INNOVATIVE TECHNOLOGY
Summary Report

DOE/EM-0614

Membrane System for the Recovery of Volatile Organic Compounds from Remediation Off-Gases

Industry Programs and
TRU and Mixed Waste Focus Area

Prepared for
U.S. Department of Energy
Office of Environmental Management
Office of Science and Technology

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Summary Report

Membrane System for the Recovery of Volatile Organic Compounds from Remediation Off-Gases

OST/TMS ID 266

Industry Programs and
TRU and Mixed Waste Focus Area

Demonstrated at

McClellan Air Force Base-
National Environmental Technology Test Site
California

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://www.em.doe.gov/ost under "Publications."

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SECTION 1
SUMMARY

Technology Summary

Problem

Many Department of Energy (DOE) sites contain volatile organic compound (VOC)-contaminated soil and groundwater, and large volumes of mixed low-level wastes contaminated with VOCs. Treatment technologies, such as air stripping, soil vapor extraction, air sparging, steam stripping, and vitrification, generate VOC-laden off-gasses. Current technologies for the treatment of VOC contaminated off-gasses can expensive to operate and more cost effective technologies are needed.

Solution

Membrane Technologies and Research, Inc. (MTR) has developed an innovative, membrane-based treatment technology for the removal of VOCs from remediaiton off-gasses. MTR's technology utilizes a permselective membrane to separate the organic components of an off-gas stream. The permselective membrane is more permeable to VOCs than air. The selective permeation of VOCs over air allows for the separation of VOCs. The product of the membrane separation process is concentrated VOC liquid (permeate) stream and a treated air stream depleted of VOCs. A treated water stream is also generated if an appreciable amount of water vapor is present in the off-gas. The treated air stream contains less than 10 parts per million (ppm) VOC by weight and the treated water stream has contains less than 1 ppm VOC. An illustration of how the permselective membrane works is presented in Figure 1. In this figure the larger circles represent hydrocarbons selectively permeating the membrane.

Technology Benefits

- VOCs removed from the off-gas are condensed into a concentrated liquid, decreasing overall waste volume;
- Treats off-gases containing flammable, chlorinated, and non-chlorinated VOCs;
- Needs only a source of electricity for operation, and
- Requires little maintenance.
-

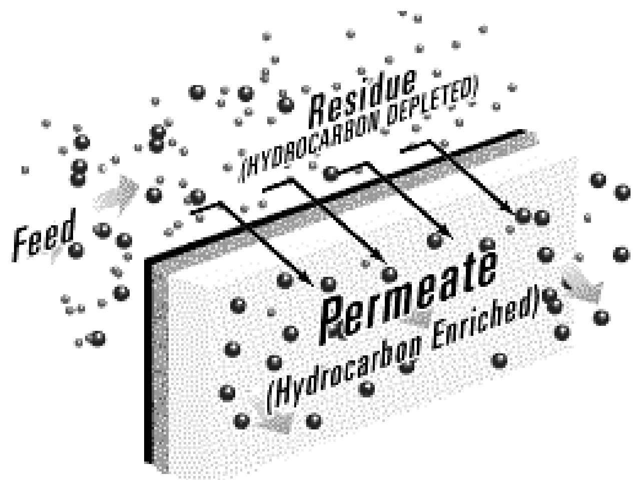

Figure 1. Illustration of permselective membrane.

Comparison to Baseline

There are two baseline technologies for removal of VOCs from off-gases: activated carbon and thermal oxidation (including thermal catalytic oxidation). Activated carbon is applied to off-gasses containing low VOC concentrations (less than 50 ppm), while catalytic oxidation is more cost effective for higher VOC concentrations. Early pilot scale testing found MTR's membrane separation to be more cost effective than activated carbon for separation of VOCs present at concentrations above 100 ppm, but another cost analysis developed after full scale demonstration revealed that MTR's membrane technology was not cost competitive with catalytic oxidation.

Demonstration Summary

The technology was demonstrated between March 1999 and February 2000 at the McClellan Air Force Base (AFB), National Environmental Technology Test Site (NETTS), located outside of Sacramento California. The demonstration system removed chlorinated VOCs from the off-gas from a soil vapor extraction (SVE) system. Operational conditions are summarized below:

- Design flowrate: 100 standard cubic feet per minute (scfm)
- VOC concentration in SVE off-gas: (total): 23 ppm to 101 ppm
- Target VOC concentration in treated off-gas: 10 ppm

The results of the demonstration were mixed. The system exhibited the ability to remove VOC to the target level, but two significant performance issues were also encountered:

- Effect of carbon dioxide (CO_2): The presence of CO_2 in the SVE off-gas at one to three percent was found to reduce the system's capacity (i.e. flowrate) by a factor of two to four. The CO_2 is produced from biodegradation of organics in the subsurface and is problematic, because it is permeable to the membrane.

