HYBRID BIOREACTORS – COST SAVING PROCESSES FOR DECONTAMINATION OF WATER AND AIR

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Biographical Sketch of Authors
Both authors are employed by the Tennessee Valley Authority (TVA) at the Environmental Research Center in Muscle Shoals, Alabama. Mr. Boles is a chemical engineer with 26 years at TVA in process/product development and the past 7 years in biofilter/bioreactor development. Mr. Gamble is an environmental technician with 25 years experience at TVA in laboratory analysis and process/product development with the last 10 years specializing in biofilter/bioreactor development. The authors can be reached at Tennessee Valley Authority, P.O. Box 1010, Muscle Shoals, Alabama 35662-1010. Mr. Boles can be reached at jlboles@tva.com
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Abstract
The Tennessee Valley Authority (TVA) has developed and patented Hybrid Bioreactors that simultaneously destroy water and air contaminants with dramatic savings over existing treatment methods. Contaminants destroyed include a wide variety of chlorinated solvents and VOCs such as TCE, DCE, methylene chloride, BTEX, and fuel components. The new bioreactors can be used in a variety of applications ranging from site restoration to industrial compliance. Cost comparisons show that Hybrid Bioreactors achieve dramatic savings over water treatment methods used at Superfund sites. For chlorinated solvent removal, water decontamination costs using Hybrid Bioreactors are generally less than one-tenth of costs reported by EPA and DOE at Superfund sites. Furthermore, Hybrid Bioreactor decontamination costs for fuel components, BTEX, and other VOCs are generally only one-tenth those for chlorinated solvents. Air stripping simply transfers water contaminants to the atmosphere, and carbon adsorption only transfers the contaminants to another medium; removal and disposal of the contaminants are still necessary. Thermal oxidation generates secondary waste streams such as NO_x, CO, and toxic by products for release to the atmosphere. However, TVA's Hybrid Bioreactors destroy both water and air contaminants in a single step and generate no contaminated off gases or other secondary waste streams. TVA is currently demonstrating a 300-cubic-foot mobile Hybrid Bioreactor in Muscle Shoals, Alabama, to develop design information for commercial deployment. Further information is available at:
http://www.tva.com/environment/envservices/alw_biofilter.htm and at
http://www.tva.com/environment/envservices/alw_pubs.htm#biofilter.

HYBRID BIOREACTORS – COST SAVING PROCESSES FOR DECONTAMINATION OF WATER AND AIR

Background

Industrial operations today release large quantities of toxic materials and greenhouse gases to the environment, and improper use and handling of hazardous materials in the past have resulted in widespread contamination of soils and groundwater with pollutants such as trichloroethylene (TCE), benzene-toluene-ethyl benzene-xylenes (BTEX), methyl tertiary butyl ether (MTBE), volatile organic compounds (VOCs), and other pollutants, posing serious health risks to the public. Traditional clean-up methods such as scrubbing, stripping, and adsorption merely transfer pollutants to other media—removal or separation of the pollutants from these media and subsequent disposal of the pollutants is still necessary. Incineration can generate other toxic by-products, releasing them to the atmosphere. Such technologies generate greenhouse gases and are costly for decontaminating the low-concentration streams that are commonly encountered in environmental site remediation and industrial waste stream treatment, especially with increasing energy costs. Innovative, economical, and environmentally friendly technologies are needed to mitigate environmental contamination and detoxify industrial waste streams to reduce public health risks.

Aerobic biofilters (gas treatment) and bioreactors (liquid treatment) can convert toxic pollutants to non-toxic products and are generally more economical than traditional clean up methods at low contaminant concentrations. Dilute applications are well suited to bioreactors and biofilters, which utilize microorganisms attached to natural or synthetic packing to actually biodegrade the target pollutants rather than simply transfer them from one medium to another. In bioreactors and biofilters, contaminated streams are passed through packing containing microorganisms which degrade or mineralize the pollutants into harmless compounds such as carbon dioxide and water. In many cases, bioreactors and biofilters provide cost-saving, environmentally friendly alternatives to traditional pollution control or remediation technologies.

Direct-Metabolic and Cometabolic Processes

In many biodegradation processes of economic importance in waste treatment and clean-up operations, the microorganisms directly consume and derive food value from the target contaminants, and the waste stream can be passed continuously through the process to achieve continuous biodegradation of the target contaminants. In other words, the microorganisms directly metabolize the contaminants as sources of food and growth. Such biodegradation processes will hereinafter be referred to as direct-metabolic (D-M) processes. Contaminants easily destroyed by D-M processes include a wide variety of VOCs such as methyl ethyl ketone, toluene, xylene, benzene, styrene, and methylene chloride as well as other compounds such as carbon disulfide, hydrogen sulfide, ammonia, and odor-causing compounds.

However, certain contaminants, particularly chlorinated solvents like TCE, are not metabolized directly as food by most aerobic microorganisms and thus cannot sustain the microorganisms. In such cases, certain alternate carbon (food) sources, or primary substrates, can be supplied that the microorganisms directly metabolize, and in so doing, the microorganisms generate enzymes capable of degrading certain target contaminants that cannot be directly metabolized. In other words, the contaminants targeted for destruction are indirectly degraded by enzymes generated when the microorganisms directly metabolize another compound—a process known as cometabolism. Hereinafter, such biodegradation processes shall be referred to as cometabolic (C-M) processes. The alternate or primary food sources that the microorganisms directly metabolize can themselves be contaminants or undesirable compounds such as toluene, or they can be relatively innocuous compounds such as methane or propane.

Related Work

TVA has developed and demonstrated several biofiltration processes (gas treatment) which economically destroy a wide variety of air contaminants released from a broad cross section of industries and clean up operations. In a project funded by the U.S. Army Environmental Center (USAEC), a field demonstration was conducted of a biofiltration process (Figure 1) that efficiently and economically destroys TCE, dichloroethylene (DCE), methylene chloride (MeCl), and other contaminants in air streams generated by air stripping of contaminated groundwater or industrial operations such as degreasing. The demonstration was conducted at Anniston Army Depot (ANAD), Anniston, Alabama during 1996-1999 at a groundwater air stripping site. This biofiltration process (Figure 1) requires use of a primary substrate to induce degradation of TCE, as the microorganisms do not directly consume TCE. To achieve economical TCE degradation, the primary substrate—propane in this process—is intermittently removed from the system and alternated with periods of the waste stream feed—TCE contaminated air. This biofiltration process utilizes novel, patented processing schemes that dramatically improve process efficiency and economics. Although this biofiltration process is cost-effective for remediating contaminated air, considerable interest has been expressed in liquid-treatment bioreactor processes that would avoid air stripping altogether and decontaminate the water directly in a single step to save costs and simplify operation.

Hybrid Bioreactors

In response to stakeholder interest, TVA conducted bench-scale tests that culminated in development and patenting of new liquid-treatment bioreactor processes that economically destroy contaminants directly in groundwater or wastewater. This bioreactor design eliminates an air stripping first step and thus saves capital and operating and maintenance (O&M) costs. More importantly, these new processes destroy the water contaminants *and* preclude their release as vapor-phase contaminants, whereas air stripping merely transfers water contaminants to the atmosphere. These new patented processes were termed "Hybrid Bioreactors" because they combine certain elements of traditional gas-phase biotrickling filter processes and traditional liquid-phase bioreactor processes. In Hybrid Bioreactors (Figure 2), *contaminated water* is trickled or sprayed over and down through the packing similarly to the way in which *nutrient solution* is trickled or sprayed over the packing in a traditional gas-phase biotrickling filter. Flow of the contaminated water can be single-pass or recycled, continuous or batch. Unlike conventional aerobic bioreactors of this type, the patented process schemes employed in the new Hybrid Bioreactors preclude release of vapor-phase contaminants.
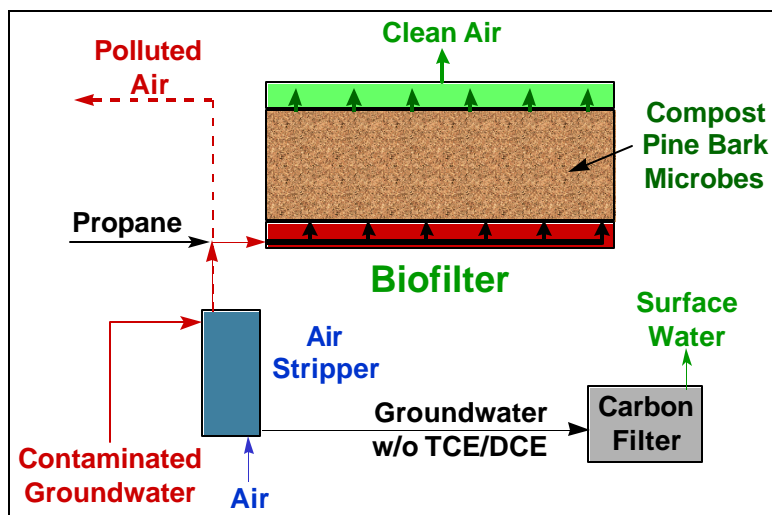

