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Demonstration of Carbon Adsorption Technology for Petroleum Dry Cleaning Plants

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DEMONSTRATION OF CARBON ADSORPTION TECHNOLOGY FOR PETROLEUM DRY CLEANING PLANTS

by

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Contract No. 68-03-2560

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OFFICE OF RESEARCH AND DEVELOPMENT
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DISCLAIMER

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This study was undertaken to demonstrate the technical feasibility of applying carbon adsorption technology to control petroleum solvent vapors emitted from the dryer exhaust of an industrial dry cleaning establishment. In addition to reducing dryer emissions by 95 per cent, the activated-carbon adsorption system was effective in recovering valuable solvents which otherwise would be emitted to the atmosphere.

This information will be of value both to the EPA's regulatory program (Office of Air Quality Planning and Standards) and to the industry itself.

For further information concerning this subject, the Industrial Pollution Control Division should be contacted.

David G. Stephan
Director
Industrial Environmental Research Laboratory
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ABSTRACT

A carbon adsorption system was designed and installed on the exhaust outlet from a dryer at an industrial dry cleaning plant utilizing Stoddard solvent for cleaning purposes. Selected design and operating parameters were varied to determine their effect on annualized operating costs and system performance. After optimization, the carbon adsorber acheived a demonstrated efficiency in reducing hydrocarbon emissions of 95 percent. Annualized operating costs were determined to be $27,000, with a resulting cost effectiveness of $560/megagram ($510/ton).

This report was submitted in fulfillment of Contract No. 68-03-2560, Task No. T5005 by the Environmental Engineering Division of TRW, Inc., under the sponsorship of the Industrial Environmental Research Laboratory of the U.S. Environmental Protection Agency. This report covers a period from October 1977 to April 1979, and work was completed as of April 1979.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

ASTM	-- American Society for Testing and Materials
Btu	-- British thermal unit
^{o}C	-- degrees Celsius
cm	-- centimeter
EP	-- end point
EPA	-- Environmental Protection Agency
^{o}F	-- degrees Fahrenheit
FID	-- flame ionization detector
f.s.	-- full scale
ft	-- foot
ft^2	-- square foot
ft^3	-- cubic foot
gal	-- gallon
h	-- hour
HC	-- hydrocarbon
hp	-- horsepower
IBP	-- initial boiling point
IERL	-- Industrial Environmental Research Laboratory
IFI	-- International Fabricare Institute
IIL	-- Institute of Industrial Launderers
in	-- inch
J	-- joule
kg	-- kilogram
kWh	-- kilowatt-hour
l	-- liter
m	-- meter
m^2	-- square meter
m^3	-- cubic meter
mg	-- milligram
Mg	-- megagram
min	-- minute
MTZ	-- mass transfer zone
MW	-- megawatt
OSHA	-- Occupational Safety and Health Administration
ppm	-- parts per million
psig	-- pounds per square inch (gauge)
scfm	-- standard cubic feet per minute
sec	-- second
TFE	-- TFE Teflon
VOC	-- volatile organic compound
yr	-- year

SYMBOLS

Br	-- bromine
C_{12}	-- carbon 12 fraction
C_{13}	-- carbon 13 fraction
C_{14}	-- carbon 14 fraction
C_{15}	-- carbon 15 fraction
C_{16}	-- carbon 16 fraction
C_{17}	-- carbon 17 fraction
C_3H_8	-- propane

ACKNOWLEDGMENTS

The cooperation of Valley Industrial Services of Anaheim, California, Mr. George Butcher, Vice President of Operations and Mr. Dennis E. Leo, Vice President-General Manager, is gratefully acknowledged. Their participation by providing a host site and their support contributed greatly to the success of this demonstration project.

SECTION 1

EXECUTIVE SUMMARY

The Environmental Protection Agency (EPA) is investigating the feasibility of establishing emission standards for volatile organic compounds (VOC) from petroleum solvent dry cleaning establishments. Emission control technologies for these sources had not been successfully demonstrated in this country. Because of EPA and industry concerns, a program was developed to determine the effectiveness of carbon adsorption in controlling VOC emissions. This consisted of fitting a prototype carbon adsorption unit to the dryer exhaust of an industrial dry cleaner (petroleum solvent); operating the system to collect performance data; and evaluating the economics of operation at this establishment.

TRW Environmental Engineering Division, under contract to EPA-IERL, provided all necessary services to specify, procure, install, test, and evaluate the demonstration carbon adsorption unit. Valley Industrial Services of Anaheim, California, was selected as the host site, and carbon adsorbers were purchased from VIC Manufacturing Company of Minneapolis, Minnesota.

The carbon adsorber system was initially operated in strict compliance with the recommendations and instructions of the adsorber manufacturer and his field representatives. Early in this test period, it became apparent that the adsorption system had been overdesigned, resulting in removal efficiencies far in excess of the specified performance guarantee of 90 percent solvent removal on a 24-h average. The test program was, therefore, amended to include an evaluation of changes to the design and operating procedures for the carbon adsorption system. Various design parameters were modified to determine their effect on the performance and cost of the adsorption system. From these studies, an optimized system was established for use in evaluating the performance, cost, and cost effectiveness of utilizing carbon adsorption technology for the reduction of VOC emissions from petroleum dry cleaning plants.

The host dry cleaning plant is a large, industrial facility utilizing a 180 kg (400 lb) dryer to process approximately 1588 kg (3500 lb) of articles per day. This throughput represents about 50 percent of the 8-h capacity of the dry cleaning dryer. Underutilization of this nature is commonplace in the industry. Data were, therefore, developed using the test program to determine the effect of the different utilization rates on the various parameters under evaluation.

The hydrocarbon emission reduction efficiency for the optimized design (applied to the dryer exhaust) was 95 percent, and varied from 93 percent for a plant with 100 percent utilization to 97 percent at 25 percent utilization. Capital costs for this system, including site preparation and equipment installation, are estimated at $128,000 (mid-1978 dollars). Cost effectiveness, defined as the annual operating cost divided by the quantity of emission reduction, is a function of equipment utilization rates, and additionally exhibits a strong dependence on the market value of the recovered solvent. A value of $0.16/l ($0.61/gal) was assumed for the basic analysis, but the effect of increases in petroleum costs on annualized operating costs was investigated. The cost effectiveness of the optimized design was $560/Mg ($510/ton), and was estimated as $1,090/Mg ($980/ton) and $220/Mg ($200/ton) for 25 percent and 100 percent utilization, respectively. When the value of Stoddard solvent reaches $0.60/l ($2.30/gal), the optimized system (50 percent utilization) will have zero annual operating costs, neglecting the rise in other operating expenses.

The results of this project demonstrate the technical feasibility of applying carbon adsorption technology to reduce the emission of hydrocarbon solvents from the dryer exhausts at petroleum solvent dry cleaning plants. The cost effectiveness of this technique, $560/Mg ($510/ton), is expected to drop significantly as the value of the reclaimed solvent, a petroleum distillate, increases. Even at the present cost effectiveness, carbon adsorption is economically comparable with the cost of emission reduction required in other industries. An additional benefit, provided by the application of carbon adsorption technology to the petroleum dry cleaning industry, is the reduction in overall consumption of petroleum products by these plants. The demonstration plant recovered solvent at a rate of 61,000 l (16,000 gal) per year which otherwise would have to be replaced with new solvent purchases.

SECTION 2

PROGRAM DESCRIPTION

The purpose of this program was to conduct a field demonstration of the technical feasibility and effectiveness of carbon adsorption in reducing hydrocarbon emissions from dry cleaning plants using petroleum solvents. Its scope included the selection of a host site for the field demonstration; the selection, installation, and start-up of the emission control system; a period of operation during which the system was evaluated in the configuration specified by its manufacturer; and a period of operation during which the effects of several modifications to the system configuration were evaluated.

SITE SELECTION

A host site was sought at an industrial petroleum dry cleaning facility which could provide an exhaust gas stream from a 180 kg (400 lb) dryer of 3.7 m^3/sec (at 0°C) (8,400 scfm) with up to 10,000 ppm of solvent (measured as propane).

Because of the large number of potential sites in the country, two industry trade associations (Institute of Industrial Launderers (IIL) and International Fabricare Institute (IFI)) were consulted in the selection of candidate establishments. In mid-November 1977, TRW met with members of IIL, IFI, the Office of Air Quality Planning and Standards (OAQPS) and the Industrial Environmental Research Laboratory (IERL) of the Environmental Protection Agency (EPA). The purpose of this meeting was the discussion of candidate sites and selection criteria along with other aspects of the task. The decision was made to perform the demonstration test in Southern California. Because of the mild weather in this area, the demonstration unit could be installed out-of-doors, thus eliminating the need for plant floor space and the requirement of protecting the equipment from inclement weather. The decision to use the exhaust from a 180 kg (400 lb) dryer was made with the knowledge that large industrial dry cleaners use this machine size and on the assumption that the test results could be scaled down to lesser capacity dryers.

Based on these ground rules, the Institute of Industrial Launderers supplied a list of eight candidate sites. Early in December 1977, TRW along with IERL and IIL made a preliminary visit to these locations, using the following screening criteria:

1. Availability of space for the demo unit and instrument trailer.

2. Location of the dryer in relation to demo unit space; e.g., a dryer in the center of a plant precludes its use since the exhaust ducting run would be excessive.

3. The attitude of the operator, including technical qualifications and housekeeping.

4. The availability of a steam source, i.e., 0.4 MW (40 boiler horsepower) is required. Other utilities are not constraining.

5. The type and condition of the dryer.

6. The products of the facility.

7. Proximity to TRW's Redondo Beach facility to minimize travel costs.

Photographs of each candidate site were made to document general layouts.

In mid-December 1977, the working group again met to present the general status of the task. At this time, the candidate site list was reduced to four, based on the screening process. From the four, Valley Industrial Services of Anaheim was chosen as the host site for the demonstration project for the following reasons:

1. The demonstration unit and instrument trailer could be located in the parking lot of the plant, near the exhaust duct of the dryer;

2. Valley's operating procedures and housekeeping are excellent;

3. The dryer used at Valley is typical for a large industrial petroleum dry cleaning establishment; and

4. Valley is within one hour's drive of TRW's Redondo Beach complex.

SITE DEVELOPMENT

A survey of domestic manufacturers of commercially available carbon adsorption units resulted in the identification of five potential suppliers who could provide systems for this application. Pertinent specifications for the carbon adsorption system were:

1. Inlet concentration <10,000 ppm (measured as propane).

2. Inlet temperature <77°C (170°F) at dryer exit.

3. Inlet flow <3.7 m^3/sec at 0°C (8,400 scfm).

4. Exhaust concentration <1,000 ppm (measured as propane).

5. Adsorbers capable of having carbon samples removed and the carbon bed changed without major disassembly.

6. Equipment must conform to all health and safety requirements of NFPA, local fire codes, all local regulations, and applicable OSHA guidelines.

The potential suppliers were asked to quote on this carbon adsorption system. Two quotations were received and reviewed for technical acceptance. Both were found to demonstrate the necessary technical and production capabilities to deliver the system in conformance with the design specifications. VIC Manufacturing Company was chosen as the equipment supplier on the basis of cost and delivery.

Three installation contractors who have had experience with carbon adsorption systems were contacted to provide quotations for the installation of the emissions control system, including ancillary equipment such as a boiler and cooling tower. A personal visit was made to each of these organizations to hold a detailed technical review meeting. This was done to ensure each contractor's understanding of the technical specifications required. Bids were evaluated on the basis of cost, related experience, and ability to complete the installation in the scheduled time frame. The Sam Gerber Company of Los Angeles was selected as the installation contractor.

The engineering design of the exhaust gas transport system was performed by TRW. TRW provided additional field supervision for the installation of all equipment and hardware. Figure 2-1 depicts the site arrangement of the equipment for the demonstration program.

OPERATION AS DESIGNED

After initial start-up, the carbon adsorption system was operated for 18 weeks, during which time all equipment was operated as specified by VIC Manufacturing Company, the carbon adsorber manufacturer. Test data were taken during this period to obtain operating data for an "off-the-shelf" system.