- Membrane Fouling: Fouling of the membrane modules with oil and water due to mechanical failure of the coalesces resulted in deteriorated separation efficiency within two weeks.

Contacts

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://www.em.doe.gov/ost under "Publications." The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST/TMS ID for Membrane System for Recovery of Volatile Organic Compounds from Remediation Off-Gases is 266.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

Removal of VOCs from air streams with membranes is a relatively new concept. To date, it has primarily been applied to recovery of VOCs from process streams in the refining and petrochemical industries. MTR began installing commercial units in 1992 and currently has more than 60 units operating in the refining and petrochemical industries worldwide. Treatment of off-gasses from environmental remediation systems is a spin-off of this technology. In the petrochemical industry, the membranes are used to recover valuable solvents from highly concentrated streams. The VOC concentrations found in the industrial process streams are typically much higher than off-gases from remediation systems. A pilot test of a membrane system at the Hanford Site proved that the process was feasible for the removal of VOCs from off-gasses containing carbon tetrachloride at concentrations ranging from 200-1,000 ppm.

MTRs vapor treatment technology is based on a permselective membrane that separates the organic components of an off-gas stream, producing a VOC-free air stream. The membranes are much more permeable to VOCs than air. The system is designed to remove the VOCs from the vapor stream, producing a concentrated VOC liquid phase and a clean vapor stream with less than 10 ppm by weight VOC. A water stream is also produced containing less than 1 ppm VOC.

A synthetic polymer membrane can separate the components of a gas stream or vapor mixture because the components permeate the membrane at different rates. MTR’s membranes are composite structures. A microporous layer provides strength and the ultrathin, permselective coating is responsible for the separation properties.

The composite membranes are incorporated into spiral-wound modules shown in Figure 2. Feed gas enters the module and flows between the membrane layers. VOCs preferentially permeate the membrane and are transported inward to a central collection pipe. The remainder of the feed stream flows across the membrane surface and exits depleted of VOCs. Modules can be connected in series or parallel flow arrangement to meet the flowrate and separation requirements of a particular application.

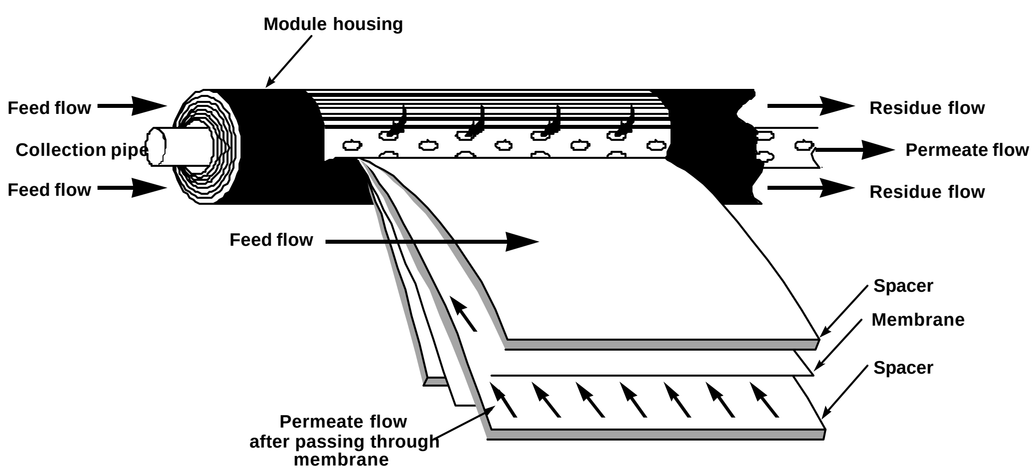

Figure 2. Schematic of a spiral-wound membrane module.

