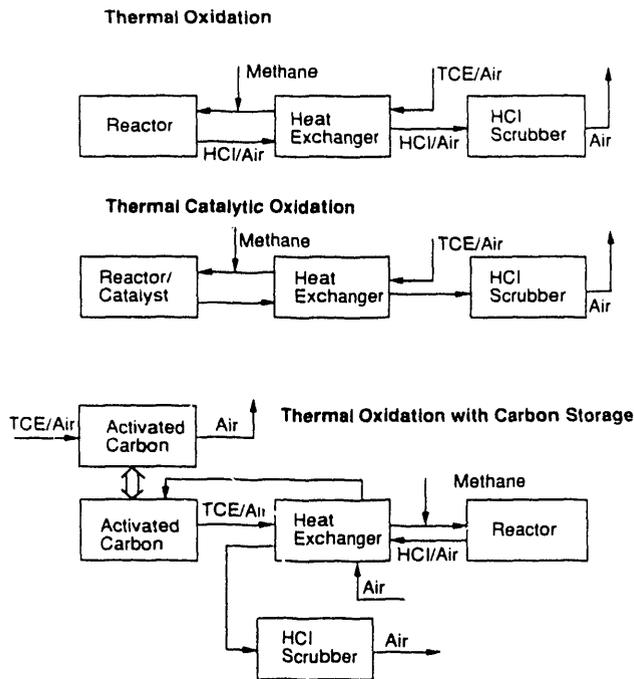


Figure 3. Thermal and Thermal Catalytic Oxidation.

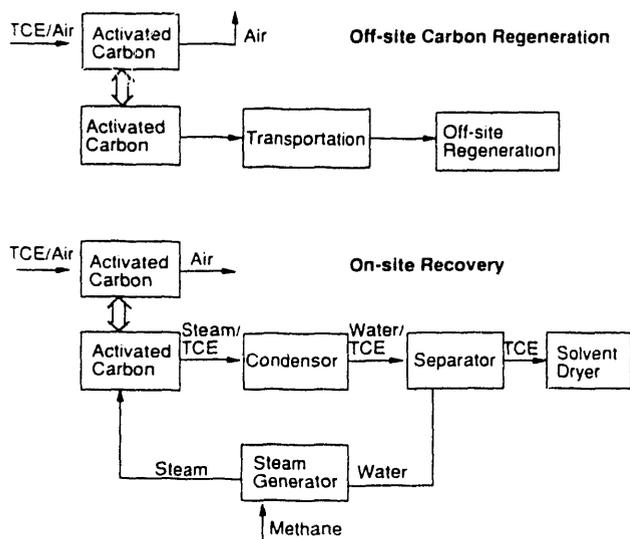


Figure 4. Off-site Carbon Regeneration and On-site TCE Recovery.

Hardware for off-site carbon regeneration includes two carbon containing vessels, each with a 45-day carbon capacity to adsorb TCE. The two vessels alternate in that one purifies the waste stream while the other's carbon is being regenerated off site. On-site recovery hardware consists of two carbon vessels, each with a 3-day capacity. The carbon is regenerated with steam from a steam generator. After exiting the carbon vessel, the steam and the TCE are condensed. TCE is separated from the aqueous phase and then dried. Depending on the exact composition of the waste stream, the recovered TCE may have value in that it can be reused on site, or it may need to be disposed of, requiring additional expense.

In performing the analysis, it was determined that the solar processes obtained an unfair advantage in using carbon storage. Carbon storage is used to allow for the intermittent availability of sunlight. However, it can also be used to concentrate the TCE waste stream such that the volumetric flow rate of gas coming off the carbon is much less than that of the original waste stream. This is especially true in cases with low TCE concentrations, allowing the solar hardware to be downsized relative to the conventional hardware for thermal oxidation and thermal catalytic oxidation.