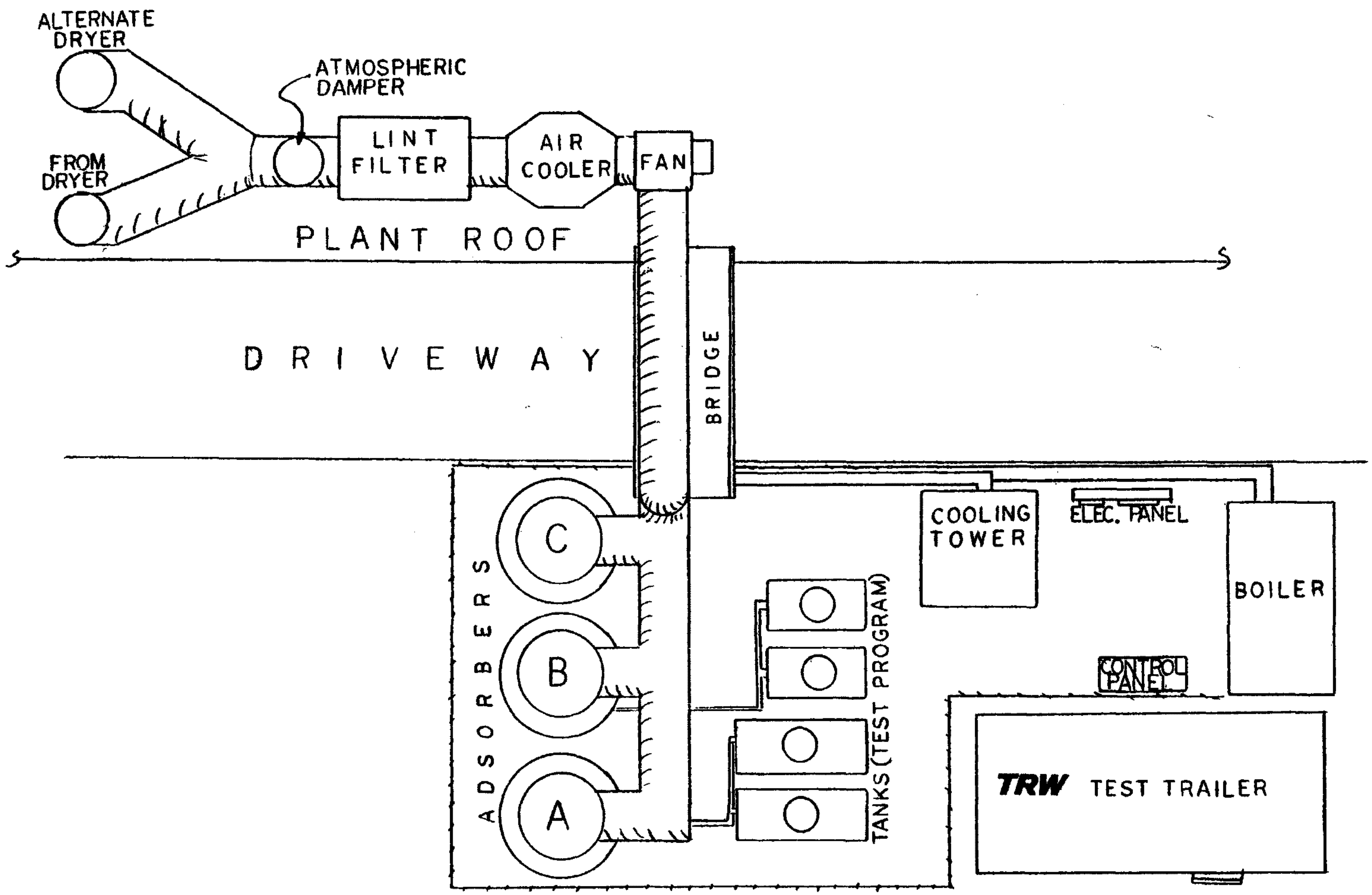

Figure 2-1. Physical layout carbon adsorption system.

OPTIMIZATION STUDIES

During the initial phase of operation, it became apparent that the carbon adsorption system was overdesigned with respect to the actual requirements for this facility. This was determined when the time-weighted concentration of solvent in the exhaust stream from the dryer was measured to be 2,100 ppm (as propane), not 10,000 ppm as designed. Also, the average exhaust gas flow rate to the adsorption system was measured to be 20 percent less than the specified design flow rate of 3.7 m^3/sec (8,400 scfm). Consequently, six design parameters were modified to determine their effect on the performance and cost of the adsorption system. From these studies, an optimized system was established for use in evaluating the performance, cost, and cost effectivness of carbon adsorption for hydrocarbon emissions reduction from petroleum dry cleaning plants. The six design modifications were as follows:

- The lint filter was modified to increase its surface area.
- The blower and adsorber controls were modified to allow the blower to cycle on and off with the dryer instead of operating continuously.
- The operation of the carbon adsorbers was modified by 1) operating with only two adsorbers; and 2) desorbing each adsorber only once a day.
- Carbon breakthrough tests were run to determine the amount of excess carbon in the adsorbers.
- The duration of the desorption cycle was altered to determine the minimum desorption time necessary for proper operation of the adsorption system.
- The cooling water flow to the air cooler was reduced in steps until it was completely eliminated. This study determined the minimum performance and size of any air cooler required for temperature reduction.

SECTION 3

PROCESS DESCRIPTION

VALLEY INDUSTRIAL SERVICES

Valley Industrial Services is a large industrial launderer and dry cleaner, providing uniform services, shop towels, fender covers, dust mops, and floor mats to establishments in the Los Angeles area. Valley dry cleans approximately 450,000 kg (1,000,000 lb) of soiled articles a year; comprised of 85 percent uniform pants and 15 percent fender covers.

Valley's dry cleaning operation utilizes Stoddard solvent (a petroleum-based solvent) as a cleaning agent. Figure 3-1 illustrates the design and interconnection of the significant solvent-containing equipment. The washer-extractor is a 230 kg (500 lb) unit manufactured by Washex. The cycle time for the washer-extractor is approximately 40 min, and Valley runs an average of seven loads per day. The dryer is a 180 kg(400 lb) unit manufactured by Challenge-Cook. Valley Industrial Services is currently operating the dryer with 110 kg (250 lb) loads which require a cycle time of approximately 20 min. In addition, Valley has two solvent stills, each with a 1890 l (500 gal) capacity, manufactured by Washex.

Solvent is pumped from the underground solvent storage tank into the washer. Water and other dry cleaning additives are automatically metered into the washer during certain sequences of the washing cycle. Solvent is discharged from the washer-extractor into a used solvent holding tank. This tank is provided to accumulate surges in the solvent discharge rate, allowing the solvent stills to operate on a continuous feed basis. Distilled solvent is returned to the underground solvent storage tank. Floor and equipment vents are provided to remove fugitive solvent from the workplace and discharge it to the atmosphere. The dryer is a non-recovery type which continuously vents the dryer exhaust to the atmosphere.

Valley Industrial Services relies on manual techniques to load and transfer articles to dry cleaning equipment. Figure 3-2 illustrates this operation. Soiled articles are placed in a cart and weighed to control each load at approximately 230 kg (500 lb). This cart is then pushed to the washer-extractor where its load is put into the machine. At the conclusion of the extraction cycle, the clothes are then placed into two carts, each containing equal weights. One cart is loaded into

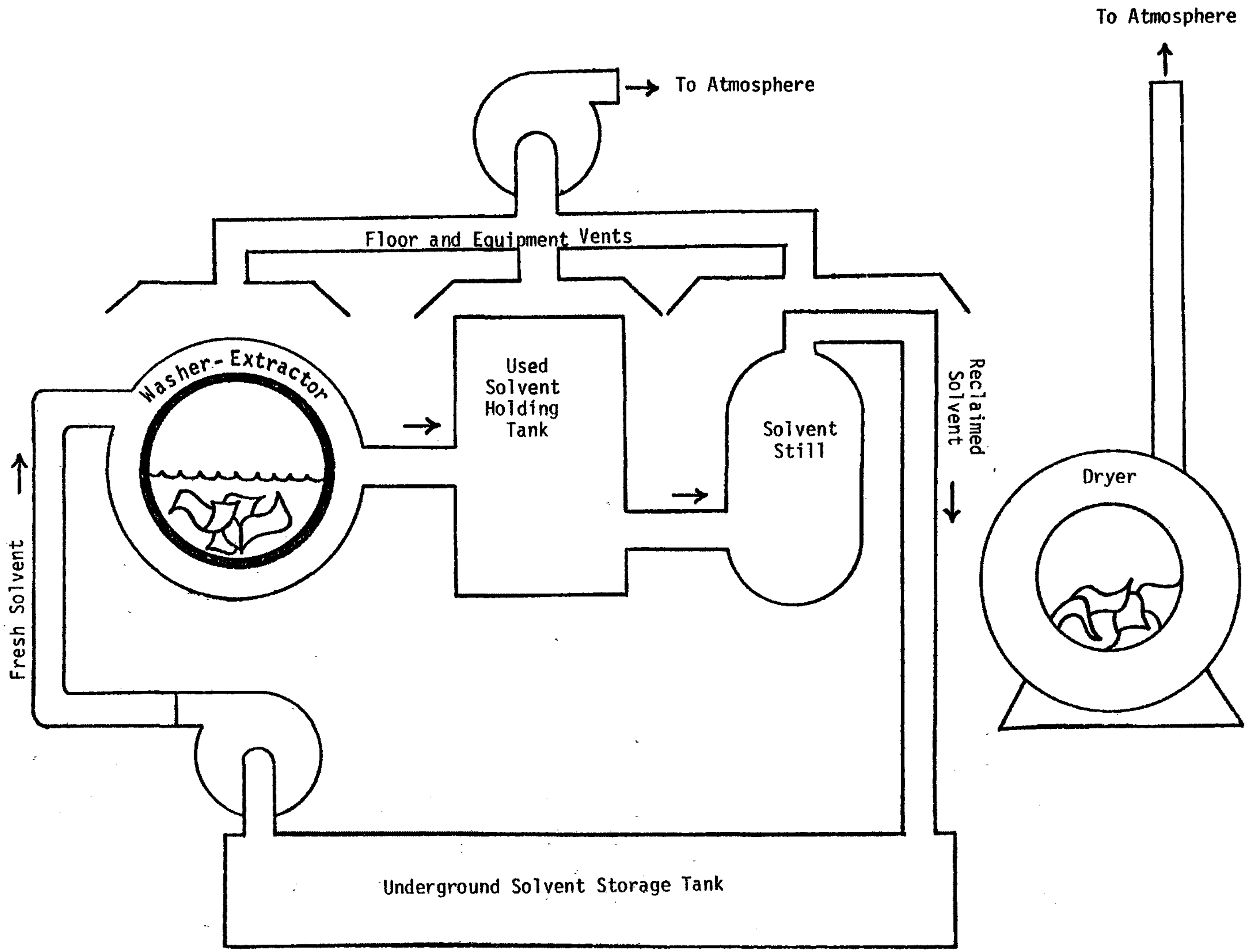

Figure 3-1. Dry cleaning equipment containing solvent.

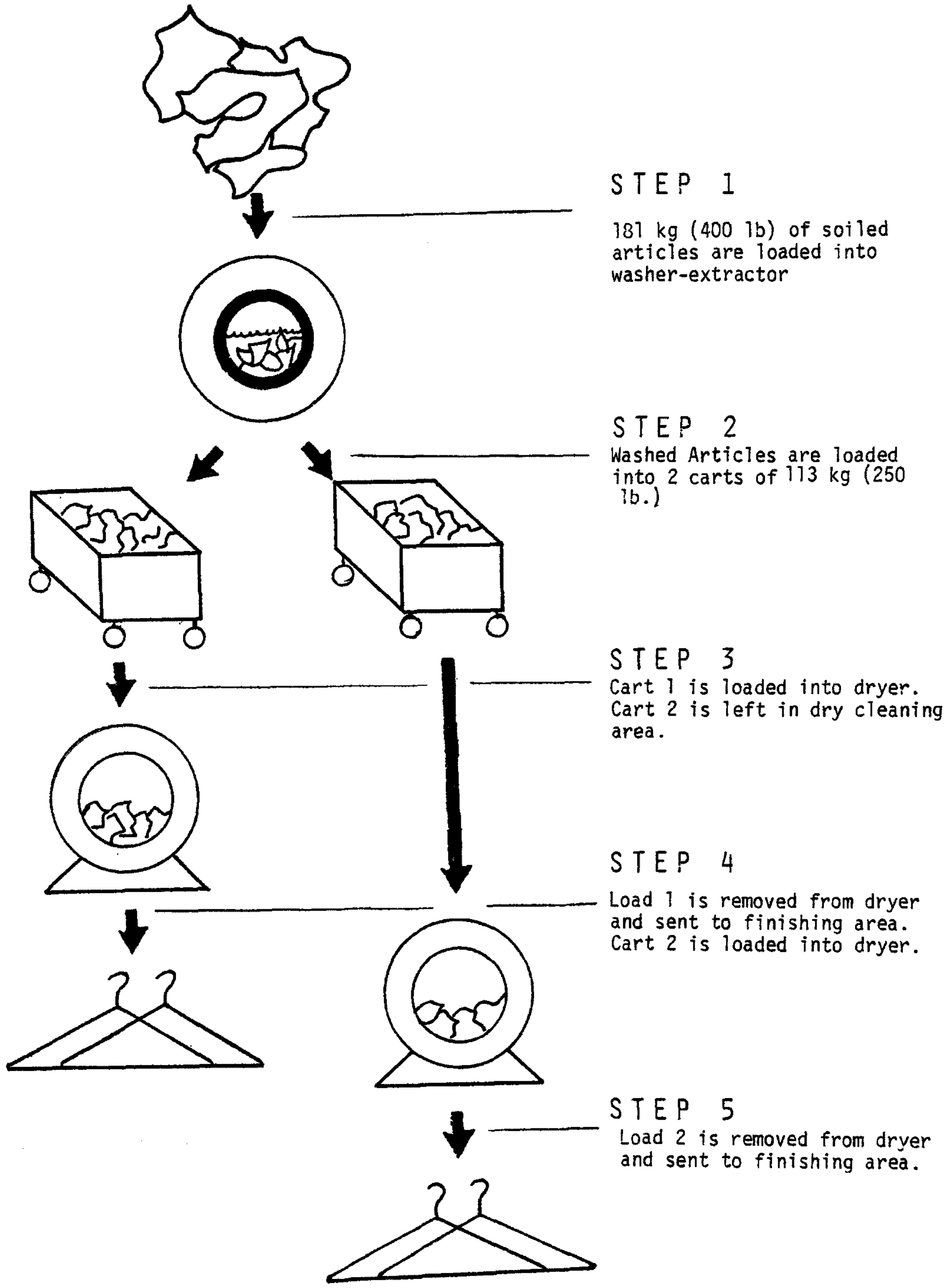

Figure 3-2. Operating procedure.

the dryer, while the second cart is left standing in the dry cleaning area. At the conclusion of the drying cycle, the dryer is emptied and the second cart is loaded into the dryer.