System Operation

A flow schematic of the membrane system is presented in Figure 3. Feed air, typically including water vapor (1-2%), and VOCs (0-2%), enters the system and is compressed to a pressure of 190 psia. Most of the water vapor and some of the VOC content is condensed out by a compressor followed by an air cooler. A small air stripper removes the VOCs from the condensed water so that the water can be discharged. The air leaving the air cooler enters two sets of membrane separation modules in series. Most of the VOCs and some of the air permeate the membrane in the first membrane step; this VOC-enriched permeate stream is recompressed in a liquid-ring vacuum pump. The exhaust from the air stripper is also sent to this vacuum pump. The vacuum pump compresses the air to about 80 psia, after which the VOC content is condensed in a heat exchanger. Liquid VOC is removed from the system at this point. The air leaving the heat exchanger still contains an appreciable amount of VOC, most of which is removed in a second stage membrane separation module. The VOC-enriched permeate is returned to the vacuum pump, thereby creating a concentration loop for the VOCs that facilitates their condensation in the heat exchanger. The VOC-depleted stream produced by the first membrane step is fed to the second membrane step where the remaining VOCs are removed to achieve the 10 ppm VOC discharge level. The permeate stream produced by the second membrane is returned to the inlet of the compressor. The system is a self-contained turnkey unit, skid mounted and completely automatic, requiring only electric power. Operation of the system is intended to be fully automated and relatively maintenance free.

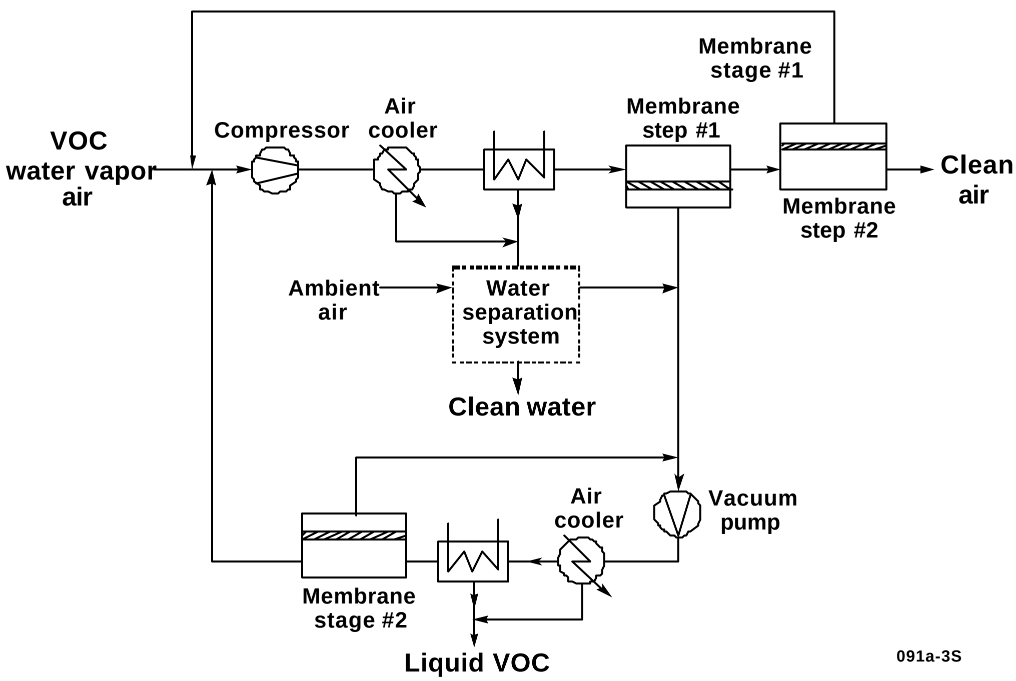

Figure 3. Schematic of membrane separation system for removal of VOCs from remediation off-gasses.

SECTION 3
PERFORMANCE

Demonstration Plan

The membrane system for recovery of VOCs from remediation off-gases was demonstrated at the McClellan AFB, NETTS, located outside of Sacramento California. The McClellan AFB, has been an active industrial facility since 1936, when it was called the Sacramento Air Depot. The McClellan AFB was selected to be a demonstration site for technologies designed to treat chlorinated solvents by the Strategic Environmental Research and Development Program (SERDP) in January 1993. Chlorinated solvents comprise much of the soil and groundwater contamination found at McClellan AFB. The demonstration site provides locations for evaluating the effectiveness of remedial technologies for treating solvents found in soil and groundwater. MTR's technology was demonstrated for the removal of VOC's from a soil vapor extraction system at the Operable Unit D (Site S). The system operated intermittently between March 1999 and May 2000. Several other innovative off-gas treatment technologies have been demonstrated at this unit; therefore, this site was an ideal location to benchmark the performance of the technology. The baseline technology for treatment of the SVE off-gas at McClellan AFB is catalytic oxidation followed by a scrubber to remove hydrogen chloride and hydrogen fluoride formed by the oxidation of halogenated VOCs.