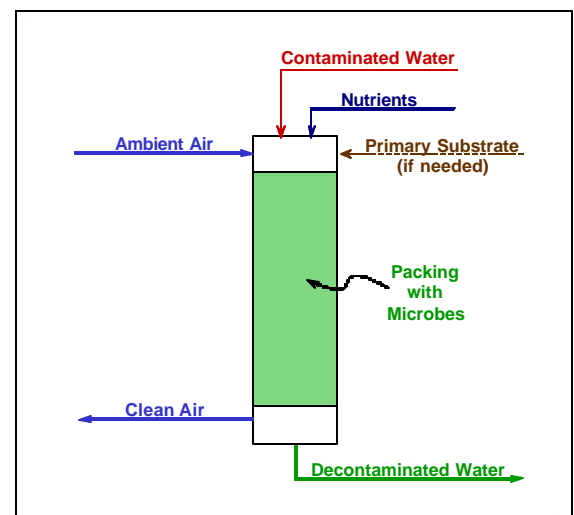**FIGURE 1**. **TCE Biofilter process demonstrated at ANAD**   **Figure 2. Hybrid Bioreactor process**

Testing of the new Hybrid Bioreactor process scheme was carried out in continuous-operation process equipment (4" dia. x 10' H) to directly detoxify TCE-contaminated water (0.5 to 20 mg/L TCE). After 4 months of operation and manipulation of critical process parameters, the single-stage Hybrid Bioreactor surpassed the performance of the two-stage, air stripper-biofilter process demonstrated at ANAD. At that stage of development, a Hybrid Bioreactor half the size of the ANAD gas-phase biofilter alone could accomplish that which required both the air stripper and the gas-phase biofilter in the ANAD demonstration. The Hybrid Bioreactor's smaller size and elimination of air stripping translate into substantial savings in capital and O&M costs. The higher performance of the Hybrid Bioreactor is a result of degrading TCE directly in the contaminated water and employment of patented processing schemes that preclude release of vapor phase contaminants. These early favorable results with the C-M (cometabolic) Hybrid Bioreactor led to a larger test program to expand development to address a variety of environmental applications and contaminants other than groundwater remediation and chlorinated solvents.

A similar D-M (direct metabolic) Hybrid Bioreactor was constructed and tested for detoxification of water contaminated with compounds that can be directly metabolized by aerobic microorganisms, benzene and toluene (4 mg/L of each). In less than 5 months of testing, the contaminated water rate had been increased 13-fold without sacrifice in performance (virtually 100% removal of benzene and toluene). A 13-fold increase in water rate without reduction in performance translates into a 13-fold reduction in the size (and costs) required for the bioreactor at a given water rate. So far, the size and consequent costs required for a commercial D-M Hybrid Bioreactor have been reduced to within the same range as that required for air stripping alone, which only transfers water contaminants to vapor phase for release to the atmosphere; carbon adsorption, incineration, or some other removal method must then be used to mitigate the contaminated air. Hybrid Bioreactors both remove and destroy the water contaminants in a single step with substantial savings and without impacting the environment. D-M Hybrid Bioreactor size and costs are generally only about one-tenth of those for C-M Hybrid Bioreactors because the contaminants are directly consumed (direct metabolism) by the microbes and do not require a primary substrate to induce cometabolic enzymatic degradation, as is the case with contaminants like TCE. Demonstration of a 300-cubic-foot mobile Hybrid Bioreactor is currently underway at TVA's Constructed Wetlands Complex in Muscle Shoals, Alabama to further optimize process parameters and develop information for scale-up to larger operations.

Treatment costs using Hybrid Bioreactors are dramatically less than those reported at Superfund sites. Economic comparisons between Hybrid Bioreactors and water treatment technologies used at Superfund sites (EPA Report 542-R-00-013, February 2001; DOE EM website, http://www.em.doe.gov/techneed/) show that Hybrid Bioreactors enjoy a remarkable economic and environmental advantage, as shown in Figures 3 and 4. Using C-M Hybrid Bioreactors (e.g. TCE), estimated treatment costs were less than one-fourth of treatment costs reported at all 17 sites using technologies that both remove and destroy water contaminants (Figure 3). C-M Hybrid Bioreactor costs were less than one-tenth of the costs reported at 75% of these sites. At the 11 sites using only air stripping (which releases the contaminants in vapor phase), Figure 4, C-M Hybrid Bioreactor estimated costs were less than one-half of reported costs at 8 of these sites. The economic advantage using D-M Hybrid Bioreactors is even much greater, since their costs are generally only about one-tenth of the costs for C-M Hybrid Bioreactors.