CARBON ADSORPTION SYSTEM

The carbon adsorption system connects with the existing plant equipment where the dryer exhaust duct penetrates the plant roof. The main components of the carbon adsorption system are depicted in Figure 3-3.

Original System Configuration

The exhaust gas from the dryer is first passed through a lint filter which utilizes a cotton filter bag with a surface area of approximately 1.0 m^2 (11 ft^2). It is then passed through an air cooler which is chilled with cooling water to reduce the exhaust gas stream temperature from 63°C (145°F) to approximately 38°C (100°F). A 0.5 MW (50 hp) blower then forces the exhaust stream downward through the carbon canisters. Three 2.4m (8 ft) diameter canisters are used, each containing 1800 kg (4000 lb) of petroleum-based carbon. As supplied, the operation of the unit is as follows: two tanks are in the adsorb mode whereby they are connected to the outlet of the blower, while the third tank is in a desorb mode. This arrangement lasts for approximately 1 hr, at which time the tank which had been desorbing is brought back to an adsorb mode and one of the tanks which had been adsorbing is desorbed (this tank is the one which had been in the adsorb mode the longest). This cycle is then repeated hourly.

During the desorption cycle, steam passes through the carbon bed in an upward path. After leaving the adsorber, it is introduced into a water-cooled condenser where the steam and stripped Stoddard solvent are condensed and the two-phase liquid stream is collected in a decanter. The organic and water phases are separated and individually drawn off. The recovered solvent is directed to a holding tank, while the wastewater stream is discarded into the city sewer system. Analysis of the wastewater stream shows the solvent content to be less than 0.3 ppm.

Modified System Configuration

During the optimization studies, several modified system configurations were studied, as outlined in Section 2. The final optimized system configuration was similar to the original configuration, except that only two adsorbers, which were desorbed only once each day, were used and no air cooler was utilized.

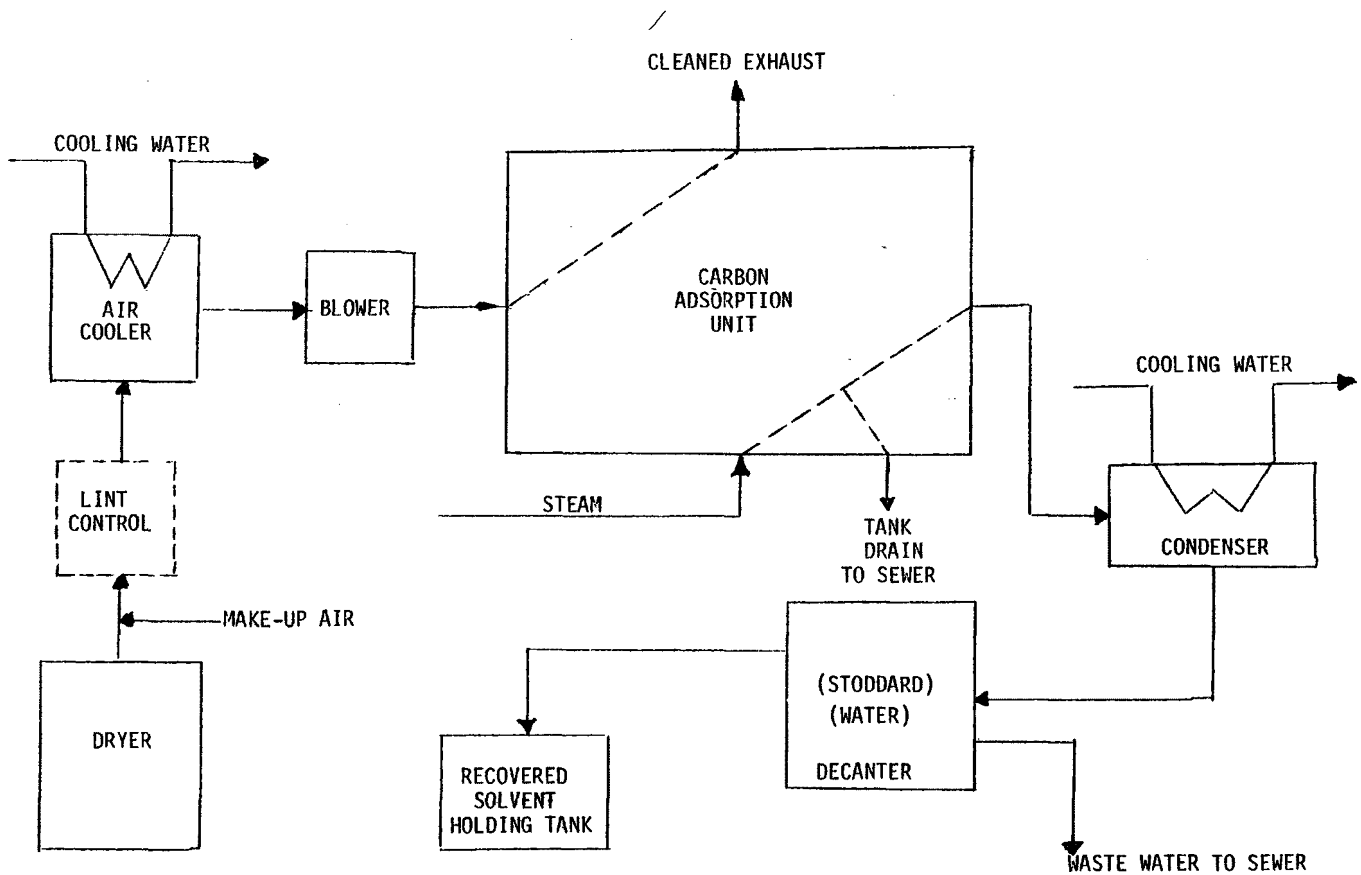

Figure 3-3. Block diagram of carbon adsorption system.

SECTION 4

TEST METHODS

This chapter explains the test and calibration procedures used by TRW during the carbon adsorption test program.

PRE-OPTIMIZATION TEST PROGRAM

Methods Summary

Hydrocarbon Concentration Determination--

Continuous sampling of the gas streams to and from the carbon adsorption unit was accomplished using two Beckman 400 flame ionization detectors (FID). Sample lines to both detectors were 1 cm (3/8") Teflon (TFE), heated to 93°C (200°F) (using resistance heating) to prevent sample degradation. A fine particle filtration system for each sample line was used to prevent contamination of the FIDs. In addition, an in-line condenser was used to remove water vapor from the sample gas stream.

Combustion air for the two FIDs consisted of certified hydrocarbon-free (<1.0 ppm) zero gas.

Calibration of the FIDs consisted of introducing the following known concentration gases into the respective analyzers:

Inlet	Outlet
zero gas (<1.0 ppm HC)	zero gas (<1.0 ppm HC)
11,000 ppm C_3H_8	1,060 ppm C_3H_8

A dual-pen strip chart recorder was used to continuously record the output of the FIDs during the working hours of the carbon adsorption unit.

Exhaust Gas Flow Rate Determination--

The inlet gas stream flow rate was continuously monitored using a hot-wire anemometer; the output of the anemometer was electronically linearized to give a direct signal output corresponding to the gas stream velocity.

The relationship of this velocity to the average flow was determined by measuring the gas stream flow rate using EPA Method 2 (40 FR 23060, August 18, 1977), and comparing this to the average measured velocity from the anemometer.

Temperature Measurements of Various Streams--

The temperatures of the various liquid and gas streams were monitored continuously using J-type (iron-constantan) thermocouples.

Electricity Consumption--

Two kilowatt-hour meters were used to determine: (1) the total electrical power usage of the carbon adsorption unit plus the instrument trailer and (2) the electrical power consumption of just the instrument trailer. Thus, by determining the difference between (1) and (2), the electrical power usage of the carbon adsorption unit was determined.

Natural Gas Consumption--

A displacement gas totalizer was used to determine the natural gas consumption rate.

Water Usage--

Five water meters were used to determine the following:

1. Water consumption of boiler.

2. Water makeup needs of cooling tower.

3. Rate of decanted water discharged to sewer system.

4. Cooling water demand of air cooler.

5. Cooling water demand of condenser.

Steam Flow Rate to Adsorption Unit--

Steam flow was measured continuously using a permanently installed orifice meter.

Solvent Recovery Rate--

Recovered solvent was measured by collection in a holding tank and using a calibrated tank gauge to determine the quantity of recovered solvent.

Solvent Analysis--

Two composite solvent samples (one of recovered solvent and one of solvent introduced into the dry cleaning process) were made up by combining five equal-volume daily samples of the respective solvent into two separate weekly samples and both were then analyzed for the following:

1. Composition using a gas chromatograph (results were reported as percent C_{12}, percent C_{13}, percent C_{14} and C_{15}, percent C_{16}, and percent C_{17} or greater).

2. Flash point using ASTM test method D56, flash point by tag closed tester.

3. Distillation range using ASTM test method D86, distillation of petroleum solvents.

4. Kauri-Butanol value using ASTM test method D1133, Kauri-Butanol value of hydrocarbon solvents.

5. Acidity using ASTM test method D1093, acidity of distillate residues on hydrocarbon liquids.

6. Bromine number using ASTM test method D1159, bromine number of petroleum distillates and commercial aliphatic olefins by electrometric titration.

In addition, water concentrations in the recovered solvent were determined on a daily basis using the Karl Fisher determination (ASTM test method D1364, water in volatile solvents).

Solvent Concentration in Decanted Water and Bottom Drain--

A flow proportional weekly composite sample was made from the decanter water outlet and the bottom drain from the carbon adsorption unit. Solvent concentration of this sample was then determined by extraction and subsequent analysis using flame ionization.

Analysis of Carbon in Bed--

Samples were taken from the top, middle, and bottom of a carbon bed to determine carbon activity and retentivity. Carbon activity was measured using perchloroethylene adsorption at 21°C (70°F), while carbon retentivity was measured by air desorption at 21°C (70°F).

Sampling Positions and Frequencies of Sampling

The sampling positions for each parameter measured during the carbon adsorption pre-optimization test and the frequencies of sampling are given in Table 4-1.

OPTIMIZATION PROGRAM TEST PLAN

Evaluation Requirements

In order to determine the optimum operating design of the carbon adsorption system, the following criteria were employed:

Task 1 - Change of filter system.

Extent to which operating labor can be reduced.

Task 2 - Blower cycle alteration.

Electricity savings induced by less than full-time operation of the 0.5 MW (50 hp) blower.

TABLE 4-1. PRE-OPTIMIZATION PROGRAM SAMPLING POSITIONS AND FREQUENCIES OF SAMPLING

	Parameter to be measured	Sampling location	Frequency of sampling
1.	Inlet solvent concentration of exhaust gas	Between air cooler and carbon adsorption unit	Continuous
2.	Outlet solvent concentration of exhaust gas	Carbon adsorption unit vent	Continuous
3.	Exhaust gas flow rate to adsorber	Between air cooler and carbon adsorption unit	Every 2.5 min
4.	Temperature of exhuast gas to adsorber	Between air cooler and carbon adsorption unit	Every 2.5 min
5.	Electrical consumption of process	Main power line and power line to trailer	Kilowatt meter
6.	Natural gas consumption of process	Gas line to boiler	Gas totalizer
7.	Steam flow rate to adsorber	Inlet to adsorber	Continuous
8.	Steam temperature at inlet to adsorber	Inlet to adsorber	Every 2.5 min
9.	Water consumption of boiler	Water line to boiler	Flow totalizer
10.	Steam temperature at outlet of adsorber	Outlet of adsorber	Every 2.5 min
11.	Concentration of solvent in water phase stream of decanter	Between decanter and sewer entrance	Weekly composite sample

(continued)

TABLE 4-1. (continued)

	Parameter to be measured	Sampling location	Frequency of sampling
12.	Quantity of recovered solvent	Solvent holding tank	Daily measurement
13.	Quality of recovered solvent	Solvent holding tank	Weekly composite sample
14.	Carbon analysis	Grab sample of carbon out of tank	Three times: a. New carbon b. Middle of test period c. End of test period
15.	Inlet cooling water temperature of air cooler	Before air cooler	Every 2.5 min
16.	Outlet cooling water temperature of air cooler	After air cooler	Every 2.5 min
17.	Inlet cooling water temperature of condenser	Before condenser	Every 2.5 min
18.	Outlet cooling water temperature of condenser	After condenser	Every 2.5 min
19.	Quantity of decanted water	Waste line to sewer	Flow totalizer
20.	Water consumption of air cooler	Water line to air cooler	Flow totalizer
21.	Water consumption of condenser	Water line to condenser	Flow totalizer
22.	Quality of raw solvent	Solvent feed tank	Weekly composite sample

Task 3 - Adsorption/desorption alteration.