Demonstration System Parameters

The off-gas from the SVE system at McClellan AFB contains over twenty VOCs; the three typically present at the highest concentrations are 1,1,1-trichloroethane, trichloroethene, and tetrachloroethene. System parameters are listed below:

- Influent VOC concentration (total): 23 ppm to 101 ppm
- Design Capacity: 100 scfm
- Target VOC concentration in treated off-gas: 10 ppm

The demonstration site at Site S at McClellan AFB utilizes a catalytic oxidation unit after the innovative technology being tested (the MTR unit in this case). The catalytic oxidation unit ensures the off-gas is treated sufficiently before being discharged, and provides a measure of safety should the innovative technology not perform properly.

Results

Early in the demonstration, an unforeseen problem was encountered. The SVE off-gas contained CO_2 at concentrations ranging from 1 to 3 percent. The CO_2 was generated from the aerobic biodegradation of the VOCs present in the soil. The presence of CO_2 at these levels decreases the capacity of the membrane treatment system. The presence of CO_2 is problematic because the membrane is permeable to CO_2 and CO_2 is not very condensable; therefore, the CO_2 builds up in the system's recirculation loop, lowering the capacity to handle the feed stream. The problem related to the CO_2 became apparent in the first hours of operation when a loss of pressure and decreased flowrate was observed. Studies by MTR concluded that the presence of CO_2 at one to three percent is sufficient to reduce the capacity (flowrate) of the system by a factor of two to four. The presence of CO_2 is not uncommon to SVE off-gasses, but was not considered in the design of the system.

The system was restarted on April 20, 1999 and operated at a reduced flowrate; which ranged from 25-45 scfm for the remainder of the demonstration. Throughout the demonstration, inlet and discharge air samples were collected and analyzed for VOC content at an off-site analytical laboratory using EPA Method 8021. A graph of the VOC concentrations in the inlet and discharge gasses is provided in Figure 4. As evident in the graph, the discharge VOC concentration increased over time and eventually exceeded the target of 10 ppm. At the end of the first test period, a mixture of oil and water was noticed in the discharge air stream. Inspection of the system revealed that membrane modules, as well as the system's piping, contained oil and water. Teardown of the system revealed that the source of the oil was the second stage liquid ring pump. The liquid ring vacuum pump oil/gas separator was not operating properly and was the cause of the oil contamination. The water found in the system was most likely a result of poor draining of the first-stage condenser and subsequent flooding of the downstream coalescing filter. Field modifications were made in an attempt the address these problems.

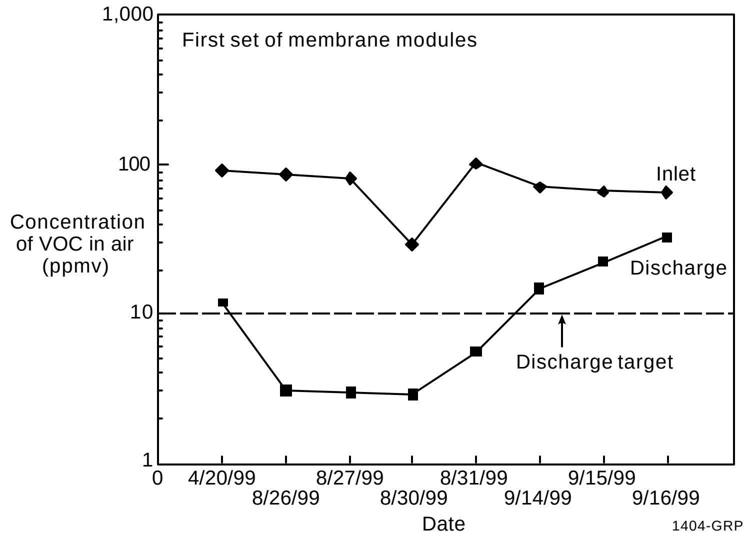

Figure 4. VOC concentration in the membrane system inlet air (the SVE off-gas) and in the system discharge stream.

A replacement set of membranes was inserted into the system, which was then restarted on March 16, 2000. A graph of the total VOC concentrations for the inlet and outlet is presented in Figure 5. The system performance was excellent initially, but as in the first test period, the discharge VOC concentration increased over time and eventually exceeded the target of 10 ppm. After completion of the experiment, oil and water were again present in the system.