Process Equipment and Operation

A simplified process flow sheet for both Hybrid Bioreactors is shown in Figure 2. The process equipment for the C-M Hybrid Bioreactor consisted of a 304 stainless steel cylindrical vessel four inches in diameter and ten feet long. The bioreactor was filled with eight feet of packing consisting of one-half-inch ceramic saddles and supported by a 304 stainless steel screen to provide approximately one-foot void areas at the top and bottom of the bioreactor. The total bioreactor internal volume was approximately 1 cubic foot. The ceramic packing void fraction was 0.73, and the total bioreactor voids volume was approximately 0.8 cubic feet.
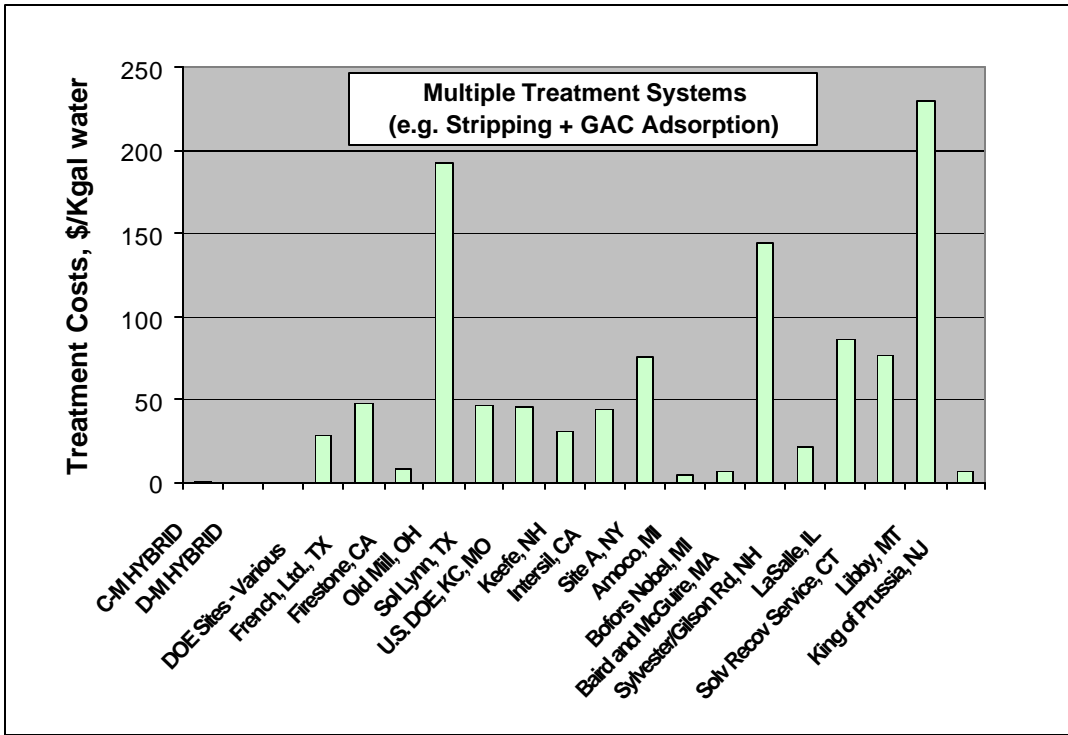
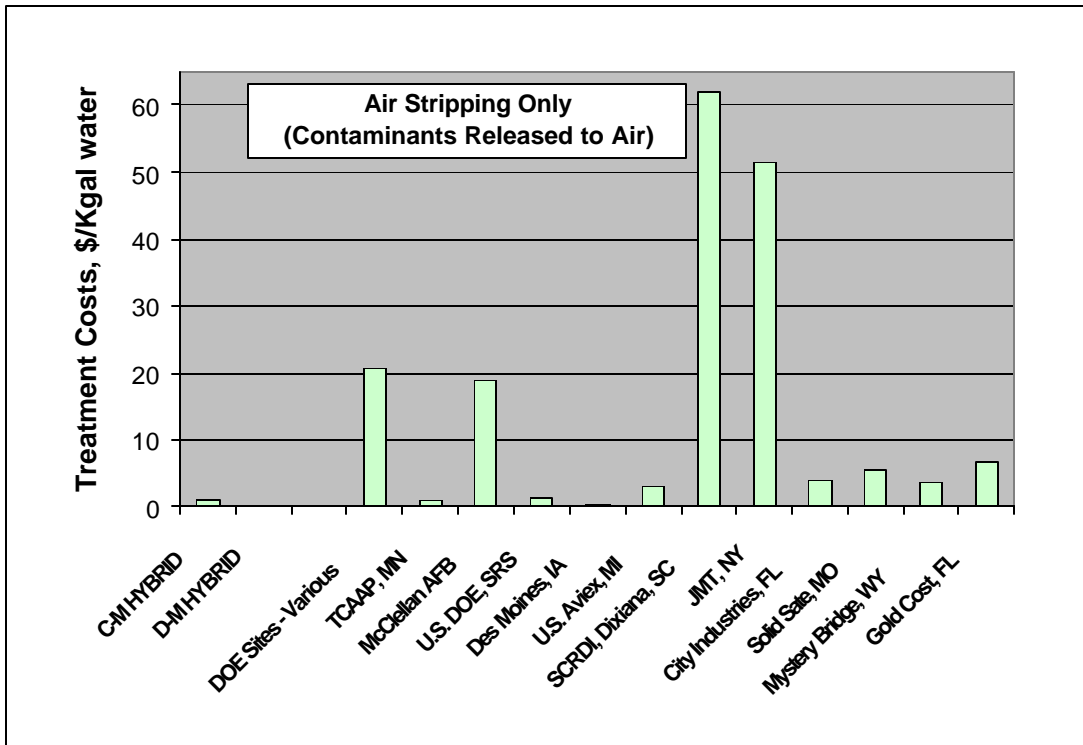**FIGURE 3. Hybrid Bioreactor cost comparison with multiple treatment systems used at Superfund sites**

Figure 4. Hybrid Bioreactor cost comparison with air stripping systems used at Superfund sites

The C-M Hybrid process was operated analogously to the TCE Biofilter process demonstrated at ANAD except that the contaminated stream was water containing TCE rather than air containing TCE. Process operation consisted of continuous alternation between a waste stream cycle and a separate propane feeding cycle to avoid intermingling of the TCE and propane, which competitively inhibits TCE degradation. The TCE-contaminated water was fed to the top void area of the bioreactor (Figure 2) and allowed to flow by gravity through the packing and out of the bottom of the bioreactor on a single-pass basis. Air was fed cocurrent to water flow. In the subsequent feeding cycle, propane gas was fed into the bioreactor cocurrent to air flow on an intermittent basis and was consumed by the microorganisms.

The process equipment for the D-M Hybrid Bioreactor was the same as that for the C-M Hybrid, except the packing consisted of 0.5-inch diameter lava rock. In the D-M Hybrid, pollutant degradation is accomplished by direct metabolism, so the primary substrate (propane) feeding cycle as described for the C-M Hybrid does not exist. Operation of the D-M Hybrid was essentially the same as that of the C-M Hybrid during the waste stream operation except that the water contaminants were benzene (4 mg/L) and toluene (4 mg/L). Direct-metabolic processes are generally much more efficient than cometabolic processes because the bioreactor is receiving the waste stream continuously without interruptions for the primary substrate feeding cycle. This, coupled with direct consumption of the pollutants, yields higher degradation rates and efficiencies and lower costs.

Sampling and Analysis Methods

Influent water was sampled from a septum-equipped port in the influent water line, effluent water was sampled from a septum-equipped port at the bottom of the bioreactor or in the effluent water line, and process air was sampled from septum-equipped ports on the bioreactor. All liquid samples were taken with glass, gas-tight syringes with Teflon plungers or with all-glass liquid syringes. Process samples were analyzed by gas chromatography (GC) using a Varian 3400 GC equipped with an electron capture detector (ECD) for TCE analysis and a flame ionization detector (FID) for propane and VOC analysis. Process water samples were analyzed for TCE or VOCs via a typical vapor equilibrium technique or headspace method. The experimental headspace GC analysis was then correlated with calibration curves obtained for known original water concentrations and their resulting equilibrated headspace concentrations to determine the original contaminant water concentrations as collected from the process. The process air samples were analyzed by GC immediately as collected from the process. Headspace and process air samples were collected and injected into the GC using 25-uL or 250-ul glass, gas-tight syringes with Teflon plungers.

C-M Hybrid Bioreactor Tests and Results

To facilitate better understanding of the results, definition of certain process operating variables or performance parameters follows:

- Load, mg/day-L – Influent mass rate of contaminant per unit volume of packing (milligrams fed per day per liter of packing volume)
- Degradation efficiency, % - Percent of contaminant removed from the water that was degraded in the bioreactor
- Elimination efficiency, % - Percent of influent contaminant that was removed from the water *and* degraded in the bioreactor
- Degradation rate, mg/day-L - Mass rate of contaminant degraded in the bioreactor per unit volume of packing (milligrams degraded per day per liter of packing volume)
- (Degradation rate / Load x 100 = Elimination efficiency)
- Hybrid-to-biofilter size ratio - size of a single-stage Hybrid Bioreactor relative to the size of the ANAD TCE Biofilter alone that will match the maximum performance level achieved in the two-stage stripper/biofilter process used in the ANAD field demonstration. Since biofilter/bioreactor capital and O&M costs are

mostly a function of size, this size ratio yields a comparison of Hybrid Bioreactor costs relative to the costs for the gas-phase biofilter alone, which would also require a prior air stripping step (added cost) to accomplish that which the Hybrid Bioreactor can accomplish in a single step.

Based on laboratory and field experiences with the gas-phase TCE Biofilter, certain process variables were known to be critical to performance and were therefore manipulated in tests with the C-M Hybrid Bioreactor so as to optimize performance parameters (e.g. TCE elimination efficiency and degradation rate). However, a microbial growth period was first necessary to establish an abundant microbial population in the packing, as is the case with any biofilter or bioreactor process at startup. One of the most favorable process schemes developed during the ANAD TCE Biofilter Demonstration consisted of a 2-hour waste stream cycle followed by a 4-hour feed cycle, so this scheme was used as a basis for startup of the C-M Hybrid Bioreactor. This process cycle scheme resulted in a 6-hour full cycle that was repeated 4 times per day and will hereinafter be referred to as the "2:4 scheme".