To provide a fairer comparison, an additional case was run using thermal oxidation that included the use of carbon storage to concentrate the TCE (Figure 3). Carbon storage was not considered for thermal catalytic oxidation because the catalyst in this process can be poisoned by chlorinated organics at concentrations above 1,000 ppmv. It was assumed that the concentration of TCE coming off the carbon for thermal oxidation was 1.5% by volume (15,000 ppmv), the same concentration as that of photothermal oxidation. The thermal oxidation reactor, however, still operates 24 hr/day such that the TCE flow rates entering and exiting the carbon vessels are the same. Because the effect of the carbon is to concentrate the TCE, the volumetric flow rate of gas exiting the carbon vessels is much less than that of the stream entering the carbon vessels. This allows the thermal oxidation hardware to be downsized in the same manner as the solar hardware.

METHODOLOGY

A method was developed for sizing and costing process hardware. Hardware for the solar processes includes activated carbon and carbon storage vessels, parabolic dishes or troughs, reactors, and scrubbers. Hardware for thermal oxidation and thermal catalytic oxidation includes the reactor, heat exchanger, and scrubber. Hardware for off-site carbon regeneration includes activated carbon and carbon storage vessels. Hardware for on-site TCE recovery includes activated carbon and carbon storage vessels, steam generator, condenser, separator, and dryer.

Activated Carbon and Storage Vessels

The quantity of activated carbon required for a given process and TCE-stream was determined using TCE adsorption isotherms (Calgon, 1969). The isotherms give the TCE carbon loading (in weight-percent) as a function of TCE gas-phase concentration. This information, along with TCE flow rate, provides an estimate of the quantity of carbon required to adsorb TCE from the waste stream for a given period of time (three days for the solar processes). The cost of the activated carbon was \$2.25/lb. as quoted by Calgon.

The carbon storage vessels were sized to hold the appropriate volume of activated carbon. The purchase cost, assuming a vertical, carbon steel process vessel, was determined from cost tables in Ulrich (1984). The purchase cost was in 1991 dollars. The purchase cost of vertical process vessels varies with volume to the 0.52 power.

Solar Trough/Reactor

The solar PHOCAT process operates at ambient temperature (25 °C) and relatively low flux levels compared to PHOTOX and SOLTOX. This process was based on a parabolic trough having an aperture length of 2.1 m and a tube diameter of 0.051 m. These dimensions result in a concentration ratio of 26. Flux to the reactor was determined as a product of the following factors: direct normal UV flux (22 W/m²), concentration ratio (26), intercept factor (0.98), reflectivity (0.90), transmission through the tube wall (0.96), and average cosine factor (0.83). A direct-normal UV flux of 22 W/m² in the bandwidth from 285 to 385 nm corresponds to an air mass of 1.5.

The tube volume was determined as the product of the gas volumetric flow rate and residence time. The gas volumetric flow rate is based on a flow rate of TCE desorbing off the carbon at a factor of 4 (24/6) greater than the TCE waste stream flow rate and a TCE reactor concentration of 1000 ppmv. Residence time was determined from a kinetic rate expression derived from laboratory experiments. Tube length and trough area were determined from tube volume. Tube purchase cost was \$21/m and catalyst purchase cost was \$13/m. Trough purchase cost (uninstalled) was \$25/m².

Solar Dish/Reactor

The PHOTOX and SOLTOX processes use a 25-kWth (40-m²) parabolic dish for concentrating sunlight to the reactor. It was assumed that the dish can deliver 25-kW for an average of 4 hr/day. The uninstalled dish cost was \$10,000 (\$250/m²). The reactor is cylindrical and has a constant length-to-diameter ratio of 2. Because the dish power is constant at 25 kW, reactor diameter and volume were determined from the solar flux requirement to the reactor. Volumetric flow rate and residence time are highly dependent on temperature, such that all three variables were determined simultaneously by performing an energy balance on the reactor. The energy balance terms were solar power to the reactor, radiative power loss out the window, heating rate required to bring the inlet stream to the desired temperature, and rate of energy release from the reaction. The reaction may be either exothermic or endothermic. The PHOTOX (oxidation) reaction is moderately exothermic (4,100 Btu/lb), but the SOLTOX (reforming) reaction is slightly exothermic (170 Btu/lb) for TCE.