Reduction in operating labor.
Reduction in capital costs.
Reduction in steam consumption rate.
Reduction in gas and electricity consumption rates.
Reduction in cooling water consumption rate.

Task 4 - Carbon bed depth adjustment.

Reduction in hydrocarbon emission rate.
Reduced design capital requirements.

Task 5 - Desorption alteration.

Effect on quality of recovered solvent.
Reduction in quantity of steam per quantity of recovered solvent.
Reduction in total steam consumption.

Task 6 - Air cooler reduction.

Change in inlet gas temperature to beds.
Reduced design capital requirements.
Reduced water demand.

Test Elements

Test Parameters--

To fulfill the objectives of the Optimization Program, the following test parameters were monitored:

1. Solvent concentration of the inlet gas stream to the adsorber.
2. Solvent concentration of the outlet exhaust gas stream from the adsorber.
3. Gas flow rate to the adsorber.
4. Temperature of gas to the adsorber.
5. Electrical consumption of the adsorption unit and the boiler.
6. Natural gas consumption of the boiler.
7. Steam flow rate to the adsorber.
8. Steam temperature to the adsorber.
9. Water consumption of the boiler.
10. Temperature of the desorb steam at carbon adsorber exit.
11. Temperature of bed during desorption.
12. Quantity of recovered solvent.
13. Analysis of recovered solvent for composition, flash point, impurities, distillation range, and Kauri-Butanol value.
14. Concentration of solvent in carbon samples.
15. Temperature of supply water to air cooler.
16. Temperature of exit water from air cooler.
17. Temperature of supply water to condenser.
18. Temperature of exit water from condenser.

19. TRW test operator's log, including number of dry cleaning cycles and corresponding total operating time on daily basis.
20. Machine operator's log listing dry, extracted, and clean weights of clothes.
21. Quantity of decanted water.
22. Water flow rate into air cooler.
23. Water flow rate into condenser.

Sampling Positions and Frequency--

Sampling positions for the various parameters to be measured as well as sampling frequencies are given in Table 4-2.

Test Methods

All test methods listed in the pre-optimization test program were used during the optimization test with one exception. A positive displacement flow meter was installed in the solvent return line with a measurement accuracy of ±1 percent. This superseded the calibrated tank gauge used in the pre-optimization study. No other measurement techniques were changed.

TABLE 4-2. OPTIMIZATION PROGRAM SAMPLING POSITIONS AND FREQUENCIES OF SAMPLING

Parameter to be measured	Sampling location	Frequency of sampling
1. Inlet solvent concentration of exhaust gas	Between air cooler and carbon adsorption unit	Continuous
2. Outlet solvent concentration of exhaust gas	Carbon adsorption unit vent	Continuous
3. Exhaust gas flow rate to adsorber	Between air cooler and carbon adsorption unit	Every 2.5 min
4. Temperature of exhaust gas to adsorber	Between air cooler and carbon adsorption unit	Every 2.5 min
5. Electrical consumption of process	Main power line and power line to trailer	Kilowatt meter
6. Natural gas consumption of process	Gas line to boiler	Gas totalizer
7. Steam flow rate to adsorber	Inlet to adsorber	Continuous
8. Steam temperature at inlet to adsorber	Inlet to adsorber	Every 2.5 min
9. Water consumption of boiler	Water line to boiler	Flow totalizer
10. Steam temperature at outlet of adsorber	Outlet of adsorber	Every 2.5 min
11. Carbon bed temperature	Bottom of carbon bed	Every 2.5 min

(continued)

TABLE 4-2. (continued)

Parameter to be measured	Sampling location	Frequency of sampling
12. Quantity of recovered solvent	Solvent line to holding tank	Flow totalizer
13. Quality of recovered solvent	Solvent holding tank	Three times a. End of task 3 b. End of task 4 c. End of task 6
14. Carbon analysis	Grab sample of carbon out of tank	Two times a. End of task 4 b. End of task 6
15. Inlet cooling water temperature of air cooler	Before air cooler	Every 2.5 min
16. Outlet cooling water temperature of air cooler	After air cooler	Every 2.5 min
17. Inlet cooling water temperature of condenser	Before condenser	Every 2.5 min
18. Outlet cooling water temperature of condenser	After condenser	Every 2.5 min
19. Quantity of decanted water	Waste line to sewer	Flow totalizer
20. Water consumption of air cooler	Water line to air cooler	Flow totalizer

(continued)

TABLE 4-2. (continued)

	Parameter to be measured	Sampling location	Frequency of sampling
21.	Water consumption of condenser	Water line to condenser	Flow totalizer
22.	Quality of raw solvent	Solvent feed tank	Weekly composite sample

SECTION 5

RESULTS AND CONCLUSIONS

SUMMARY OF RESULTS

The carbon adsorption system was initially designed to provide a level of control in excess of that which was specified for the demonstration program. This occurred because of two factors. First, because of the long lead time associated with the purchase and installation of the carbon adsorbers, specifications for the adsorption system were prepared prior to the final selection of the host site. Valley Industrial Services, the host site, has a dryer utilization of approximately 50 percent which results in a lower concentration of solvent in the exhaust gas reaching the adsorbers than what was originally anticipated. Second, Vic Manufacturing Company, the carbon adsorber supplier, responded to the specification requirement for a guaranteed 90 percent removal efficiency by including a significant amount of excess capacity to ensure that the carbon beds would not become overloaded.

This overdesign resulted in an emission control system which achieved a reduction in hydrocarbon emissions, after system equilibration, of 98.8 +0.5/-0.7 percent based on a daily average. The cost effectiveness of this design was $990/Mg ($900/ton).

A program was then initiated to modify the carbon adsorber system. The goal of this modification was to optimize the design of the carbon adsorbers for the specific requirements of the host site. These modifications included changes in both the size and complexity of the carbon adsorbers to reduce the capital costs, and in the operating procedures to reduce the operating costs.

The final optimized system produced a hydrocarbon emission reduction of 94.8 +2.0/-3.2 percent based on a daily average. The cost effectiveness of this design was $560/Mg ($510/ton).

The cost effectiveness figures presented above are highly dependent on the value of the recovered solvent. Stoddard solvent is a petroleum distillate and its value, therefore, rises proportionately with the cost of petroleum. A value of $0.16/l ($0.61/gal) was used to derive the cost effectiveness of this emission control system. This value is approximately equal to the cost of Stoddard to the host site in the fall of 1978, the time of the testing. When the value of Stoddard solvent reaches \$0.60/l (\$2.30/gal), the optimized system configuration will have zero annual operating costs, neglecting the rise in other operating expenses.

The cost effectiveness of the carbon adsorption system is also highly dependent on the utilization rate of the dry cleaning dryer, the principal source of solvent vapors. During the test program, Valley Industrial Services operated the dryer under test at 51 percent of its capacity, based on operations at the rated dryer load for an 8-h day, 5 days per week. Such underutilization appears to be commonplace in the dry cleaning industry. Calculations were performed to determine the cost effectiveness of the optimized carbon adsorption system resulting from variations in this rate of dryer utilization. At a utilization rate of 25 percent, the cost effectivness was \$1,090/Mg (\$980/ton), and at a utilization rate of 100 percent, the cost effectiveness was \$220/Mg (\$200/ton), also based on the \$0.16/l (\$0.61/gal) value for the recovered solvent.

Confirmation of the emission reduction efficiency was attempted by comparing the solvent mass flow rate out of the dryer with the quantity of recovered solvent. This analysis technique produced an indicated solvent recovery efficiency of 88.1 percent, but was subject to a considerable experimental error of +23/-17 percent.

The recovered solvent was analyzed and compared with fresh solvent for distillation range, acidity, Kauri-Butanol value, bromine number, flash point, and solvent composition. In all cases, the recovered solvent was found acceptable for reuse by the dry cleaning facility without requiring any additional purification.

OPTIMIZATION STUDIES

The carbon adsorption system was evaluated during a series of optimization studies from December 4, 1978, through March 23, 1979. The following six studies were conducted during this period:

1) Filter modification.
2) Blower cycle alteration.
3) Adsorption/desorption cycle alteration.
4) Carbon bed depth adjustment.
5) Desorption alteration.
6) Air cooler reduction.

This section summarizes the results of these studies and the respective effects on performance of the system.

Objectives

The objectives of each of the optimization studies are listed below:

1. Filter modification - The objective was to reduce the daily labor requirements associated with filter changing and cleaning.

2. Blower cycle alteration - The objective was to reduce the electricity consumption of the system.

3. Adsorption/desorption cycle alteration - The purpose was to reduce design capital requirements and operating costs of the system by removing one bed from operation and by operating the boiler only at the end of the day.

4. Carbon bed adjustment - The goal was to determine if some portion of the carbon could be removed from the beds in use, thereby reducing the design capital requirements of the system.

5. Desorption alteration - The purpose was to determine if operating costs could be reduced by altering the desorption parameters.

6. Air cooler reduction - The purpose was to determine if design capital requirements could be reduced by operating the system without a cooling system in the ductwork leading from the dryer to the carbon beds.

Results

This section describes the results of these optimization studies and also describes the "optimized system."

Filter Modification--

The original 1.0 m^2 (11 ft^2) cotton filter bag and its housing in the dryer exhaust ductwork were replaced with a 1.8 m^2 (19 ft^2) bag and housing. The new filter could be operated for an entire operating day without being changed. Approximately 30 min were required to change and clean a filter bag. The original system required three changes daily. The new filters, therefore, reduced the daily operating labor associated with filter changing and cleaning from 1.5 h to 0.5 h.

Blower Cycle Alteration--

The adsorption system was modified in such a way as to allow the 0.5 MW (50 hp) booster fan to be activated and deactivated by the dryer being tested, except when manually operating for desorption or other reasons. Previously, the blower was turned on in the morning with the rest of the system and off in the evening. It, therefore, ran continuously all day, regardless of whether or not the dryer was in operation.

There was some concern that the electrical modifications would actually result in an increase in electricity consumption due to the power surge required to activate the large blower. This was proven to be a false concern, however, since the modification resulted in a net decrease in electricity costs by 10 percent.

Adsorption/Desorption Cycle Alteration--

The adsorption system, as supplied by VIC Manufacturing, operated automatically on schedule where two beds were absorbing while a third was being desorbed. Every hour a cycle change occurred during which adsorb mode and a bed on the adsorb was switched to desorption. The net result of the cycle was that each bed was desorbed after 2 h of operation. This optimization test changed the operation to a schedule where two beds were in the adsorb mode for the entire day and were each desorbed for 1 h at the end of the day. The third carbon bed remained dormant for the duration of the program.

An initial indication of the unacceptability of this mode of operation would be the attainment of breakthrough during daily operations and a drastic decrease in adsorber efficiency. This phenomenon, which would be determined when the concentration of solvent in the exhaust stream began to rise dramatically from its normal "baseline" of 100 ppm, was not observed. Therefore, the system can be operated in the described manner making the third carbon bed unnecessary. For new systems, this can result in a reduction in capital costs. As discussed in the Carbon Bed Depth Adjustment section, this is independent of the utilization rate of the dryer involved in the test.

An additional benefit derived from this task was a reduction in operating costs resulting from a reduction in the natural gas consumption of the boiler. By operating the boiler for desorption only at the end of the day, as opposed to all day as designed, a reduction in gas consumption of 47 percent was achieved.

An associated reduction in capital costs is also achieved by operating the system in this manner. By desorbing only at the end of the day, when the laundry's process steam requirements are down, it is possible to desorb the beds with the existing plant steam system. This would negate the need for the additional boiler. Additionally, at the end of the day, the plant's cooling water system could be used to operate the carbon system condensers which are needed only during desorption. This, in conjunction with the air cooler reduction test to be described in the Air Cooler Reduction section, could eliminate the need for the auxiliary cooling tower presently installed with the system.

Carbon Bed Depth Adjustment--

This task involved two breakthrough tests during which the carbon adsorption system was operated without desorption until complete saturation of the carbon beds was obtained. In both tests, breakthrough began to occur after 14 dryer cycles and saturation occurred during the third day of consecutive adsorption. The beds were then steamed for 3 h each and after each test, approximately 445 l (118 gal) of solvent were recovered. The two tests were conducted several weeks apart in order to ensure that the beds had returned to equilibrium prior to the second test.