Improvement in C-M Hybrid Bioreactor performance as the test program progressed is illustrated in Figure 5. Figure 5 shows that performance improved dramatically during the first month of startup. Within approximately one month, degradation efficiency had increased to nearly 100%, indicating nearly zero vapor-phase TCE losses from the bioreactor. When degradation efficiency is 100%, all of the TCE that is removed from the water is degraded in the bioreactor and none is released in vapor phase. Degradation efficiency reached 100% approximately 2 months after startup. Thereafter, even with large increases in TCE load, the TCE degradation rate and elimination efficiency continued to improve while degradation efficiency remained at 100%. Less than 4 months after startup, the performance of the single-stage Hybrid Bioreactor had surpassed that of the maximum level achieved in the ANAD two-stage biofilter-stripper process, indicating that the size and thus cost required for a Hybrid Bioreactor of equal performance would be less than that of the gas-phase biofilter alone, which also requires an air stripper.
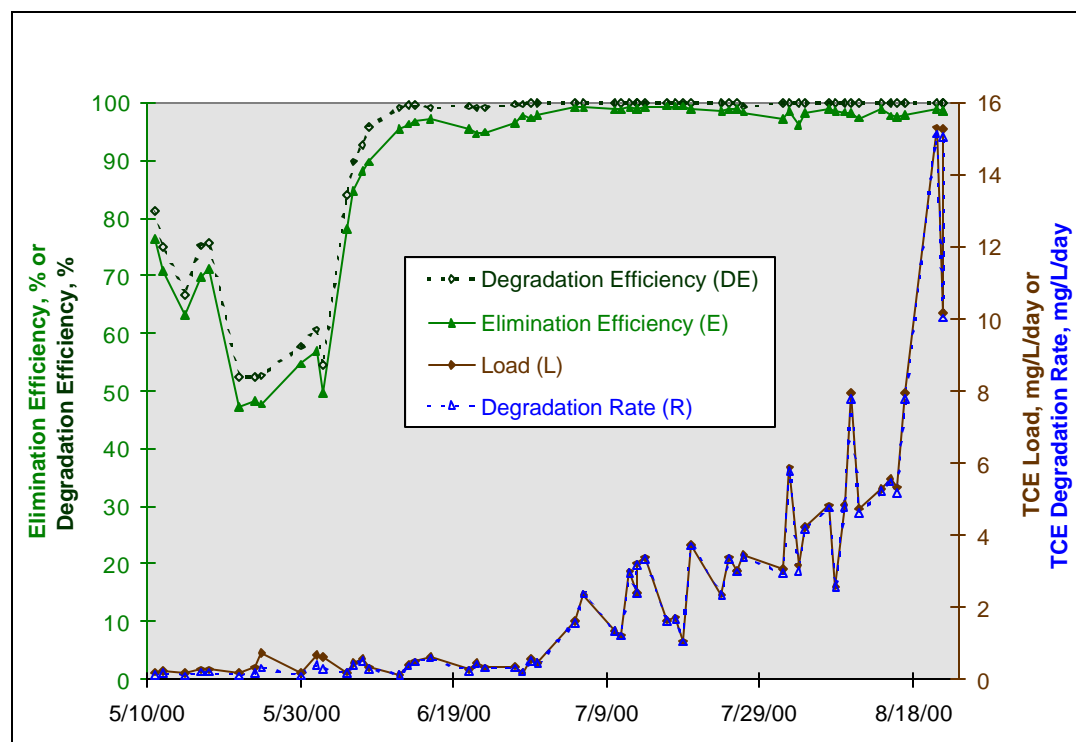

FIGURE 5. Improvement in C-M Hybrid Bioreactor performance over time

Figure 6 compares the effect of load on performance of the ANAD stripper-biofilter with that of the Hybrid Bioreactor after its microbial population had reached a level resulting in approximately steady state performance. Figure 6 shows that with increase in TCE load, the slope of the degradation rate curve for the gas-phase biofilter decreases from that of the load curve. The load curve is simply the load (L) plotted against degradation rate (R) for

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the hypothetical case in which all of the contaminant fed to the bioreactor is degraded, the elimination efficiency is therefore 100%, and the degradation rate is therefore equal to the load (R = L, R/L = 1). In this scenario, the degradation rate versus load curve is the line R = L with slope of R/L = 1. For the gas-phase biofilter, the slope of the degradation rate curve approaches zero, at which point further increases in load result in no further increase in the degradation rate and in decrease in the elimination efficiency (E) because E = 100(R/L), or the slope of the degradation curve expressed as percent. In contrast, the slope of the degradation rate curve for the C-M Hybrid Bioreactor remained nearly the same as the load line R = L, indicating that nearly all of the TCE fed to the bioreactor was degraded within the limits tested at that juncture.

Of course, with increase in TCE load, a point would eventually be reached such that the slope of the degradation rate curve for the C-M Hybrid Bioreactor would begin to fall below that of the load line R = L, and the elimination efficiency at this point would then begin to decrease. However, these results indicate that within the load ranges tested in the gas-phase biofilter, the performance limits of the Hybrid Bioreactor were not reached, indicating substantially higher performance and smaller size and cost for the Hybrid.
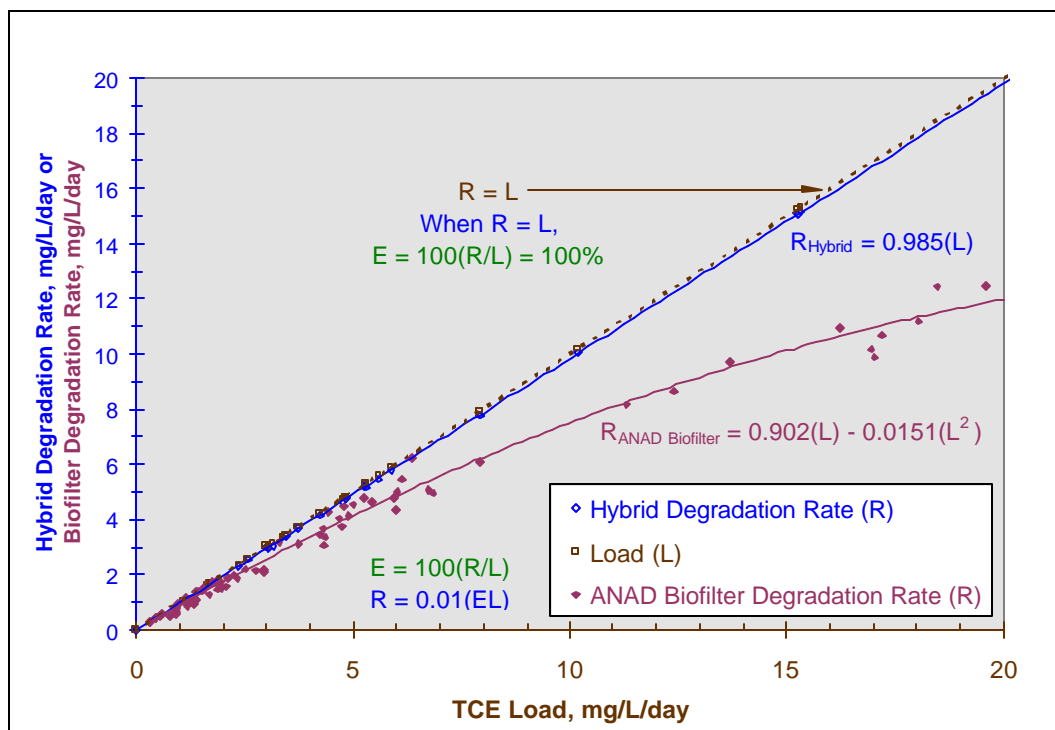

FIGURE 6. Comparison of C-M Hybrid and ANAD Biofilter performance

Figure 7 shows the effect of increase in load and degradation rate on the size required for a Hybrid Bioreactor to match performance with that of the maximum achieved in the two-stage, stripper-biofilter process demonstrated at ANAD. As these results show, the performance of the Hybrid Bioreactor has substantially exceeded that of the gas-phase biofilter, allowing use of a Hybrid Bioreactor substantially smaller and less costly than the gas-phase biofilter alone to accomplish the same as that which required both air stripping and gas-phase biofiltration at ANAD.