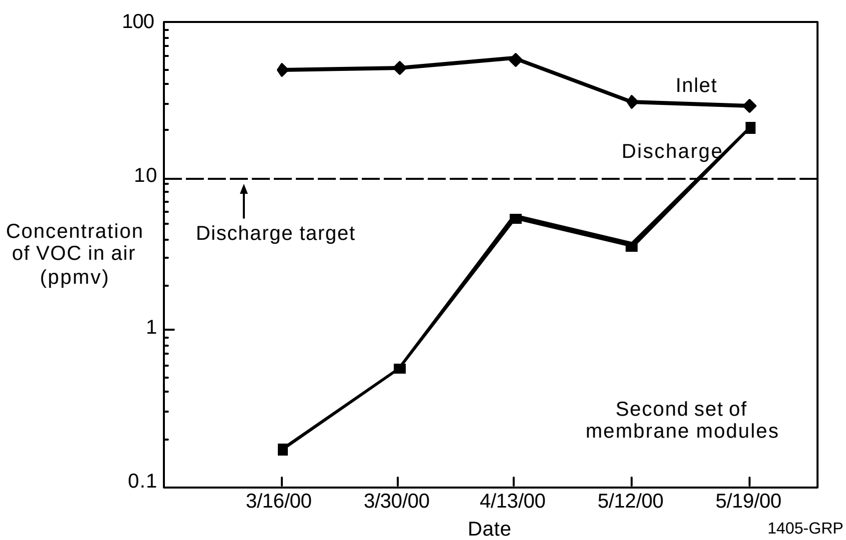

Figure 5. VOC concentration in membrane system inlet air (the SVE off-gas) and in the system discharge stream.

The performance results with respect to VOC removal are mixed. The system exhibited the ability to remove VOC to the target level, but mechanical issues resulted in deterioration in performance over time. Fouling of the membrane modules with oil and water reduced performance within two weeks. The cause of the fouling was not entirely clear to MTR. A similar system operated at Hanford for 25 days without deterioration.

Performance Conclusions

The demonstration at McClellan AFB was valuable in that it revealed two significant issues with system performance under actual field conditions. The first and most significant issue is the effect of CO_2 on system capacity. The presence of CO_2 at concentrations from one to three percent was found to reduce system capacity by a factor of two to four. This problem is significant because it is directly related to the membrane process, which is the heart of the system. This problem is not easily remedied and the presence of CO_2 is common to SVE off-gasses. It is likely this occurrence would be encountered at other sites. The second problem encountered during the demonstration was the membrane fouling with oil and water over time. This problem is a mechanical problem with system components and although the solution is not clear, it is conceivable that this problem could be solved.

Despite the problems described above, the membrane system did effectively remove VOCs from the off-gas to concentrations less than the target of 10 ppm before fouling occurred.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Technology Applicability

MTR's technology is best suited to the removal of VOCs (including chlorinated compounds) from off-gases with VOC concentrations greater than 100 ppm. The technology is capable of removing VOCs at lower concentrations, but activated carbon is much more cost effective.

A niche market for MTR's system is off-gas treatment during start-up and early operational stages of remediation system (i.e. during the first year). MTRs system is well suited to this situation because VOC concentrations are typically highest during early stages of operation when large amounts of contaminants are being removed from the subsurface. MTR's system is mobile and can be easily replaced with a carbon system after VOC concentrations decrease and stabilize. Utilizing MTR's system in this manner will also alleviate the need to over-design activated carbon systems to handle the high initial VOC concentrations that may only be seen in the early stages of operation.

As discussed in the performance section, the presence of CO_2 in the off-gas has a negative impact on the effectiveness of the membrane system. The CO_2 concentration should be determined when assessing the applicability of the membrane treatment system.

Other Applications

The membrane system for recovery of VOC from remediation off-gasses is a spin-off of MTR's VaporSep membrane process that is utilized for hydrocarbon recovery in the petrochemical, refining, and natural gas industries. MTR's process is best suited to streams with higher VOC concentrations such as those found in industrial applications.

Competing Technologies

The baseline technology for treatment of VOC-laden off-gasses, with concentrations greater than 50 ppm is thermal/catalytic oxidation. Activated carbon is widely used for VOC concentrations less than 50 ppm and is therefore not in direct competition with MTRs membrane separation technology. A brief comparison of thermal/catalytic oxidation and activated carbon treatment is provided below:

Thermal/catalytic oxidation destroys VOCs while activated carbon removes VOCs by adsorption. Each technology has advantages and disadvantages that affect application. Advantages and disadvantages of each technology are listed in Table 1 below:

Table 1: Comparison of activated carbon and thermal/catalytic oxidation

Thermal/Catalytic Oxidation System	
Advantages	**Disadvantages**
• Destroys VOCs • Cost effective for higher VOC concentrations • Low maintenance	• Higher capital cost • Some thermal/catalytic oxidation systems are not applicable to chlorinated VOCs • Certain chemicals present in off-gases can poison catalysts in catalytic systems • Acid gas scrubber may be required if halogenated compounds are present • Source of natural gas or propane required

Table 1 (continued): Comparison of activated carbon and thermal/catalytic oxidation

Activated Carbon	
Advantages	**Disadvantages**
• Low capital cost • Cost-effective for low VOC concentrations • Simple	• Operating cost increases with VOC concentration in off-gas • System must be monitored and carbon must be periodically changed-out • Spent activated carbon must be disposed as a hazardous waste or regenerated

A number of innovative technologies have been demonstrated at McClellan AFB for the treatment of VOCs in off-gasses. A complete list of these technologies is available at www.mcclellan.af.mil/EM/TECHNOLOGY/index.htm.

Patents/Commercialization/Sponsor

Development of the membrane system for recovery of VOCs from remediation off-gasses by MTR was funded by DOE's NETL through Contract No: DE-AR21-96MC3308. The project was demonstrated at the McClellan AFB NETTS. MTR has successfully commercialized the VaporSep membrane process that is utilized for hydrocarbon recovery in the petrochemical, refining, and natural gas industries. MTR holds the following patents related to the process: USP 4,553,983 and USP 5,089,033.

SECTION 5
COST

Methodology

The cost analysis presented here is a summary of a cost analysis developed by MTR for their Final Contract Report to NETL (MTR, 2000). The analysis includes a cost comparison of MTR's membrane separation technology to the baseline technology of catalytic oxidation with off-gas scrubbing. For comparison, costs for activated carbon adsorption are also provided. The cost analysis is based on a design flowrate of 500 scfm and considers various influent VOC concentrations.

The costs for the membrane separation technology are based on the 100-scfm system demonstrated at McClellan AFB, but are scaled-up to represent a system with a design capacity of 500 scfm. Basic assumptions for each technology being compared are provided in the following sub-section.

The operating costs for the membrane separation system are based on the assumption that the system operates at the design flowrate of 500 scfm. The cost estimates are best-case and do not consider the potential for decreased capacity that may result from the presence of CO_2, as experienced at the McClellan AFB demonstration. As discussed in the performance section, the presence of CO_2 at one to three percent results in a reduction in capacity by a factor of two to four. Therefore, the actual flowrate for a 500 scfm system may be reduced to 125 to 250 scfm under these conditions. The decreased cost effectiveness resulting from this reduction in capacity is addressed in the conclusion to this section.

Cost Analysis

MTR Membrane Separation System

The capital costs for a membrane separation system with a design capacity of 500 scfm, and the capability to reduces the VOC concentration from 5,000 ppm to 10 ppm are provided in Table 2. This table lists the costs of the main components and includes the engineering and fabrication costs, and manufacturer's profit. The estimated total capital cost for a 500 scfm, skid mounted, turn-key system is $660,000.

Table 2. Membrane separation system capital cost breakdown

Cost Component	**Cost**
Membrane Modules	$70,000
Module Pressure Vessels	$40,000
Screw Compressor	$40,000
Liquid Ring Pump	$73,000
Condenser/chiller	$27,000
Water Separation System	$10,000
Programmable logic controller	$10,000
Skid, piping, valving	$60,000
System engineering, fabrication, and profit	$330,000
Total	**$660,000**

Operation and maintenance (O&M) costs for the 500-scfm membrane separation system are presented in Table 3. The membrane replacement costs are based on a three-year membrane life. This lifetime has been demonstrated for MTR membranes used in commercial system in the chemical industry.

Table 3. Membrane separation system O&M costs

Cost Component	Cost
Capital Depreciation (20%/yr)	$132,000
Module Replacement	$27,500
Maintenance and Labor	$50,000
Energy ($0.07/kWh)	$250,000
Waste Disposal $1.25/kg	$215,000
Total Processing Cost per Year	**$675,000**
Total Processing Cost per Month	**$56,000**

MTR calculated O&M costs for the membrane separation system based on various influent VOC concentrations. This information is presented in Table 4. The primary cost component that increases with VOC concentration is disposal of the recovered liquid VOC.