Once temperature, residence time, and volumetric flow rate were determined, the TCE processing rate could be determined for one dish/reactor combination. TCE concentration was 1% by volume for the PHOTOX process and 5% by volume for the SOLTOX process. The total number of dish/reactor combinations were then determined based on the total required TCE processing rate.

Thermal Oxidation Reactor

The thermal oxidation reactor was sized to give a 2-sec residence time for the given waste stream volumetric flow rate at reactor temperature. The reactors were assumed to be stainless steel with 8 in. of refractory lining. Purchase costs were determined by COADE (1983). The purchase cost of incinerators varies with volume to the 0.52 power.

Thermal Catalytic Reactor

Cost data for the thermal catalytic reactor were obtained from previous work (Glatzmaier, 1991). Cost data were available for TCE concentrations of 100 and 1,000 ppmv and flow rates of 1,500 and 3,000 scfm. The reactor cost was constant with TCE concentration in this range and varied with volume to the 0.50 power. This information was used to determine reactor costs, including catalyst, at 1,000, 2,000, and 5,000 scfm.

Heat Exchanger

Heat exchangers were used in the thermal oxidation and thermal catalytic oxidation processes to recover thermal energy from the reactor exit stream. The heat exchanger size was based on the heat transfer area

required to obtain the desired heat transfer rate. Heat transfer area was determined using an overall heat transfer coefficient and log mean temperature difference. Heat exchanger costs were determined from cost tables (Uchida and Katsumi, 1984) and vary with volume to the 0.66 power.

Scrubber

A scrubber to remove HCl from the reactor exit stream was required in all three solar processes and the thermal oxidation and thermal catalytic oxidation processes. The scrubber consists of a tower that sprays an aqueous solution of Ca(OH)₂ that contacts the gas stream (Uchida and Katsumi, 1984). HCl in the gas stream is adsorbed into the aqueous solution and neutralized to CaCl₂. The scrubber size is based on a gas-liquid contact time of 10 sec. Therefore, scrubber size and cost are only dependent on the reactor exit stream volumetric flow rate and not on HCl concentrations. Scrubber cost varies with scrubber volume to the 0.62 power.

Steam Generator, Condensor, Separator, Dryer

On-site TCE recovery required a steam generator, condensor, separator, and dryer. The steam generator capacity was based on a requirement of 5-lb steam to regenerate 1 lb of carbon (Ulrich, 1984) and a regeneration period of 24 hr.

Because of the relatively small volume of liquid TCE that is recovered in all cases, the condensor, separator, and dryer were all specified as the minimum size that is commercially available. The costs for these items (COADE, 1983) were the same for all waste streams.

Total Fixed Capital, Operating Costs, Levelized Costs

Total fixed capital consists of purchased capital multiplied by an appropriate factor to include installation, site preparation, contingency, and fee. Purchased capital, with the exception of activated carbon, was multiplied by a factor of 4 to obtain total fixed capital. Annual operating costs consist of 15% of the total fixed capital raw materials: calcium hydroxide for the HCl scrubber; utilities: methane; and labor: 10% of total fixed capital. The levelized cost is the annual operating cost divided by the pounds of TCE processed in a year.

RESULTS

Conventional

A comparison of conventional treatment technologies (Figure 5) shows that thermal oxidation with carbon storage is the most economical. On-site TCE recovery may be preferred if the TCE can be recovered in a pure state and reused on site. Off-site regeneration is the most expensive conventional technology.

A comparison of thermal oxidation with and without carbon storage (Figure 6) shows that the use of carbon to concentrate the TCE is economical at TCE concentrations between 100 and 1,000 ppmv. Concentrating the TCE with carbon has the greatest economic impact with waste streams with low TCE concentrations.

Solar

A comparison of the solar processes with thermal oxidation with carbon storage (the least expensive conventional process) is shown in Figure 7. Two costs are shown for each solar process. The current costs are based on \$1,000/m² installed dish cost for PHOCAT and SOLTOX and \$100/m² installed trough cost for PHOCAT. The projected costs are based on \$200/m² installed dish cost for PHOTOX and SOLTOX and \$50/m² installed trough cost for PHOCAT.