The effect of influent water concentration at constant water rate is shown in Figure 8. The results show that, within the range of about 0.5 to 20 mg/L TCE, elimination efficiency was relatively unaffected, but degradation rate was directly proportional to water concentration. Simple mathematics dictates that load (mass rate) is directly proportional to water concentration at constant water rate. Since TCE elimination efficiency was relatively constant with regard to water concentration at constant water rate (constant contact time), and since degradation rate is the product of the load and the elimination efficiency, this resulted in the degradation rate being directly proportional to the influent water concentration.
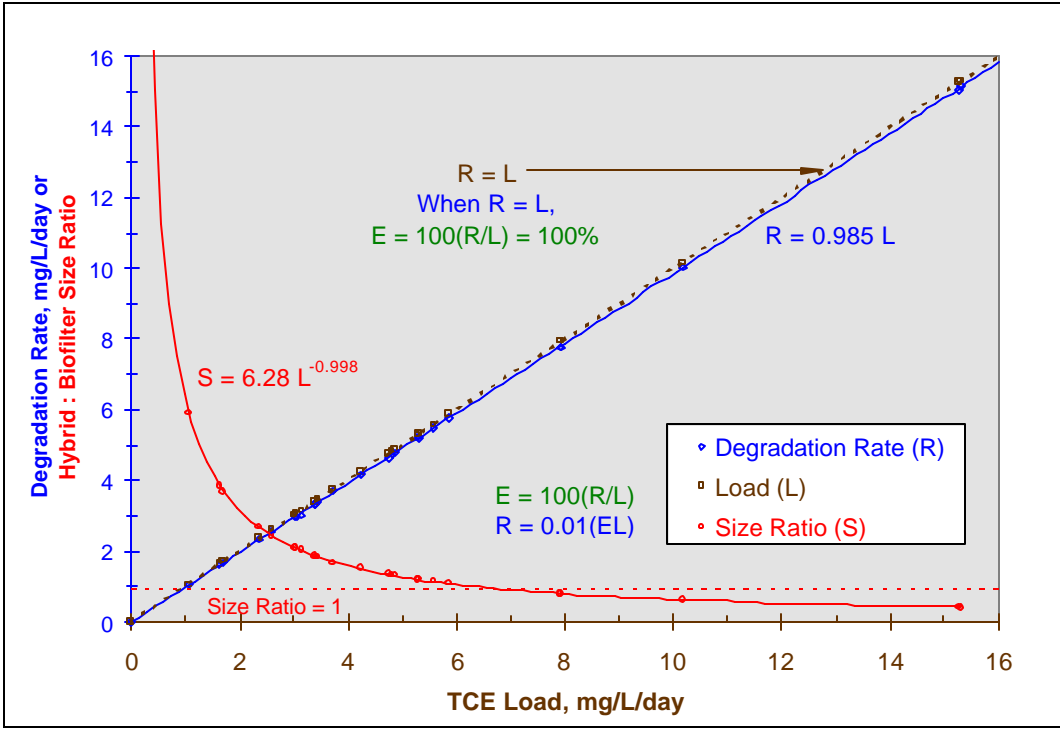
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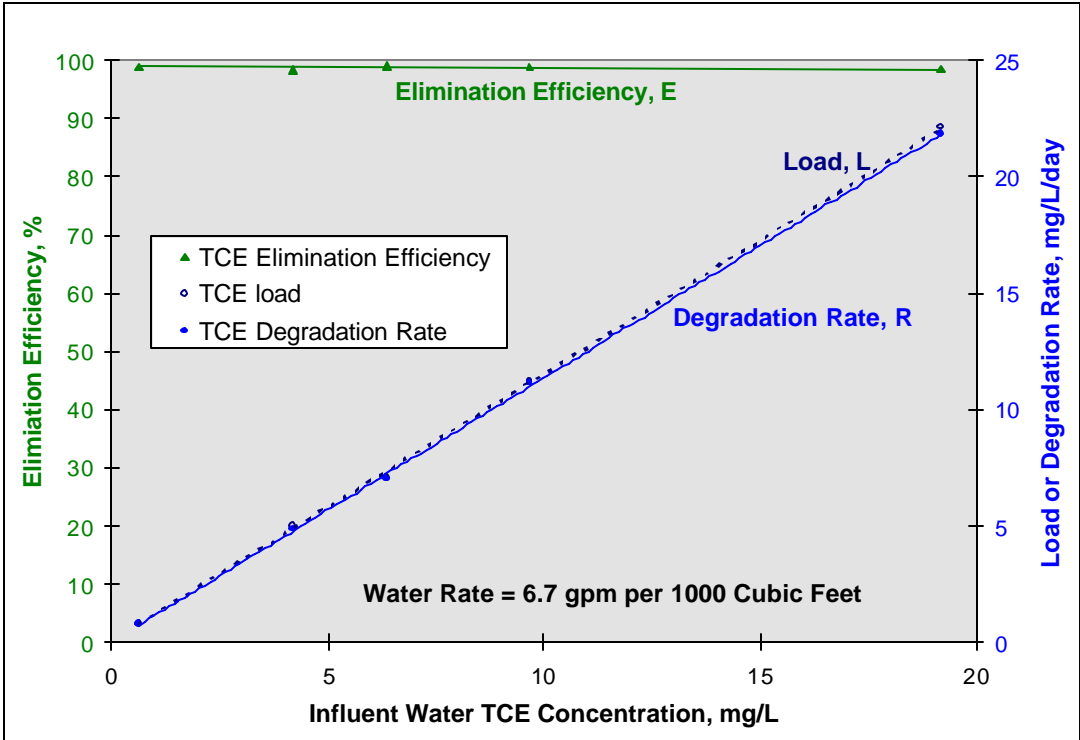**FIGURE 7**. Size comparison between Hybrid and ANAD Biofilter

FIGURE 8. Effect of concentration on load, degradation rate, and efficiency

As performance improved, it became apparent that the waste stream cycle time could be increased and the feed cycle time could be decreased to further improve performance and reduce size and costs. Figure 9 shows the results of a test series to examine the effect of influent water rate at constant influent water concentration (4-6 mg/L TCE) after increasing the waste stream cycle time to 3 hours and reducing the feed cycle time to 3 hours.
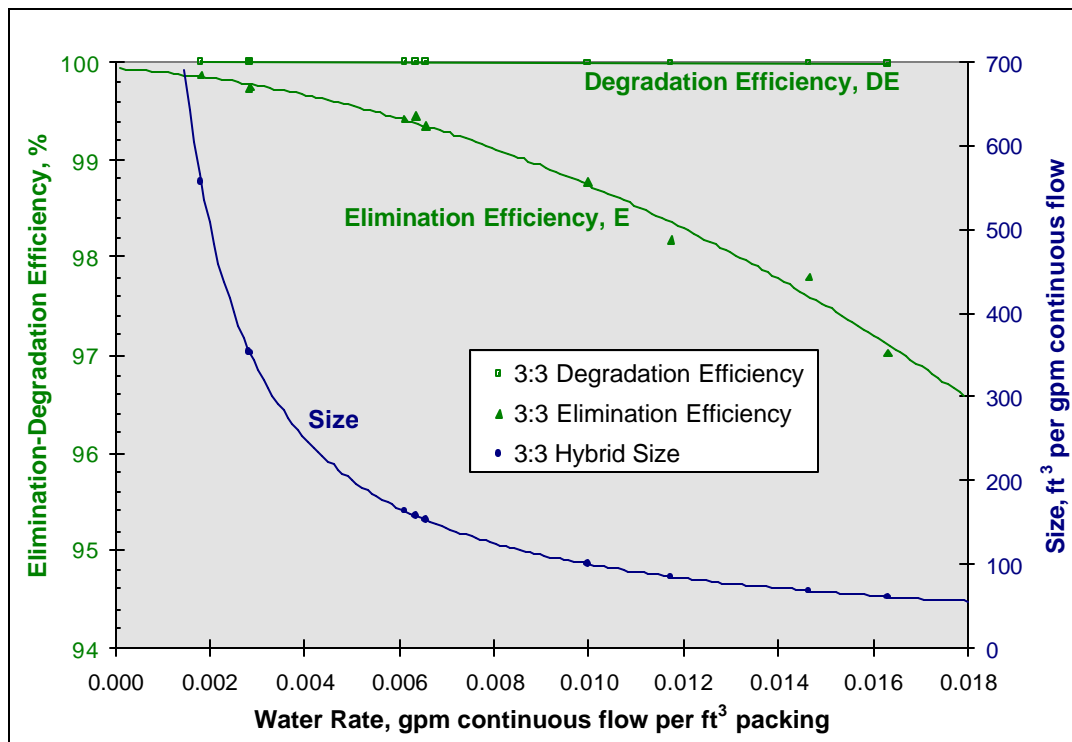
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FIGURE 9. **Effect of water rate on size and efficiency with 3:3 scheme**