Table 4. Membrane Separation O&M Costs as a function of influent VOC concentration

Influent VOC Concentration	Processing Cost per Month
100 ppm	$35,000
1,000 ppm	$41,000
5,000 ppm	$56,000
10,000 ppm	$60,000

Catalytic Oxidation

The cost information for a 500 scfm catalytic oxidation system (including scrubber) is based on information provided by McClellan AFB. The McClellan AFB utilizes an 800 scfm catalytic oxidation system, but also has cost quotes for a 400 scfm unit. For the purposes of this cost analysis, the costs (capital and operating) for a 500 scfm system were estimated by interpolating between the costs for an 800 scfm unit and a 400 scfm unit. Processing costs for catalytic oxidation are relatively independent of VOC concentration up to about 1,500 ppm at which point dilution air must be added to avoid potential melting of the catalyst.

- Capital Cost for 500 scfm system $280,000
- Monthly Operating Costs (based on capital depreciation of 20%/yr) $15,700

Activated Carbon Adsorption

Activated carbon adsorption is widely used for the treatment of off-gasses with low VOC concentrations and is very cost effective for this application. Membrane Separation Technology is designed for treatment of off-gasses with higher VOC concentrations; therefore, is not in direct competition with activated carbon. For reference, activated carbon treatment is included in the cost comparison. Two different costs are provided for activated carbon adsorption; one for off-site regeneration and one for on-site steam regeneration. On-site regeneration is more cost effective than off-site regeneration as VOC concentrations increase.

For this cost analysis the cost for off-site carbon regeneration was $2.50/kg. The costs for the on-site steam regeneration were based on a monthly system rental cost of $20,000/month plus disposal of VOC/water secondary waste at a cost of $1.25/kg.

Cost Comparison

In Figure 6, O&M costs for MTR's membrane separation technology, catalytic oxidation, and activated carbon adsorption are compared with respect to various influent VOC concentrations. The Monthly processing costs include capital depreciation cost or equipment rental costs. Key data points from Figure 6 are provided in Table 5. As evident in the figure, activated carbon is most cost effective for VOC concentrations below 50 ppm. Catalytic oxidation becomes the most cost effective technology at concentrations above 50 ppm. The membrane technology is more cost effective than activated carbon at concentrations above 400 ppm, but is not as cost effective as catalytic oxidation.

Table 5. Comparison or processing cost as a function of VOC concentration (from Fig. 6)

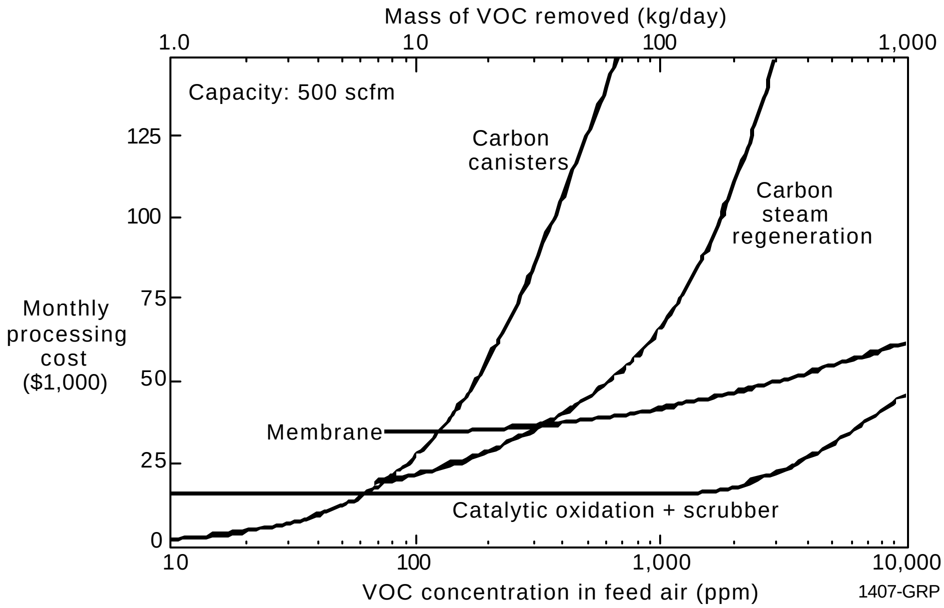

Figure 6. Processing costs as a function of VOC concentration in a 500-scfm air stream for a membrane system and for competing technologies.