The depth of the mass transfer zone (MTZ) of the carbon beds was calculated by the following equation:[1]

$$MTZ = 0.8 \left(\frac{S_S - S_B}{S_B} \right)$$

where MTZ = Mass transfer zone depth (m)

S_S = quantity of solvent recovered at saturation (l)

S_B = quantity of solvent recovered at breakthrough (l)

0.8 = depth of carbon beds (m)

As previously mentioned, breakthrough began to occur with this system after 14 dryer cycles. The value S_B, therefore, was the average quantity of solvent recovered after days using 14 dryer loads.

The results of the breakthrough test showed an MTZ of 0.8 m (30 in). With this information, it was immediately obvious that no carbon could be removed from the beds without seriously affecting the system efficiency.

An additional result of the breakthrough tests was an analysis of the capacity of a two-bed carbon adsorption system versus the operating utilization of the Valley dry cleaning facility. Present operations average 14 dryer loads per day at 113 kg (250 lb) per load. This yields a total cleaning rate of 1582 kg (3420 lb) per day with 227 kg (500 lb) of solvent transferred from the dryer to the adsorber. Based on a dryer capacity of 181 kg (400 lb) per load and an operating maximum of 17 loads per an 8-h day, full utilization of the Valley dryer would process approximately 3077 kg (6770 lb) of clothes with 445 kg (980 lb) of solvent entering the adsorber. The dryer is, therefore, being operated at approximately 51 percent utilization. From the breakthrough analysis, it is estimated that approximately 480 kg (1060 lb) of solvent can be adsorbed before the emission reduction efficiency (Method 1) drops below the 90 percent level (see Figure 5-1). This is equal to 0.132 kg solvent per kg of carbon. On the basis of this information, it can be concluded that the existing two-bed system is of sufficient size to handle the emissions from the Valley dryer when 100 percent utilized. Figure 5-2 depicts the relationship between the dryer utilization and the emission reduction efficiency. Included in this figure is a representation of the estimated adsorber efficiency if 15 cm (6 in) of carbon were added to the beds. It is estimated that this addition, which could easily be accomplished with the existing carbon tanks, would add approximately 68 kg (150 lb) of adsorptive capacity to the beds. This would allow more dryer cycles to be adsorbed; however, the estimated impact upon the emission reduction efficiency would be negligible.

Desorption Alteration--

Steam rates were varied in order to obtain the optimum desorption parameters. The first step involved increasing the steam gauge pressure from 10.3×10^4 to 13.8×10^4 pascals (15 - 20 psig) in order to obtain

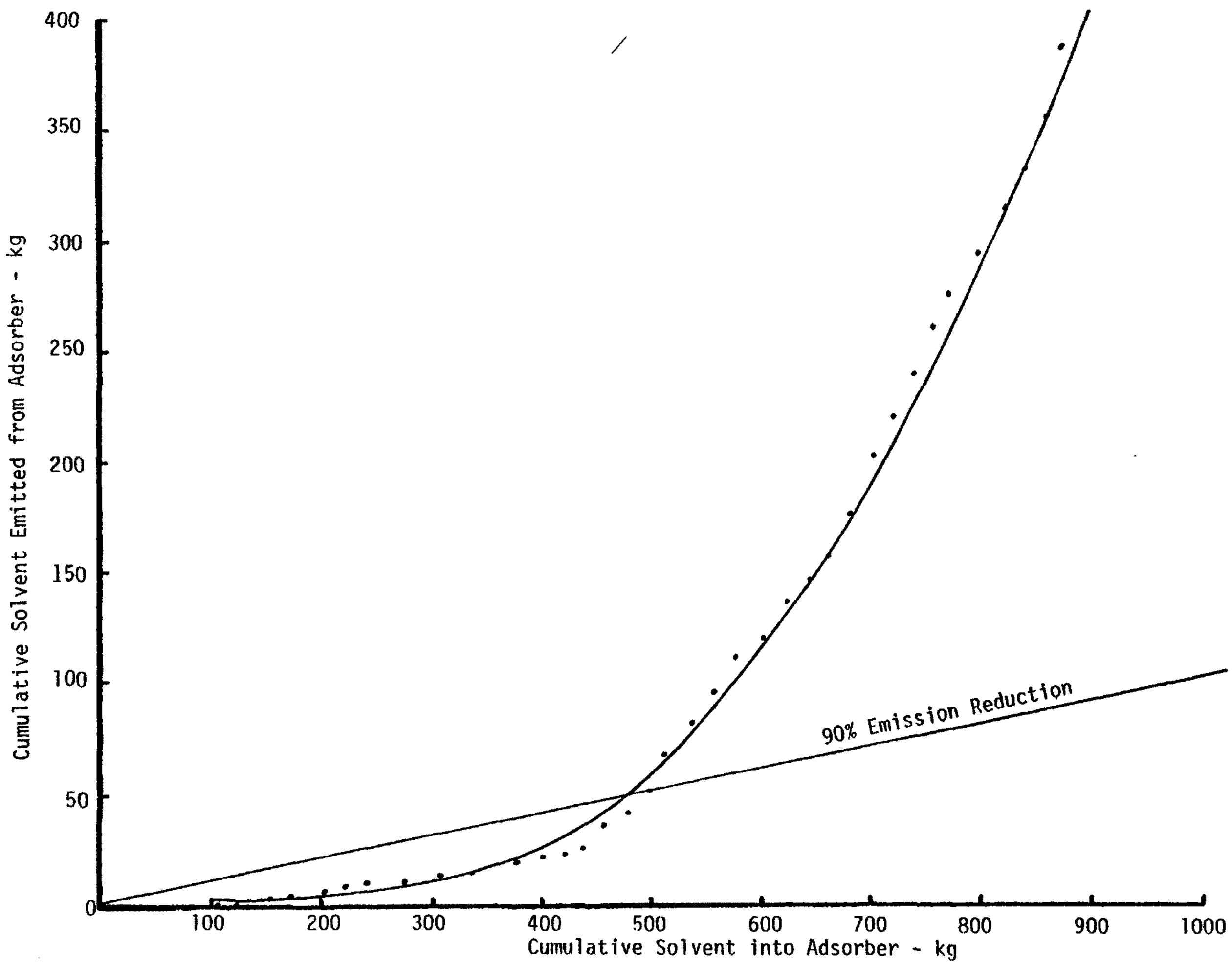

Figure 5-1. Breakthrough test: Cumulative inlet and outlet measurements.

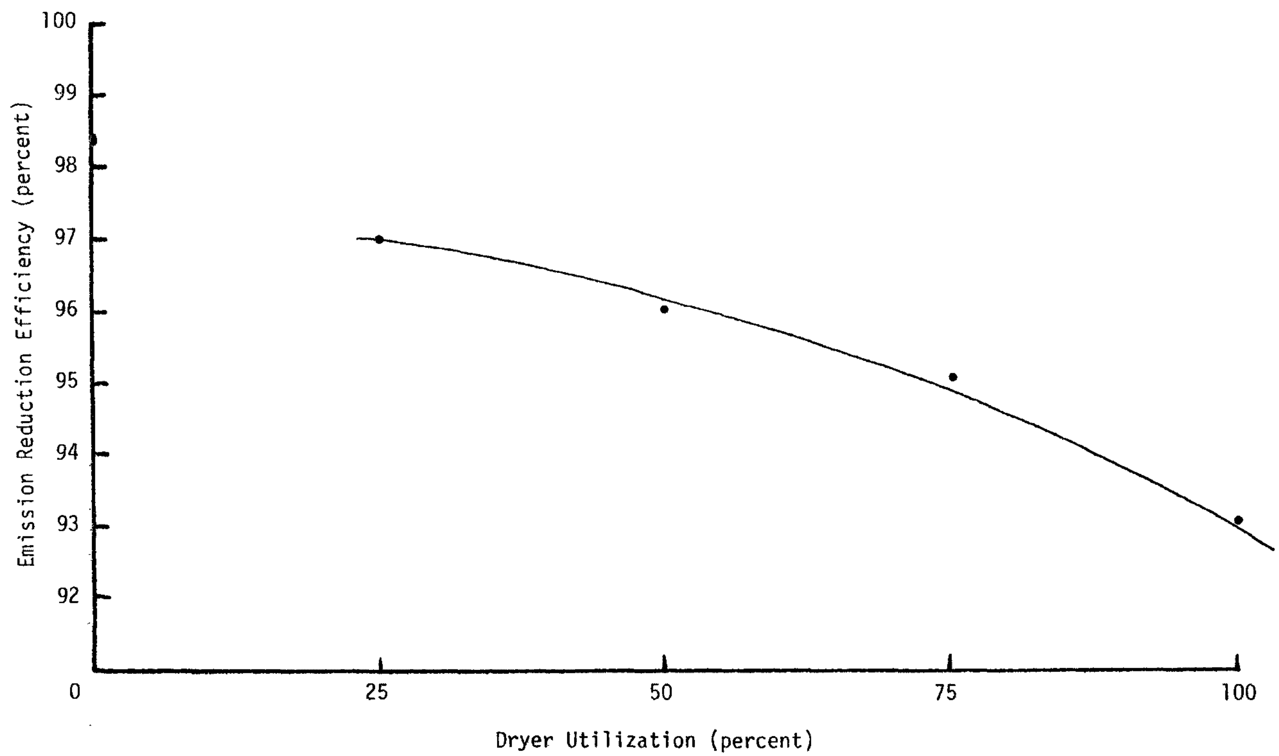

Figure 5-2. Emission reduction efficiency versus dryer utilization.

a higher temperature steam. No change in efficiency was noted and the increased steam temperature was considered to be potentially detrimental to the carbon.

The next step involved a reduction in the length of the steam cycle from the design length of 60 min. Desorption was conducted at 590 kg/h of steam (1300 lb/h) for 45 min. with the result being a noticeable reduction in the adsorber efficiency. The length of the steam cycle was then increased to 50 min. A reduction in efficiency was still noted. The optimum desorption parameters were, therefore, determined to be as follows:

Steam gauge pressure - 10.3×10^4 pascals (15 psig).

Steam flow rate - 590 kg/h (1300 lb/h).

Length of cycle per bed - 60 min.

Air Cooler Reduction--

Water flow through the dryer exhaust air cooler was reduced in three steps until it was completely eliminated. The inlet air stream to the adsorbers and the carbon bed temperatures were monitored closely throughout the test. At no time did either temperature exceed the recommended maximum of 57°C (135°F).[2] The air cooler could, therefore, be eliminated, thus reducing the capital requirements of the total system. Additionally, as discussed in the Adsorption/Desorption Cycle Alteration section, this modification, in conjunction with the reduction in cooling water throughput to the condensers, eliminated the need for the additional cooling tower. Capital requirements are, therefore, further reduced.

Limiting Conditions

The extent to which modifications could be made was limited by several conditions. For the change of filter system, an excessive flow restriction would limit the extent to which the filter could be modified. Nylon bags were tested; however, they provided a flow restriction to the extent that a maximum of three dryer cycles could be completed before the bag had to be changed. When replaced with cotton bags, the problem was eliminated and one bag could be operated for an entire day.

The only possible limiting condition for the blower cycle alteration would be an increase in electricity consumption due to the start-up surge. This was not witnessed; therefore, the condition does not affect this system.

The limiting condition for the adsorption/desorption cycle alteration, carbon bed depth adjustment, and desorption alteration was a reduction in system efficiency. As previously delineated, no significant reduction was noted when the system was switched to the continuous operation of two beds. For the carbon bed depth adjustment, this limit was passed during the desorption alteration and a reduction in efficiency was noted. The alterations were, therefore, reversed and the efficiencies returned to normal.

EVALUATION OF TECHNICAL EFFICIENCY

Techniques

This section describes the techniques which are used to evaluate the technical efficiency of the demonstration carbon adsorption system. Three analysis criteria are used:

1. Emission reduction efficiency (Method 1).

2. Solvent recovery efficiency (Method 2).

3. Quality of recovered solvent.

Desired Technical Efficiency--

The minimum emission reduction efficiency deemed acceptable for this system is 90 percent on a daily average basis. No minimum efficiency was established for solvent recovery; however, it is directly related to Method 1 and should, therefore, be comparable. The only requirement for the quality of the recovered solvent is that it must be acceptable for reuse in the dry cleaning plant.