This process cycle scheme will hereinafter be referred to as the 3:3 scheme, and the previous process cycle scheme will be referred to as the 2:4 scheme. The results obtained with the 3:3 scheme (Figure 9) exhibited the same relationships between the water rate and the elimination and degradation efficiencies as were obtained with the 2:4 scheme. With increase in water rate, the TCE elimination efficiency decreased, as expected due to decrease in the contact time between the contaminated water and the microorganisms, but the reduction in elimination efficiency was small relative to the decrease in bioreactor size. With increase in water rate, degradation efficiency remained at virtually 100%, indicating virtually zero vapor-phase TCE losses from the bioreactor. As was the case for the 2:4 scheme, the size (costs) required for a Hybrid Bioreactor using the 3:3 scheme decreased with increase in water rate per unit volume of packing.

Figure 10 compares bioreactor size and performance for the 2:4 and the 3:3 schemes as functions of water rate. These results show that when very high elimination efficiencies (e.g. > 99.8%) are unnecessary, the 3:3 scheme was clearly superior to that of the 2:4 scheme, in that a specific bioreactor will handle a higher water rate at the same elimination efficiency, or a specific water rate will require a smaller bioreactor at the same elimination efficiency. On the other hand, the 2:4 scheme may be superior when very high elimination efficiencies are required to meet required discharge concentrations. From another perspective, bioreactor size and costs increase with increase in the elimination efficiency required for the bioreactor, as would be expected, in that longer contact times between the contaminated water and the microorganisms are needed to remove larger proportions of the contaminants.

As shown in Figure 11 with influent TCE concentrations of 4-6 mg/L, substantial reduction in bioreactor size reduces elimination efficiency only slightly, and very high elimination efficiencies require dramatic increases in size and costs. In such instances where very high elimination efficiencies are required, other techniques, such as use of a small bioactive carbon adsorption bed within the bioreactor or recycling of the contaminated water in the bioreactor, may be more cost effective than simply building a larger bioreactor.
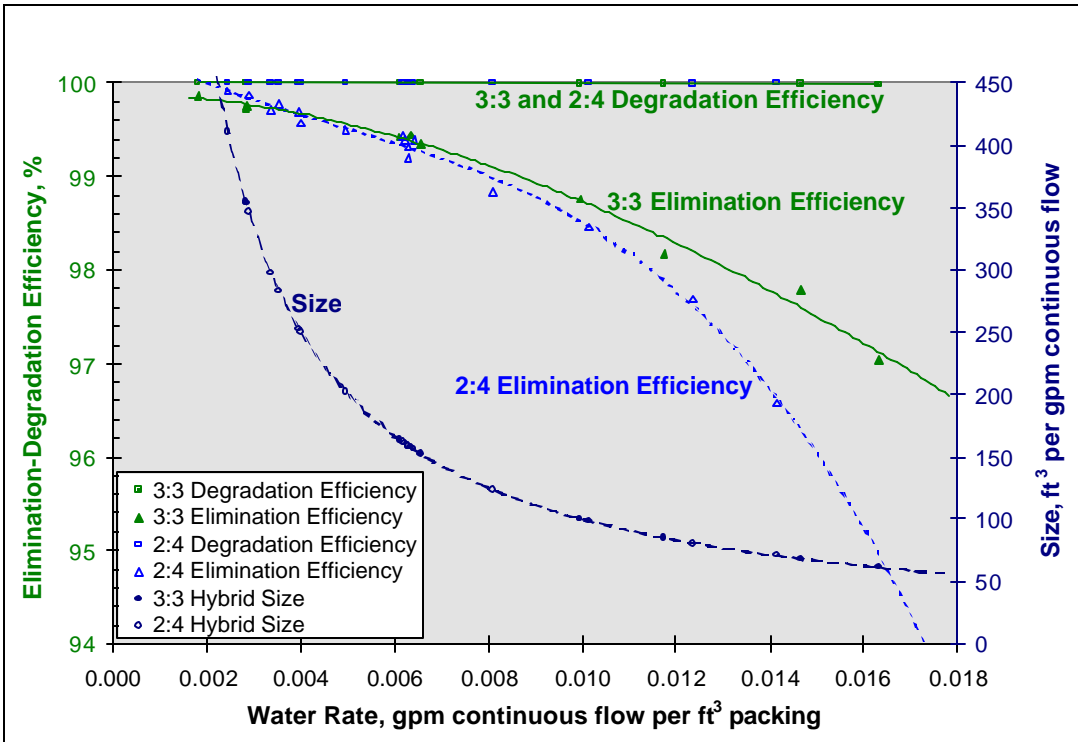
FIGURE 10. Improving efficiency and reducing size with 3:3 process scheme
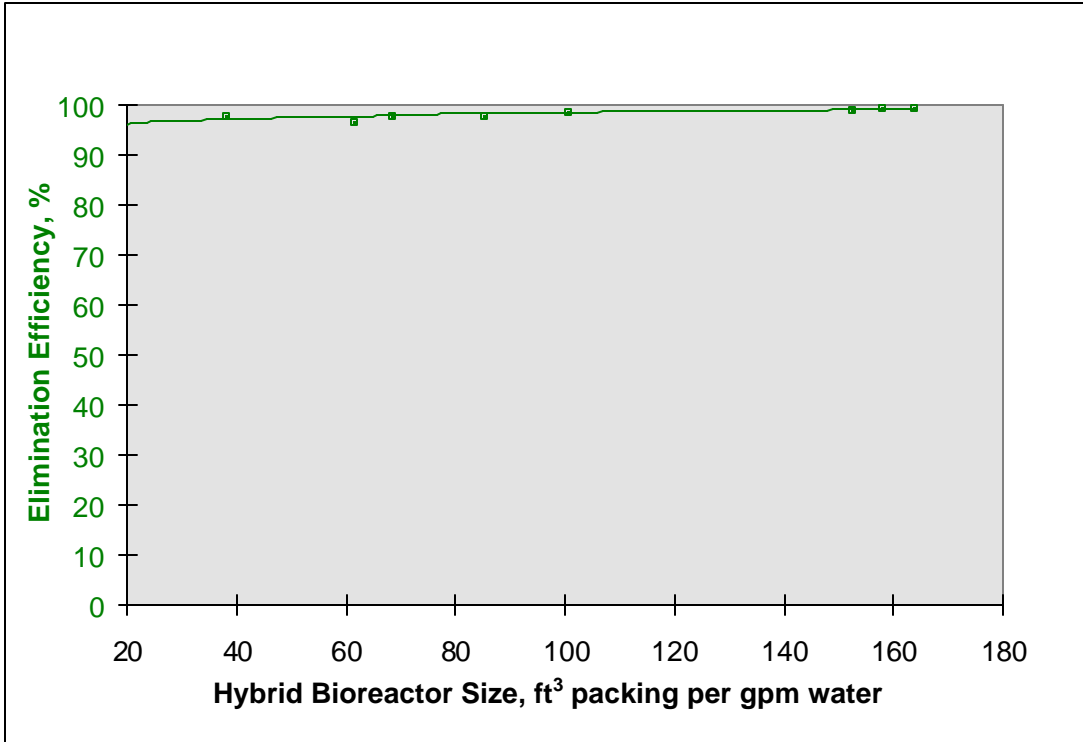