Photocatalytic oxidation (PHOCAT) is the most economical destruction process using current costs. PHOTOX has better economics than SOLTOX. However, both are competitive with the best conventional

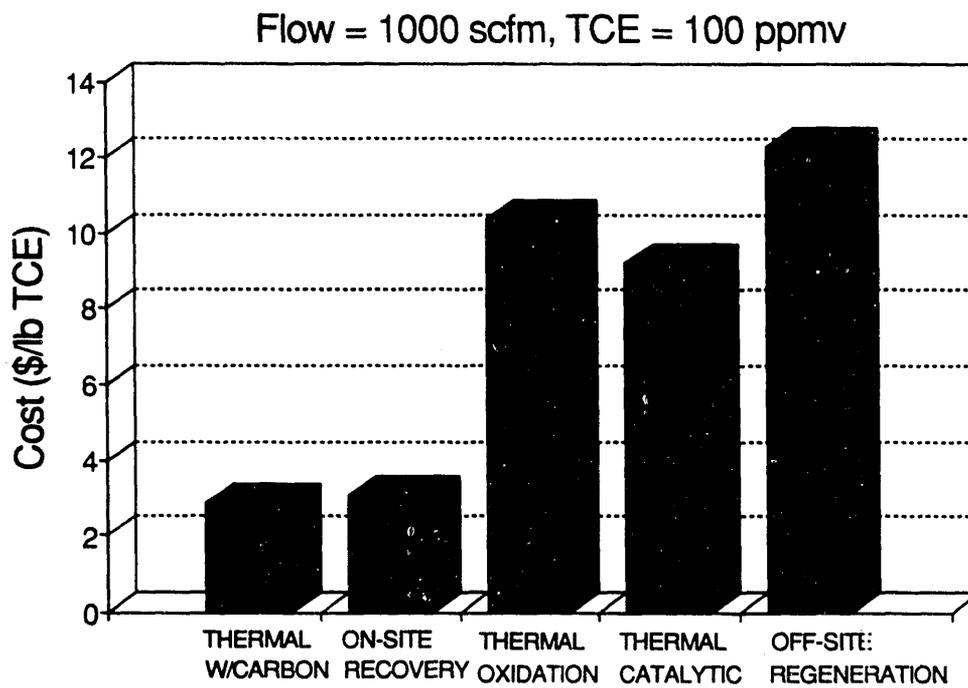


Figure 5. Cost of Conventional Processes.

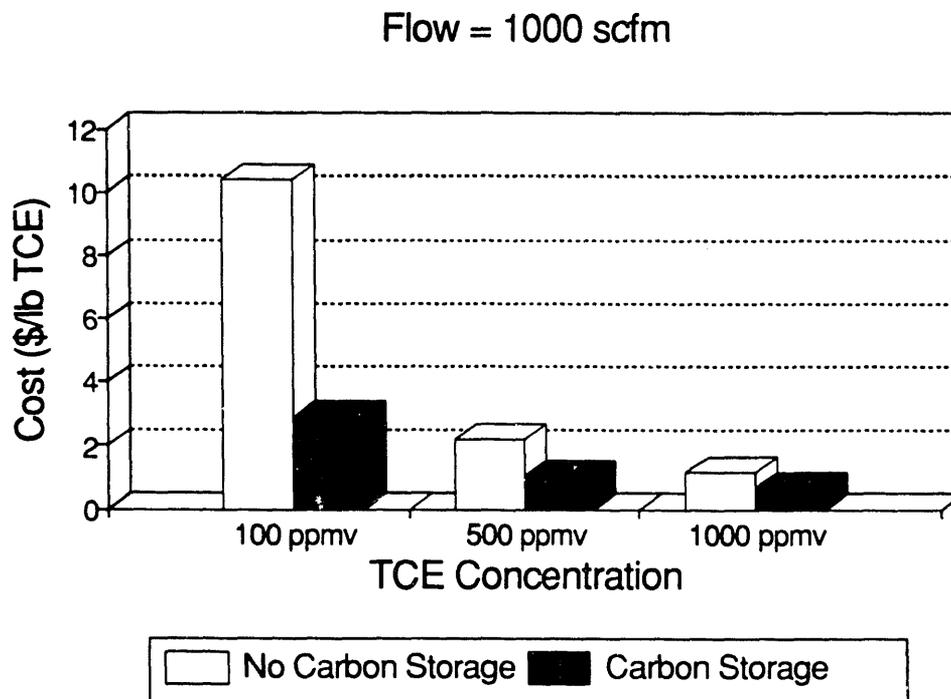


Figure 6. Cost of Thermal Oxidation With and Without Carbon Storage.