Emission Reduction Efficiency--

As described in Section 4 of this report, the reduction in effluent mass flow rate was determined by measuring the amounts of solvent entering and exiting the carbon adsorption unit. The unit efficiency was calculated by the following equation:

$$S_1 = 100 \quad 1 - \frac{S_o}{S_i}$$

where S_1 = Method 1 efficiency %

S_o = Solvent air emissions exiting the adsorption unit (1)

S_i = Solvent entering the adsorption unit (1)

As defined in Section 7 of this report, there are potential errors involved in the measurement of the inlet and outlet solvent mass flow rates which may have an impact on the calculated adsorber efficiencies. Thus, in order to determine the statistical confidence of the calculated adsorber solvent emission reduction efficiency, the following equations are used:

Minimum adsorber solvent emission reduction efficiency

$$S_{1_{min}} = 100 \quad 1 - \frac{S_{o_{max}}}{S_{i_{min}}}$$

where $S_{1_{min}}$ = minimum emission reduction efficiency

$S_{o_{max}}$ = maximum solvent air emissions from adsorber assuming measurement errors are all on the low side (l/yr)

$S_{i_{min}}$ = minimum solvent flow rate to adsorber assuming measurement errors are all on the high side (l/yr)

Maximum adsorber solvent emission reduction efficiency

$$S_{1_{max}} = 100 \left(1 - \frac{S_{o_{min}}}{S_{i_{max}}}\right)$$

where $S_{1_{max}}$ = maximum emission reduction efficiency

$S_{o_{min}}$ = minimum solvent air emissions from adsorber assuming measurement errors are all on the high side (l/yr)

$S_{i_{max}}$ = maximum solvent flow rate to adsorber assuming measurement errors are all on the low side (l/yr)

Solvent Recovery Efficiency--

The amount of solvent that was recovered for reuse by Valley was measured daily. The Method 2 or solvent recovery efficiency was calculated by the following equation:

$$S_2 = 100 \left(\frac{S_R}{S_i}\right)$$

where S_2 = Method 2 efficiency (%)

S_R = Solvent recovered for reuse (l)

S_i = Solvent entering the adsorption unit (l)

Maximum and minimum solvent recovery efficiencies are calculated in the same manner as the emission reduction efficiency.

Quality of Recovered Solvent--

Samples of recovered solvent were taken periodically during the test program and subjected to a series of laboratory analyses. The results from these analyses were compared with the expected values for fresh solvent to determine the acceptability of the recovered solvent. Laboratory tests included:

1) Distillation range.
2) Acidity.
3) Kauri-Butanol value.
4) Bromine number
5) Flash point.
6) Solvent composition (by gas chromatograph).

Results: Pre-optimization

The carbon adsorption system was operated from July 24 through November 30, 1978, in the manner which was specified by the manufacturer. This section summarizes the data collected during that period.

Emission Reduction Efficiency--

Throughout the test period prior to optimization, a total of 22,834 l (6,032 gal) of solvent entered the adsorber and 193 l (51 gal) of solvent were emitted into the atmosphere from the adsorber outlet. This yielded an efficiency of 99.2 percent. It must be noted that approximately 7 weeks of operation were required to fully develop a "solvent heel" in the carbon beds. A solvent heel is a quantity of solvent which is adsorbed by the carbon but is never desorbed during normal steaming. It is, therefore, constantly retained in the beds. After this heel was formed, the emissions increased slightly. After this point, a total of 15,077 l (3,983 gal) of solvent entered the adsorber and 174 l (46 gal) of solvent were emitted to the atmosphere, yielding an efficiency of 98.8 percent. This latter figure is more representative of the long-term operations of this system since the heel remains constant and has no further effect on the unit operation.

To calculate $S_{o_{min}}$, $S_{o_{max}}$, $S_{i_{min}}$, and $S_{i_{max}}$, the maximum expected error for each of the respective process operating parameters, as calculated in Section 7, is used in conjunction with the measured solvent flow rates into and out of the carbon adsorption unit.

Using the above equations, the following values can be calculated for the demonstration program before optimization:

	Minimum	Maximum
S_i - l (gal)	18,267 (4,826)	28,085 (7,419)
S_o - l (gal)	41 (11)	243 (64)
S_1 Efficiency	98.7%	99.9%

For the period of operation after attainment of the heel, the minimum and maximum values for solvent flow rate into the adsorber, solvent air emissions from the adsorber, and emission reduction efficiencies are:

	Minimum	Maximum
S_i - l (gal)	12,062 (3,186)	18,545 (4,899)
S_o - l (gal)	134 (35)	228 (60)
S_1 Efficiency	98.1%	99.3%

Even under the assumption of worst possible measurement errors, the emission reduction efficiency of the adsorption unit far exceeds the minimum requirement of 90 percent.

Solvent Recovery Efficiency--

Throughout the entire demonstration program, a total of 16,202 l (4,280 gal) of solvent was recovered. When compared to the solvent inlet of 22,834 l (6,032 gal), this yields a Method 2 efficiency of 71.0 percent. After attainment of the heel in the beds, 11,424 l (3,018 gal) of solvent were recovered, while 15,077 l (3,983 gal) entered the system from the dryer exhaust. The solvent recovery efficiency during this period increased to 75.8 percent.

As with the emission reduction efficiency calculations, potential errors exist in the measurement of recovered solvent. The minimum and maximum solvent recovery efficiency, based on the errors associated with measurement of the recovered solvent during the demonstration period, are presented below:

	Minimum	Maximum
S_i - l (gal)	18,267 (4,826)	28,085 (7,419)
S_R - l (gal)	13,771 (3,638)	18,632 (4,922)
S_2 Efficiency	49%	102%

The following data are for the adsorption unit after formation of the heel, but before optimization:

	Minimum	Maximum
S_i - l (gal)	12,061 (3,186)	18,545 (4,899)
S_R - l (gal)	9,711 (2,565)	13,138 (3,471)
S_2 Efficiency	52%	109%

Comparison of Methods--

The reported Method 1 and Method 2 efficiencies for the demonstration program of 99.2 percent and 71 percent, respectively, leave 28.2 percent unaccounted for in the carbon adsorption system. However, within the confines of the measurement errors imposed on the system, this difference is considered insignificant as shown by the maximum Method 2 efficiencies both for the full demonstration period and after attainment of the heel being greater than 100 percent (i.e., the maximum quantity of solvent recovered is greater than the minimum quantity of solvent entering the carbon adsorption system).

Quality of Recovered Solvent--

In order for the recovered solvent to have any economic value, it must not undergo any physical or chemical changes during the adsorption and desorption stages. Analyses of the unused and recovered solvents were conducted weekly during the demonstration program. Invariably, there was no difference detected between the two solvent samples. In addition, no reduction in cleaning quality was reported by Valley. Some of the solvent which was tested had been through the cycle several times and still showed no signs of degradation. The obvious conclusion of these tests is that carbon adsorption and subsequent desorption did not adversely affect the quality of the Stoddard solvent in any way. The results of the laboratory analyses are presented in Section 6 of this report.

Results: Optimized System

The optimization of the carbon adsorption system removed the need for the auxiliary boiler, cooling tower, air stream cooler, and one of the three carbon beds. The optimized system utilized parallel adsorption with two carbon beds for the entire operating day. Desorption occurred at the end of the day thus making it possible to use the existing plant steam and cooling water systems if desired. The specific desorption parameters are presented in the Optimization Studies section.

Emission Reduction Efficiency--

The emission reduction efficiency (Method 1) was calculated for the optimized system configuration. During the time when the system was operated at the optimum conditions, a total of 7,336 l (1,938 gal) of solvent entered the adsorber and 379 l (100 gal) of solvent were emitted to the atmosphere. This yielded an efficiency of 94.8 percent. Taking into account the maximum possible inlet and outlet measurement errors, the following ranges of figures were calculated for the optimized system:

	Minimum	Maximum
S_i - l (gal)	5,871 (1,551)	9,023 (2,384)
S_o - l (gal)	291 (77)	496 (131)
S_1 Efficiency	91.6%	96.8%

As with the data from the demonstration program, the system efficiency exceeded the minimum requirement of 90 percent for a daily average, even under the assumption of worst possible measurement errors.

Solvent Recovery Efficiency--

The solvent recovery efficiency (Method 2) for the optimized system was determined as follows. During the time when the system was operated at the optimum conditions, a total of 6,462 l (1,707 gal) of solvent was recovered. When compared with the inlet of 7,336 l (1,938 gal), an efficiency of 88.1 percent was calculated. The effect of maximum possible errors on these figures is:

	Minimum	Maximum
S_i - 1 (gal)	5,871 (1,551)	9,023 (2,384)
S_R - 1 (gal)	6,397 (1,690)	6,526 (1,724)
S_2 Efficiency	71%	111%

Comparison of Methods--

Again, within the confines of measurement error, it was shown that the difference in the quantity of solvent introduced into the carbon adsorption system and the quantity of recovered solvent was insignificant (as shown by the maximum Method 2 efficiency being greater than 100%).

COST ANALYSIS

Cost Analysis for Non-Optimized System

Capital cost data for the carbon adsorption system as originally installed at the Valley site are presented in Table 5-1. These costs include all necessary expenditures, including equipment costs, installation labor charges, contractor and subcontractor fees, engineering service charges resulting from the design and installation of the carbon adsorption system, and other related charges.

The costs included in this analysis are for the carbon adsorber; carbon; all ancillary equipment; shipping costs for the carbon adsorber from Minneapolis, Minnesota, to Anaheim, California; and the carbon shipping charges from West Virginia. Included in the cost of the boiler and cooling tower are charges for water softening and water treatment chemicals. Engineering labor charges under the heading "Procurement, Design, and Installation Supervision Costs" include those costs necessary to develop the design parameters for the original carbon adsorption system; to provide engineering supervision during the installation and start-up of the system; and technical labor charges for assistance in the installation and start-up period. Also included in the engineering labor charges are those costs associated with project management.

It should be noted that some of the costs comprising the total capital cost of the carbon adsorption system are site-specific and would not necessarily be required if such a system were installed at some other dry cleaning facility. The following items are considered site-specific for the Anaheim site:

1. Bridge.

2. Boiler - steam supply is inadequate for both plant needs and requirements of carbon adsorption system.

3. Air compressor - compressed air supply is inadequate for both plant needs and requirements of carbon adsorption system.

TABLE 5-1. CAPITAL COSTS FOR THE NON-OPTIMIZED CARBON ADSORPTION SYSTEM
(All costs are in mid-1978 dollars)

EQUIPMENT COSTS:		
Equipment	Cost	
Carbon adsorber (less carbon)+	$59,000.*	
Carbon (5500 Kilograms) (1200 lb)	18,100.*	
Boiler (0.5MW) (50hp)	12,100.	
Cooling tower	4,400.	
Bridge	2,200.	
Pump (cooling tower)	700.	
Air compressor	800.	
SUBTOTAL EQUIPMENT COSTS.		$ 97,300.
SITE PREPARATION AND INSTALLATION COSTS:		
Equipment or Service Provided		
Field-construction services, necessary installation equipment, foundation, duct-work, piping, electrical work, and other necessary ancillary equipment	$44,200.	
SUBTOTAL SITE PREPARATION COSTS.		$ 44,200.
PROCUREMENT, DESIGN, AND INSTALLATION SUPERVISION COSTS:		
Service Provided		
Engineering labor	$18,000.	
Travel	5,000.	
Procurement expenses	5,000.	
Miscellaneous	1,000.	
SUBTOTAL PROCUREMENT, DESIGN, AND INSTALLATION SUPERVISION COSTS		$ 29,000.
TOTAL CAPITAL COSTS		$170,500

*Includes shipping charges.

+Carbon adsorber sized for flow rate of 220 Nm^3/min.

4. Cooling tower - cooling water needs for both the plant and the carbon adsorption unit exceed the existing capacity.

In addition, since many variables enter into the required engineering labor hours, depending on plant location, these costs could vary either up or down for individual plant sites.

From the above costs, annualized operating costs for the non-optimized adsorption system can be estimated using the following inputs:

1. Capital recovery factor calculated using 10 percent annual interest rate, 15 yr equipment life, plus 4 percent of installed capital cost for property taxes, insurance, and administration.

2. Operating labor cost computed at \$8.00/h plus an additional 60 percent for overhead.

3. Natural gas cost of \$0.0763/m^3 (\$0.0022/ft^3).

4. Electricity cost of \$0.0528/kWh.

5. Process water cost of \$0.108/1000 l (\$0.410/1000 gal).

Operating labor hours were those hours attributed to proper operation and maintenance of the carbon adsorption system and are identified in Section 6 of this report.

For the 18 week Demonstration Test, before optimization, the annualized operating costs are given in Table 5-2. From operating data obtained during this period, it was determined that 3.2 h of operating and maintenance labor were required each day to properly operate and maintain the carbon adsorption system. For purposes of computing annualized operating labor charges, it was assumed the plant operated 5 days per week, 52 weeks per year. Utilities costs were derived from actual rates charged to the dry cleaning plant during the Demonstration Test. Since a full year's data were not available to determine the actual maintenance materials expenditures, an estimate was made based on the Demonstration Test period and manufacturer's recommendations. Due to the extremely limited data available on the life of carbon used in a petroleum dry cleaning carbon adsorption system, it was assumed no change of carbon was needed during the expected life of the system (15 yr). This assumption is based on manufacturer's estimates. The annualized cost for the land on which the carbon adsorption system is located was computed using a discount rate of 10 percent per year and a land appreciation rate of 5 percent per year. The land charge was based on a 15 yr operating period.