Figure 11. Effect of size on TCE elimination efficiency with 3:3 scheme

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D-M Hybrid Bioreactor Tests and Results

Figure 12 illustrates the dramatic improvement in performance of the D-M Hybrid Bioreactor as growth and establishment of biomass progressed. As performance improved, the water rate was increased, which increased the VOC (food) load and in turn further increased biomass levels. As water rate was increased and performance improved, elimination efficiency of both benzene and toluene reached 100% with degradation rate equal to load, and the size required for the D-M Hybrid Bioreactor for a given elimination efficiency decreased from over 100 to less than 10 cubic feet per gallon-per-minute of water flow.

In all tests with the D-M Hybrid Bioreactor at steady state conditions, toluene degradation efficiency was 100%, indicating zero toluene vapor-phase losses from the bioreactor. Benzene degradation efficiency ranged from 99.97% to 100.00%, indicating zero or virtually zero vapor-phase benzene losses from the bioreactor. A degradation efficiency of 99.97% means that only 0.03% of the contaminants removed from the water are released as vapor phase from the bioreactor. With air stripping of VOCs, essentially 100% of the contaminants removed from the water are released as vapor-phase to the atmosphere.
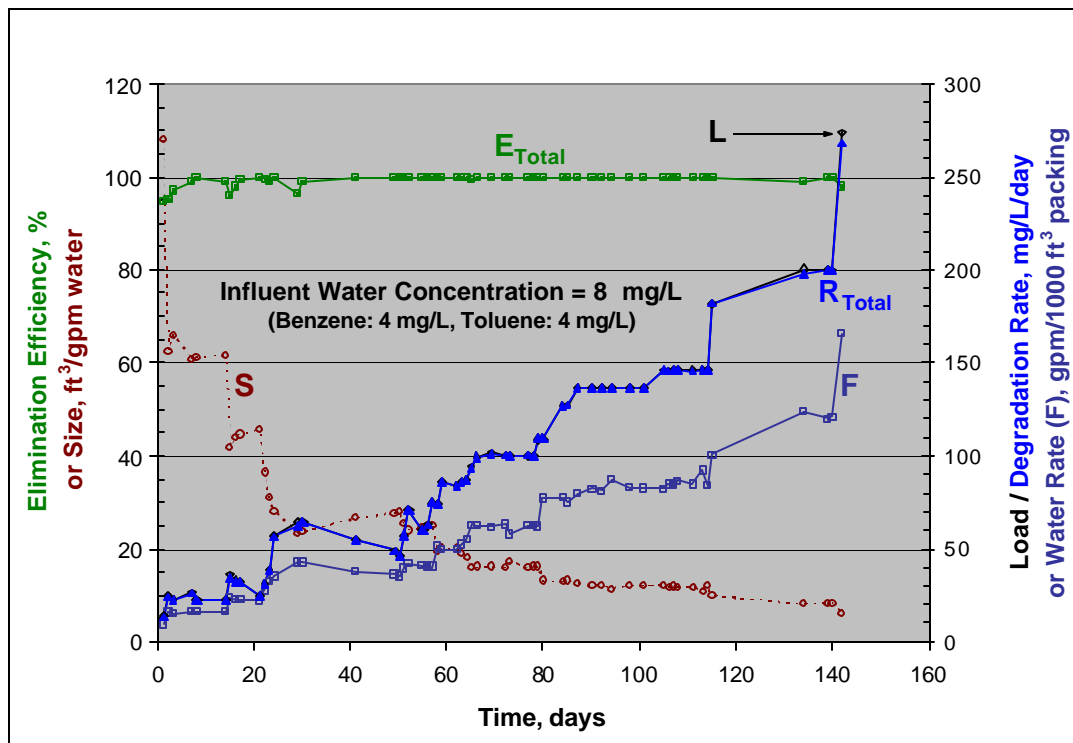

Figure 12. D-M Hybrid Bioreactor performance – total VOCs

The results in Figures 13 and 14 show the effect of water rate and load, respectively, on performance of the D-M Hybrid Bioreactor at steady state conditions. With increase in water rate and load, the elimination efficiency remained at 100% but decreased slightly (to 98%) at the highest water rate and VOC (food) load tested. This was due to excess biomass causing partial obstruction of the water and air flows through the 0.5-inch lava rock packing at the highest water rate and VOC load. The packing was then removed and replaced with larger lava rock (1.5-inch) to provide more void areas for water and air flow.
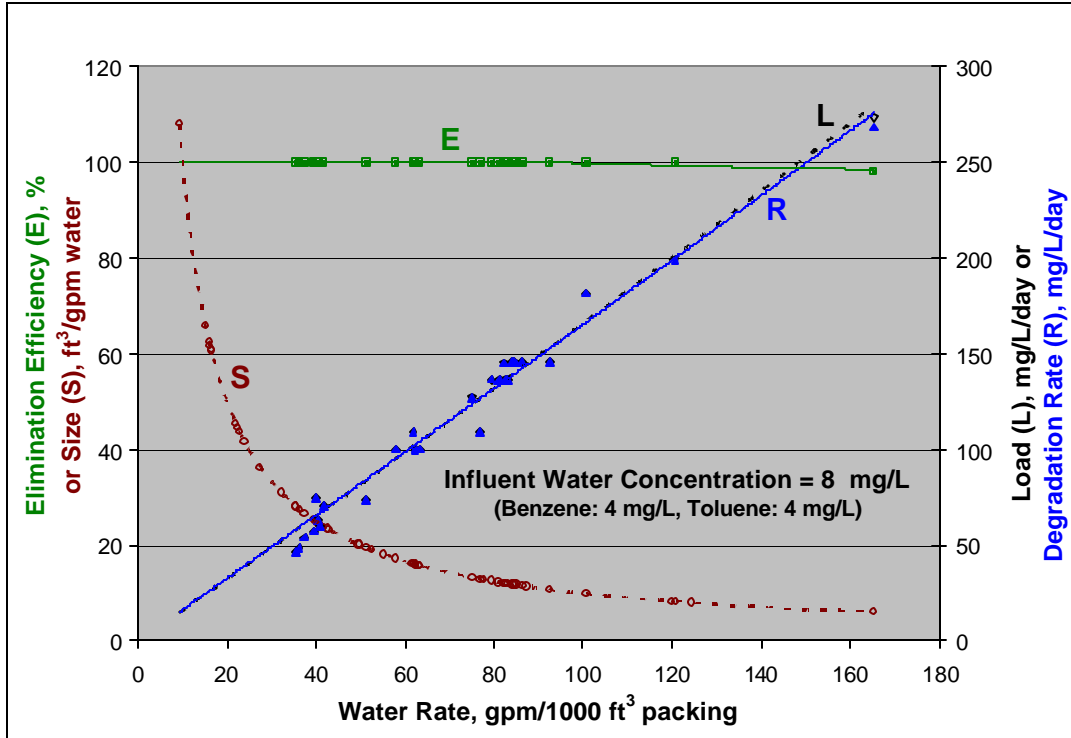