Flow = 1000 scfm, TCE = 100 ppmv

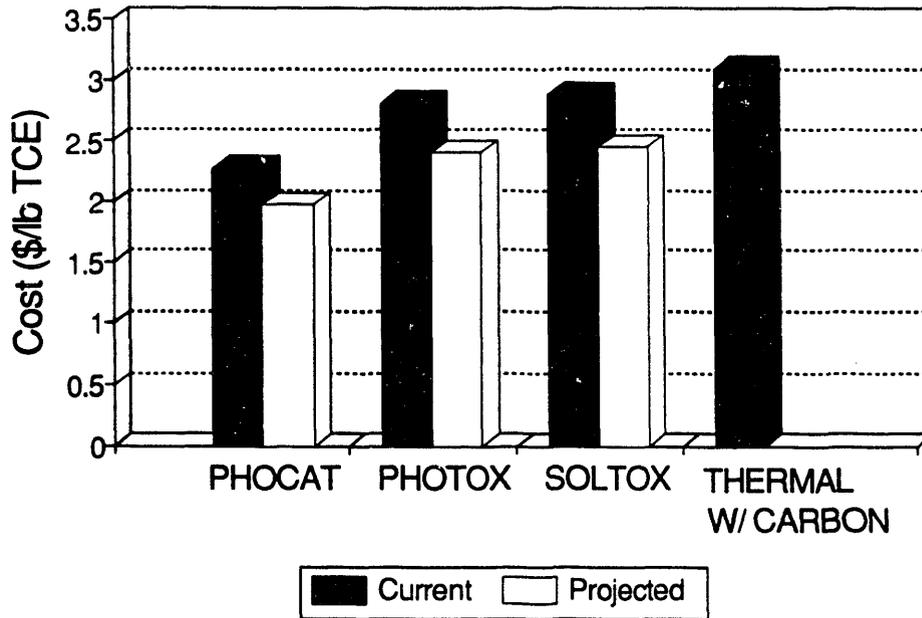


Figure 7. Cost of Solar Processes as Compared to That of Thermal Oxidation With Carbon Storage.

destruction process, thermal oxidation with carbon storage. When the projected costs for the solar processes are used, all three processes show significantly better economics than thermal oxidation. In addition, as discussed earlier, TCE does not exhibit a strong photoeffect. For cases where the photoeffect is greater, the economics for PHOTOX will improve correspondingly.

PHOCAT shows the best economics of the solar processes because of high reaction rates at low temperatures. The applicability of this process to wastes other than TCE, however, is not known. PHOTOX shows better economics than SOLTOX because more thermal energy is required to generate steam for SOLTOX as opposed to air for PHOTOX. This results in higher solar hardware costs for SOLTOX as compared to air for PHOTOX. This results in higher solar hardware costs for SOLTOX as compared to PHOTOX.

CONCLUSIONS

1. Thermal oxidation with carbon storage shows the best economics of all the conventional destruction processes.
2. Photocatalytic oxidation (PHOCAT) shows the best economics of all the destruction processes but its applicability to wastes other than TCE has not yet been demonstrated.
3. PHOTOX is more economical than SOLTOX and conventional thermal oxidation. TCE does not absorb in the solar spectrum and, therefore, does not exhibit a strong photo-enhanced reaction rate. For wastes such as dioxins, PCBs, and nitrated organics, a strong photoeffect will result in even more favorable economics of PHOTOX relative to SOLTOX and thermal oxidation.
4. When projected costs are used for the solar hardware, all three solar processes have significantly better economics than thermal oxidation.

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