Taking into account solvent recovery credits (using a solvent recovery value of \$0.16/l (\$0.61/gal), the annualized operating cost of the non-optimized carbon adsorption system as originally installed was estimated to be \$42,500.

TABLE 5-2. ANNUALIZED OPERATING COSTS OF NON-OPTIMIZED CARBON ADSORPTION SYSTEM
(All costs are in mid-1978 dollars)

DIRECT COSTS:

Utilities	Annual Quantity	Unit Cost	Total Annual Cost
Natural gas	45,600 m^3 (1,612,000 ft^3)	\$0.0763/m^3 (\$0.0022/ft^3)	\$3,500
Process water	1,338,400 l (353,600 gal)	\$0.108/1000 l (\$0.410/1000 gal)	100
Electricity	70,900kWh	\$0.0528/kWh	3,700
Operating Labor			
Direct labor	310 man-hours	\$12.60/man-hour	3,900
Supervision	15% of Direct labor		600
Maintenance			
Labor	470 man-hours	\$12.60/man-hour	5,900
Material			< 200
Recovered Solvent (credit)			
	54,800 l (14,500 gal)	\$0.16 l (\$0.61/gal)	(8,800)
SUBTOTAL DIRECT COSTS			\$ 9,100

INDIRECT COSTS:

	Total Annual Cost
Capital Charge at 13.15% of Total Capital Costs Plus 4.0% of Equipment Costs	\$26,300
Overhead	
Plant (50% of operating labor and maintenance)	5,300
Payroll (20% of operating labor)	900
Land Charge	900
SUBTOTAL INDIRECT COSTS	\$33,400
TOTAL ANNUAL OPERATING COSTS	\$42,500

Cost Analysis for Optimized System

Cost data for the optimized carbon adsorption system are the same as for the non-optimized system except as follows:

1. No boiler or cooling tower is required, since the existing plant equipment can be utilized.

2. Only two of the three carbon adsorption system canisters are needed to operate the optimized system (with a resultant reduction in carbon requirements).

3. No cooling tower pump is required, since the cooling tower is not needed.

4. No air compressor is required, since the plant air supply system can be used for the after-hours desorption.

5. Field-construction services, necessary equipment, foundation work, electrical work, and the like are reduced, though not linearly.

6. No change is experienced in procurement, design, and installation supervision costs.

7. No air cooler is needed, since the temperature of the gas stream entering the carbon adsorption system never exceeded the recommended maximum of 57°C (135°F).

8. The land requirements of the optimized carbon adsorption system are reduced by approximately 40 percent, since equipment requirements have been reduced.

Using the above assumptions, the capital costs for the optimized system are given in Table 5-3.

It was felt that no decrease in procurement, design, and installation supervision costs would be experienced. Additionally, it was assumed that the site preparation and installation costs for the optimized adsorption system would be 90 percent of the comparable costs for the originally designed system, since foundation work, piping needs, ducting requirements, and electrical installation work (which make up the majority of site preparation and installation costs) are basically the same for the originally-designed system and the optimized system.

Using the same costing data (capital recovery factor, operating labor, and the like) as the original carbon adsorption configuration, with the additional cost of $0.0763/kg ($0.0346/lb) of low-pressure steam, annualized costs for the optimized system are estimated (Table 5-4).

TABLE 5-3. CAPITAL COSTS FOR THE OPTIMIZED CARBON ADSORPTION SYSTEM
(All costs are in mid-1978 dollars)

EQUIPMENT COSTS:		
Equipment	Capital Cost	
Carbon adsorber (less carbon)	$45,200.*	
Carbon (3,600 kilograms) (7,900 lb)	12,100.*	
Bridge	2,200.	
SUBTOTAL EQUIPMENT COSTS. . . .		$ 59,500.
SITE PREPARATION AND INSTALLATION CHARGES:		
Equipment or Service Provided		
Field-construction services, necessary installation equipment, foundation, duct-work, piping, electrical work, and other necessary ancillary equipment	$39,800.	
SUBTOTAL SITE PREPARATION COSTS. . . .		$ 39,800.
PROCUREMENT, DESIGN, AND INSTALLATION SUPERVISION COSTS:		
Service Provided		
Engineering labor	$18,000.	
Travel	5,000.	
Procurement expenses	5,000.	
Miscellaneous	1,000.	
SUBTOTAL PROCUREMENT, DESIGN AND INSTALLATION SUPERVISION COSTS. . . .		$ 29,000.
TOTAL CAPITAL COSTS. . . .		$128,300.

*Includes shipping charges.

TABLE 5-4. ANNUALIZED OPERATING COSTS OF OPTIMIZED CARBON ADSORPTION SYSTEM (51% Utilization)

DIRECT COSTS:

Utilities	Annual Quantity	Unit Cost	Total Annual Cost
Steam	322,600 kg (709,700 lb)	$0.0073/kg ($0.0033/lb)	$ 2,400
Process water	767,600 l (202,800 gal)	$0.108/1000 l ($0.410/1000 gal)	<100
Electricity	61,200 kWh	$0.0538/kWh	3,200
Operating Labor			
Direct labor	200 man-hours	$12.60/man-hour	2,500
Supervision	15% of Direct labor		400
Maintenance			
Labor	320 man-hours	$12.60/man-hour	4,000
Materials			<200
Recovered Solvent (credit)			
	61,500 l (16,200 gal)	$0.16/l ($0.61/gal)	(9,800)
		SUBTOTAL DIRECT COSTS. . . .	$ 3,000

INDIRECT COSTS:

Capital Charge at 13.15% of Total Capital Costs Plus 4.0% of Equipment Costs	$19,300
Overhead	
Plant (50% of operating labor and maintenance)	3,600
Payroll (20% of operating labor)	600
Land Charge	500
SUBTOTAL INDIRECT COSTS. . .	$24,000
TOTAL ANNUAL OPERATING COSTS. . .	$27,000

These costs are based on the following inputs:

1. 2.1 hours of operating and maintenance labor per day are required to ensure satisfactory performance.

2. Plant operation is 8 hours per day, 5 days per week, 52 weeks per year.

3. No carbon change is necessary during the useful life of the adsorption system (based on manufacturer's estimates).

Computation of the annualized operating costs for the optimized carbon adsorption system gives a result of $27,000. This result, coupled with the estimated annual solvent emissions reduction of 48 Mg (53 tons) per year, gives a cost effectiveness of $560/Mg ($510/ton) of solvent emissions reduction. Cost effectiveness, as computed on a cost per unit of emissions reduction, is used by both EPA and industry as a means of evaluating various pollution control technologies on a common basis.

Effect of Dryer Utilization--

A sensitivity analysis was performed to determine the effect of dryer utilization on both the annualized operating costs and cost-effectiveness (Figures 5-3 and 5-4, respectively). This analysis is based on the following assumptions:

1. Steam and process water requirements at 100 percent dryer utilization are unchanged from the 51 percent utilization case. Steam and process water requirements at 25 percent dryer utilization are halved from the 51 percent utilization case because desorption is required only every other day.

2. Electricity costs are directly proportional to dryer utilization.

3. Operating labor and materials do not vary for the 100 percent dryer utilization case, but are reduced by one-third for the 25 percent dryer utilization case.

4. Solvent recovery credits are linearly proportional to dryer utilization (since the change in the time-weighted solvent emissions reduction is not significant).

Annualized operating costs for a 25 percent dryer utilization rate and a 100 percent dryer utilization rate are given in Tables 5-5 and 5-6, respectively.

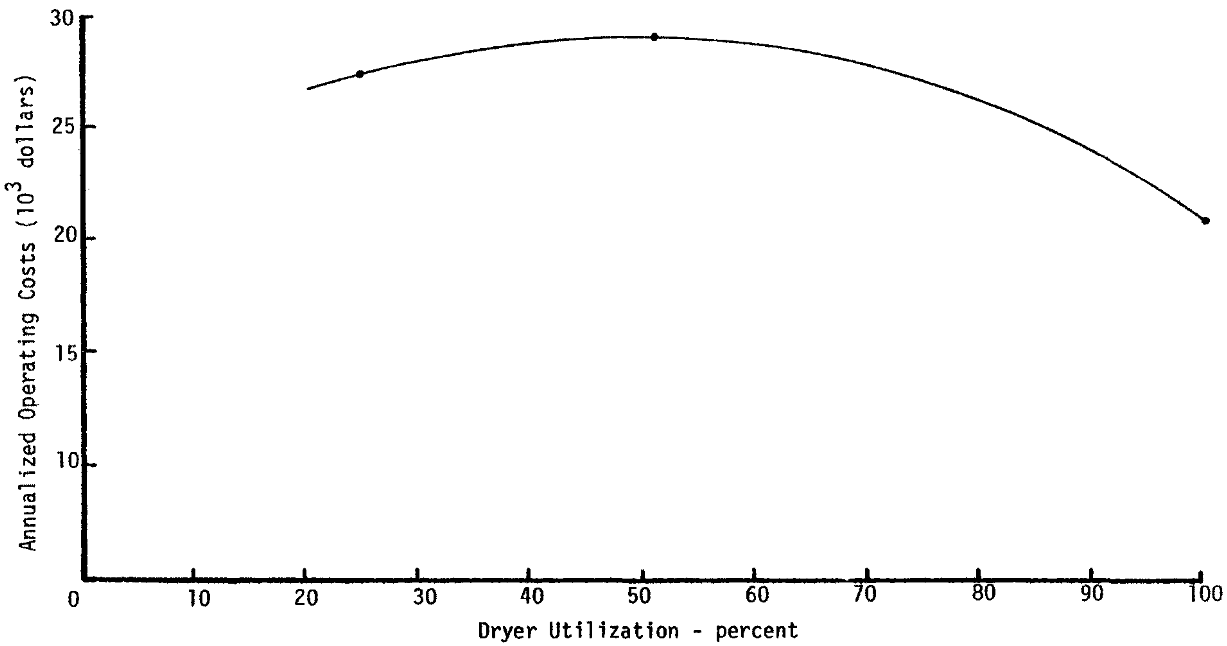

Figure 5-3. Effect of dryer utilization on annualized operating costs.

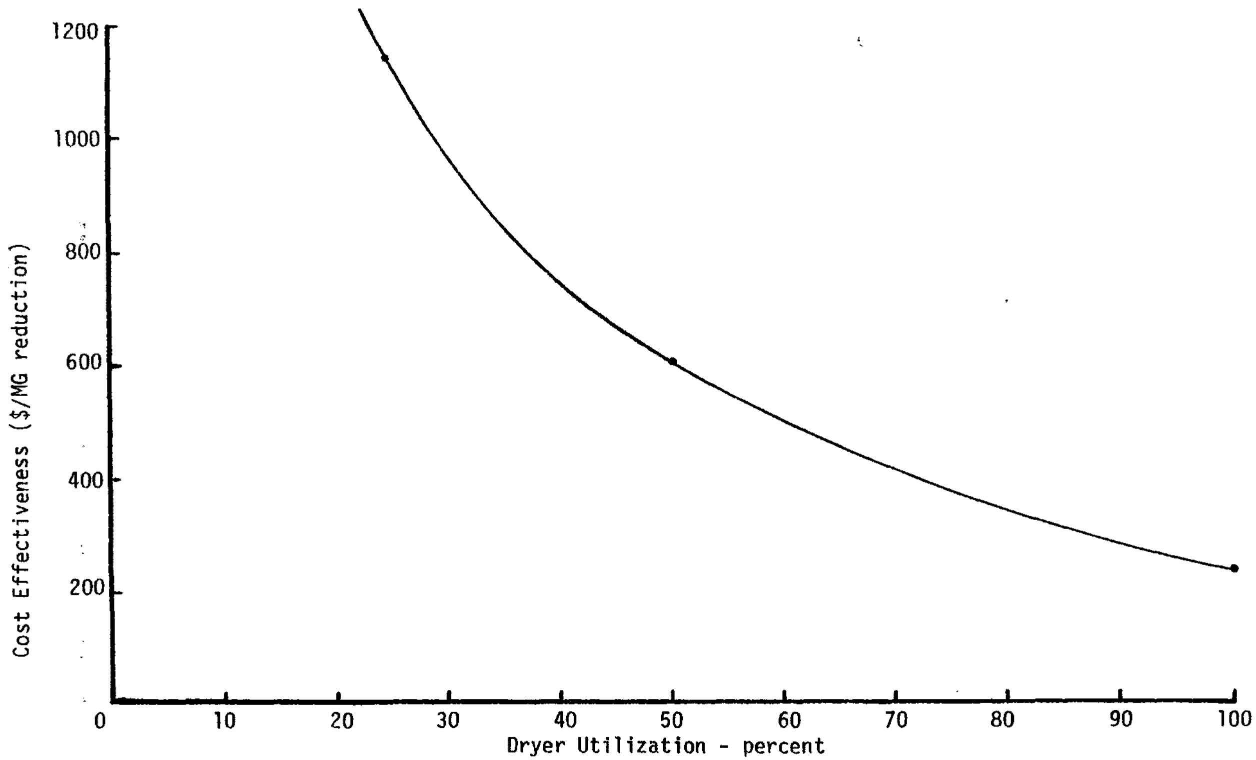

Figure 5-4. Effect of dryer utilization on cost effectiveness.