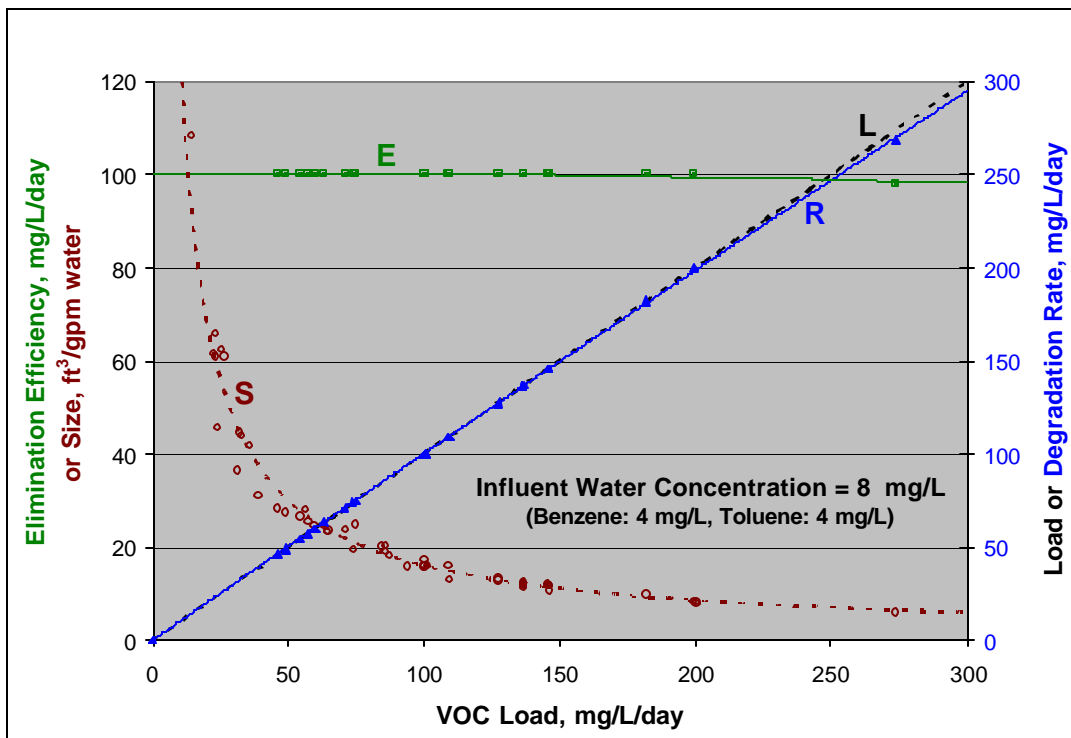**Figure 13. Effect of water rate on performance and size of D-M Hybrid**

Figure 14. Effect of VOC load on performance and size of D-M Hybrid

Figure 15 shows that detoxification of water containing directly consumable VOCs can be accomplished in bioreactors 1/10 or less the size (capital and O&M costs) of that required for detoxifying water contaminated with TCE. Further improvements in process performance have been achieved since the data in Figure 15 were collected. At the current stage of development, the D-M Hybrid Bioreactor has achieved 98% benzene and toluene destruction with 5 cubic feet of packing per gallon-per-minute of continuous water flow at influent concentrations of 2.5 mg/L each. With 10 cubic feet of packing per gallon-per-minute of continuous water flow, the D-M Hybrid has achieved 100% benzene and toluene destruction at influent concentrations of 5 mg/L each. The C-M Hybrid Bioreactor has achieved 97% destruction of TCE with approximately 40 cubic feet of packing per gallon-per-minute of continuous water flow at an influent concentration of 1.6 mg/L. With 150 cubic feet of packing per gallon-per-minute of continuous water flow, the C-M Hybrid has achieved greater than 99.9% TCE destruction at an influent concentration of 6 mg/L. For lower influent contaminant concentrations and/or less stringent contaminant removal requirements, the size and consequent costs of both the D-M and the C-M Hybrid Bioreactors can be reduced substantially. In short, the designs, sizes, and costs for Hybrid Bioreactors are functions of the contaminant species present, the concentrations of the contaminants, the degree of contaminant removal required to meet discharge regulations, and the flow rate of the contaminated water stream. Thus, the designs, sizes, and costs for Hybrid Bioreactors are site specific, as is the case with other pollution control and remediation technologies.
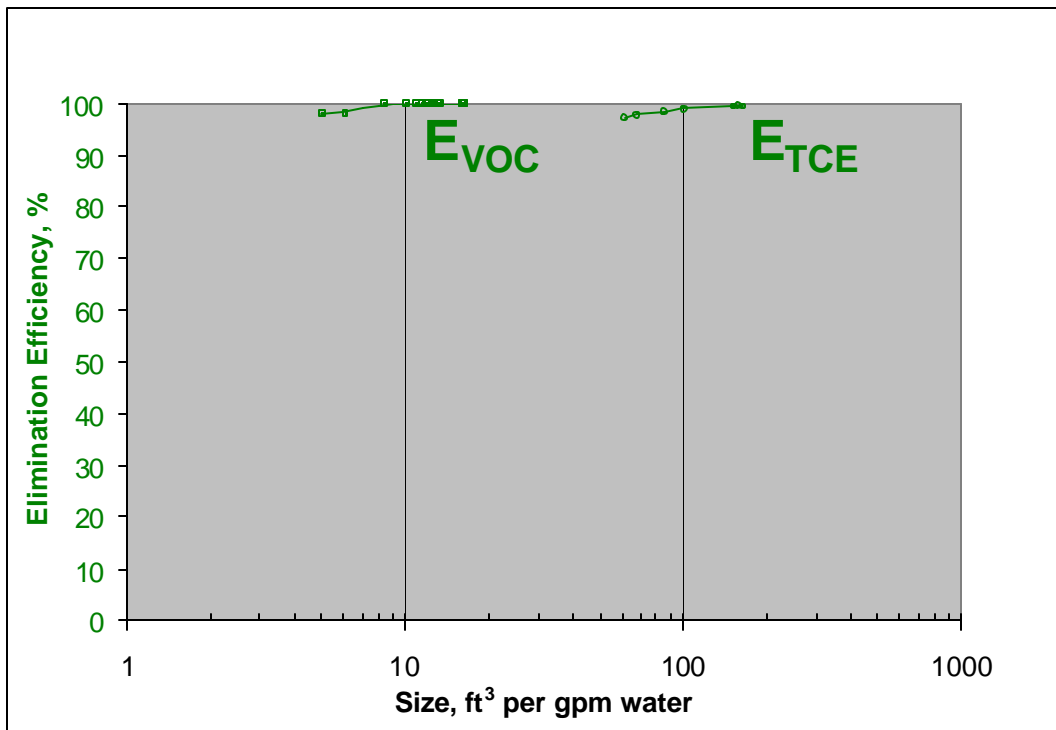

Figure 15. D-M and C-M Hybrid Bioreactor size comparison

Conclusions

Tests with Hybrid Bioreactors were highly successful in detoxifying TCE- or VOC-contaminated water in a single step without air stripping and with zero or virtually zero vapor phase losses. With increase in load or water rate, degradation rate increased and the size and cost decreased dramatically with relatively slight decrease in elimination efficiency. The high performance achieved in the Hybrid Bioreactors resulted from degradation of the contaminants directly in the contaminated water and employment of patented process schemes to eliminate vapor-phase loss of contaminants from the bioreactors. Economic comparisons show that Hybrid Bioreactors enjoy a remarkable economic and environmental advantage over other water treatment technologies, with treatment costs generally less than one-tenth those reported at Superfund sites. Designs and costs for Hybrid Bioreactors are site specific, as is the case with other technologies, and are functions of the contaminant species present, the concentrations of the contaminants, the degree of contaminant removal required to meet discharge regulations, and the flow rate of the contaminated water stream. Advantages of Hybrid Bioreactors include:

- Dramatic cost savings over existing technologies
- Decontaminates both water _and_ air in a single step
- Removes _and_ destroys the contaminants
- Handles a wide range of contaminants
- Does not generate contaminated off gases
- Does not generate secondary waste streams
- Simple, automatic, remote process operation requiring minimal labor

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