	Monthly O&M Costs for Various Influent VOC Concentrations			
Technology	**50 ppm**	**100 ppm**	**500 ppm**	**1000 ppm**
Activated carbon	$13,000	$26,000	$130,000	-
Activated carbon with on-site steam regeneration	$13,000	$23,000	$50,000	$45,000
Catalytic oxidation with scrubber	$15,700	$15,700	$15,700	$15,700
Membrane separation technology	$35,000	$35,000	$35,000	$41,000

Cost Conclusions

The conclusion from the cost analysis is that the processing costs of the membrane separation system are higher than that of catalytic oxidation, which is the baseline technology for treatment of off-gas containing high VOC concentrations. Catalytic oxidation followed by scrubbing is the most economical treatment technology for off-gasses containing VOC concentrations greater than 50 ppm.

The economic viability of MTR's technology is further hindered by the problems associated with the presence of CO_2 in the off-gas. Since the presence of CO_2 reduces the capacity of the membrane separation system, a much larger, more expensive system would be required to handle a given capacity. This would further increase the cost of the membrane system in comparison to catalytic oxidation, effectively pricing it out of competition.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

The membrane separation technology separates the VOCs from a contaminated air stream, producing three streams: a treated air stream, liquid-phase VOC, and a water stream. Each of these streams has regulatory considerations as described below.

- Treated air stream with less than 10 ppm VOCs;
  - regulated by Clean Air Act;
  - State and/or Local Air Permit typically required.
  - Discharge limits and monitoring requirements will be dictated by specific permit

- Liquid-phase VOC
  - this may be hazardous waste depending on contaminants present
  - RCRA or CERCLA regulations may apply
  - Handling, storage, transportation and disposal of this waste must be done in accordance with applicable Federal, state, and local regulations.

- Water stream with less than 1 ppm VOCs;
  - regulated by Clean Water Act;
  - National Pollution Discharge Elimination System (NPDES) permit would be required if discharge to surface water
  - An industrial discharge permit will likely be required if discharged to sanitary sewer.

During the demonstration at the McClellan AFB, the treated air stream exiting MTR's membrane separation system was directed through a catalytic oxidation unit. This is standard procedure for testing innovative technologies at the site. The McClellan AFB has an air permit for the catalytic oxidation system through the California Resources Board. Because the discharge from the membrane separation system was directed through the catalytic oxidation system, a separate air permit for the membrane separation system was not needed. The water stream generated by the membrane separation system was sent to an on-site wastewater treatment plant for further treatment. The liquid VOC stream was disposed as a hazardous waste through a commercial disposal vendor.

If the membrane separation technology is deployed at a Federal Government-owned site, a National Environmental Policy Act (NEPA) review would be required.

Safety, Risks, Benefits, and Community Reaction

MTR's membrane separation technology may benefit from the public's negative perception of open flame incineration technologies. The baseline technology, catalytic oxidation, destroys VOCs by a catalyzed thermal oxidation process that is a form of incineration. Incineration technologies tend to have a negative public perception due to the potential for toxic emissions. The membrane separation technology is unique in that the VOCs are separated and recovered as a liquid. Although the public may have little familiarity with MTR's membrane separation technology, it may benefit in this area from being an alternative to thermal incineration technologies.

SECTION 7
LESSONS LEARNED

Implementation Considerations/Technology Selection Considerations

The following factors should be considered prior to implementation of the membrane separation technology:

- MTR's membrane separation technology is designed for removal of VOCs from remediation off-gases present at high concentrations (greater than 100 ppm).

- The presence of CO_2 in SVE off-gasses was found to significantly reduce the capacity of the membrane separation system.

Technology Limitations and Needs for Future Development

The membrane separation technology proved to be capable of removing VOCs from remediation off-gasses to desired levels, but also experienced performance problems during the demonstration. From a cost perspective, the technology was not found to be cost effective compared to the baseline.

For the technology to be successful the following issues would need to be addressed:

- The reduced system capacity resulting from the presence of CO_2 must be addressed without adding complexity and cost to the technology.

- The mechanical system failures with the condenser and liquid ring pump that resulted in oil and water fouling of the membranes must be resolved.

- The cost of the technology must be lowered to compete with the baseline technology, catalytic oxidation. The technology was found to be too expensive under the best case scenario, not considering the performance issues described above.

APPENDIX A
REFERENCES

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APPENDIX B

ACRONYMS AND ABBREVIATIONS

CO_2	Carbon Dioxide
DOE	Department of Energy
kWh	kilowatt-hour
MTR	Membrane Technology Research, Inc.
NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
NETTS	National Environmental Technology Test Site
NPDES	National Pollution Discharge Elimination System
ppm	parts per million
scfm	standard cubic foot per minute
SEDRP	Strategic Environmental Research and Development Program
VOC	Volatile Organic Compound