TABLE 5-5. ANNUALIZED OPERATING COSTS OF OPTIMIZED CARBON ADSORPTION SYSTEM (25% Utilization)

	Annual Quantity	Unit Cost	Total Annual Cost
DIRECT COSTS:			
Utilities			
Steam	161,300 kg (354,900 lb)	$0.0073/kg ($0.0033/lb)	$ 1,200
Process water	471,300 l (110,200 gal)	$0.108/1000 l ($0.410/1000 gal)	<100
Electricity	30,000 kWh	$0.0528/kWh	1,600
Operating Labor			
Direct labor	140 man-hours	$12.60/man-hour	1,800
Supervision	15% of Direct labor		300
Maintenance			
Labor	210 man-hours	$12.60/man-hour	2,600
Materials			<200
Recovered Solvent (credit)	30,200 l (8,000 gal)	$0.16/l ($0.61/gal)	(4,800)
SUBTOTAL DIRECT COSTS. . . .			$ 3,000
INDIRECT COSTS:			
Capital Charge at 13.15% of Total Capital Costs Plus 4.0% of Equipment Costs			$19,300
Overhead			
Plant (50% of operating labor and maintenance)			2,400
Payroll (20% of operating labor)			400
Land Charge			500
SUBTOTAL INDIRECT COSTS. . .			$22,600
TOTAL ANNUAL OPERATING COSTS. . .			$25,600

TABLE 5-6. ANNUALIZED OPERATING COSTS OF OPTIMIZED CARBON ADSORPTION SYSTEM (100% Utilization)

DIRECT COSTS:			
Utilities	Annual Quantity	Unit Cost	Total Annual Cost
Steam	322,600 kg (709,700 lb)	$0.0073/kg ($0.0033/lb)	$ 2,400
Process water	767,600 l (202,800 gal)	$0.108/1000 l ($0.410/1000 gal)	<100
Electricity	119,900 kWh	$0.0528/kWh	6,300
Operating Labor			
Direct labor	200 man-hours	$12.60/man-hour	2,500
Supervision	15% of Direct labor		400
Maintenance			
Labor	320 man-hours	$12.60/man-hour	4,000
Material			<200
Recovered Solvent (credit)	120,100 l (31,700 gal)	$0.16/l $0.61/gal	(19,200)
		SUBTOTAL DIRECT COSTS.	($3,300)
INDIRECT COSTS:			
Capital Charge at 13.15% of Total Capital Costs Plus 4.0% of Equipment Costs			$19,300
Overhead			
Plant (50% of operating labor and maintenance)			3,600
Payroll (20% of operating labor)			600
Land Charge			500
		SUBTOTAL INDIRECT COSTS. . . .	$24,000
		TOTAL ANNUAL OPERATING COSTS. . . .	$20,700

SECTION 6

TEST DATA

This section contains a summary of all data collected during the demonstration and optimization studies. A detailed analysis of these data was presented in Section 5 of this report.

OPERATION AS DESIGNED

Data was collected during the pre-optimization program which ran from July 24, 1978, to November 30, 1978. The information collected during that period is presented and summarized in this section.

Continuous Data

A listing of all daily operation data is presented in Tables 6-1 and 6-2. The methods by which these data were obtained are explained in Section 4 of this report. A summary of the data for the entire demonstration program and of data collected after the attainment of the solvent heel in the carbon beds is presented in Table 6-3.

Utility Consumption

As explained in Section 4, daily measurements were recorded of all utility consumption rates during the demonstration program. Weekly consumption rates were then tabulated and averages calculated. This information is presented in Table 6-4.

Laboratory Test Data

As mentioned in Sections 4 and 5, weekly laboratory analyses of neat and recovered solvent samples were performed during the demonstration program. The object of these analyses was to determine if any solvent degradation occurred after the adsorption and desorption process. The results of these tests are presented in Table 6-5. Shown in Table 6-6 for comparison with Table 6-5, is a sample of typical laboratory analysis results.

TABLE 6-1. SUMMARY OF DRY CLEANING CARBON ADSORPTION DEMONSTRATION PROGRAM OPERATING DATA (METRIC UNITS)

Julian date (1978)	Electrical consumption of system kWh	Natural gas consumption of boiler ft^3	Water consumption of boiler (l)	Decanted water to sewer (l)	Water flow to tower cooler (l)	Water flow to condenser (l)	Solvent introduced adsorber (l)	Solvent air emissions from adsorber (l)	Recovered solvent (l)	No. dry cleaning cycles (per day)	% Recovered (weekly)	Emissions reduction (weekly)
205	215	261	3179	1287	2915	1041	76	1.1	* ND	4		
206	743	377	5526	4542	4164	149129	125	1.9	125	6		
207	215	377	4769	4164	4277	144966	129	0.4	57	ND	79	98.9
208	223	292	ND	3028	3482	155185	95	0.8	114	4		
209	311	303	3596	3407	2763	168054	170	2.3	114	6		
212	223	145	1779	ND	1476	116200	64	0.4	38	2		
213	ND	31	492	ND	1098	4921	ND	ND	ND	4		
214	ND	173	2044	1893	2347	182816	159	0.4	102	7	58	99.7
215	263	215	2650	2271	2309	185465	151	0.4	76	6		
216	304	167	1968	1893	2612	184330	193	0.4	ND	7		
219	311	221	2763	2650	2915	188872	167	0.0	114	7		
220	225	119	1514	1514	1817	151022	129	0.4	45	6		
221	ND	204	2347	1893	2498	171461	140	0.0	106	7	66	99.9
222	309	230	2687	2650	2612	185844	125	0.0	95	6		
223	316	162	2006	1514	1741	146858	102	0.0	76	4		
226	277	167	1590	1893	2195	159727	133	0.4	ND	7		
227	299	207	2385	2271	2460	165026	133	0.4	102	6		
228	355	221	2877	2650	2990	177895	382	0.4	95	14	61	99.8
229	310	215	2612	2271	2460	116200	242	0.4	189	10		
230	310	213	2574	2271	2687	ND	333	0.4	208	12		
233	258	105	1401	757	1703	ND	363	0.4	95	12		
234	356	221	2801	3407	2952	ND	382	0.4	246	12		
235	309	184	2006	1893	2612	ND	257	0.4	170	10	57	99.8
236	356	181	2120	1893	3028	ND	413	0.4	216	16		
237	401	232	2801	4164	3558	ND	382	0.4	295	10		
240	308	181	2120	1893	2915	ND	314	0.4	170	12		
241	402	190	2120	1893	2801	ND	189	0.4	151	9		
242	351	230	2952	2271	3255	ND	401	0.4	284	18	70	99.9
243	353	184	2006	1893	2952	ND	379	0.4	246	17		
244	317	179	2082	1893	2574	ND	288	0.4	254	15		
248	264	179	2309	1893	2877	ND	288	0.4	246	13		
249	310	179	2082	1136	606	ND	454	0.4	257	15	74	99.9
250	351	184	2271	2650	2763	ND	269	0.4	246	13		
251	306	181	2082	1893	2763	ND	329	0.4	246	15		
254	263	177	2158	1893	2725	ND	318	0.4	239	14		
255	267	125	1438	1136	1703	ND	284	0.8	170	13		
256	264	128	1665	1136	2006	ND	326	3.8	151	16	67	98.8
257	224	122	1363	1136	1665	ND	273	9.5	227	12		
258	265	179	2120	1136	2347	ND	329	3.8	239	15		
262	310	190	2347	757	3444	ND	284	1.1	208	13		
263	262	136	1741	379	3066	ND	288	1.1	133	14		
264	250	142	1628	ND	3861	ND	299	1.1	208	15	59	99.6
265	199	128	1552	ND	2839	ND	276	0.8	133	12		
268	300	300	3444	ND	5678	ND	292	5.3	239	14		
269	305	139	1476	ND	3785	ND	254	3.0	114	8		
270	259	159	1930	ND	3066	ND	265	1.5	227	10		
271	349	258	3028	ND	4429	ND	284	1.5	220	11		
272	319	145	1779	ND	2915	ND	231	1.9	151	14		

(continued)

TABLE 6-1. (continued)

Julian date (1978)	Electrical consumption of system kWh	Natural gas consumption of boiler ft3	Water consumption of boiler (1)	Decanted water to sewer (1)	Water flow to tower cooler (1)	Water flow to condenser (1)	Solvent introduced adsorber (1)	Solvent air emissions from adsorber (1)	Recovered solvent (1)	No. dry cleaning cycles (per day)	% Recovered (weekly)	Emissions reduction (weekly)
275	270	105	908	ND	1628	120363	288	1.5	140	15		
276	260	173	1968	ND	2498	ND	193	1.1	227	4	81	99.4
277	81	62	908	ND	984	ND	288	1.1	76	17		
279	308	179	2120	ND	2512	ND	216	1.1	265	11		
282	312	173	2271	ND	2574	150643	250	3.0	189	13		
283	358	170	1930	ND	3066	143073	284	1.9	341	14		
284	219	133	1476	ND	2574	120742	265	1.9	151	13	91	99.2
285	260	173	2082	ND	3066	128312	265	1.9	303	12		
286	218	113	1363	1136	2120	112036	242	1.1	201	12		
289	222	173	2233	1514	2990	150643	299	1.5	303	15		
290	263	125	1476	1136	2309	112793	125	0.4	208	6		
291	262	173	2271	1514	2839	135503	299	1.1	303	14	98	99.5
292	218	125	1438	1136	2422	118849	326	1.9	189	14		
293	215	167	2158	1514	2309	129447	322	2.3	341	13		
296	85	68	871	379	1817	53747	76	1.9	95	4		
297	216	119	1552	1136	2877	99167	280	1.9	170	12		
298	263	170	2044	1514	4201	143830	344	2.3	303	15	85	99.2
299	168	125	1628	1136	3142	112036	239	1.5	170	11		
300	263	173	2082	1514	3747	135503	295	2.3	310	15		
303	219	125	1552	1136	3028	110522	231	2.7	167	11		
304	216	176	2422	1514	3520	119606	288	3.0	261	11		
305	308	179	2195	1514	4315	151022	382	3.4	254	15	73	99.0
306	265	176	3369	1514	4164	130204	292	2.7	280	13		
307	225	128	1476	1136	3066	109765	326	3.4	140	14		
310	262	173	2082	1514	4239	127555	367	1.9	257	15		
311	170	119	1401	1136	2915	90462	254	1.9	189	11		
312	305	314	3974	3028	5488	152914	227	2.3	360	15	78	99.4
313	168	116	2612	1136	2915	104088	337	1.5	102	14		
314	267	167	1930	1136	3293	117335	344	1.9	284	16		
317	176	116	1438	3407	2574	88569	239	3.4	144	11		
318	219	116	1363	757	2952	101060	299	4.5	136	14		
319	216	159	1855	1136	4239	123770	299	3.4	257	16	63	98.3
320	215	111	1249	757	3255	99546	284	3.4	174	13		
321	170	102	1476	757	2422	85541	295	9.1	182	13		
324	350	150	1779	1136	3596	189630	284	7.2	170	13		
325	220	110	1477	1136	2801	104845	337	3.4	114	15	61	97.6
326	220	153	1855	1136	3104	116960	242	10.2	238	14		
331	264	161	2082	1136	4466	131340	204	2.3	189	10		
332	173	116	1703	1136	2877	86680	269	11.0	160	14	80	95.9
333	355	272	3293	2650	6094	174870	276	22.0	295	14		
334	423	167	2157	1893	3596	105600	220	3.8	129	11		

TABLE 6-2. SUMMARY OF DRY CLEANING CARBON ADSORPTION DEMONSTRATION PROGRAM OPERATING DATA (ENGLISH UNITS)

Julian date (1978)	Electrical consumption of system kWh	Natural gas consumption of boiler ft3	Water consumption of boiler (gal)	Decanted water to sewer (gal)	Water flow to tower cooler (gal)	Water flow to condenser (gal)	Solvent introduced adsorber (gal)	Solvent air emissions from adsorber (gal)	Recovered solvent (gal)	No. dry cleaning cycles (per day)	% Recovered (weekly)	Emissions reduction (weekly)
205	215	9,200	840	340	770	275	20	0.3	ND	4		
206	743	13,300	1,460	1,200	1,100	39,400	33	0.5	33	6		
207	215	13,300	1,260	1,100	1,130	38,300	34	0.1	15	ND	79	98.9
208	223	10,300	ND	800	920	41,000	25	0.2	30	4		
209	311	10,700	950	900	730	44,400	45	0.7	30	6		
212	223	5,100	470	ND	390	30,700	17	0.1	10	2		
213	ND	1,100	130	ND	290	1,300	ND	ND	ND	4		
214	ND	6,100	540	500	620	48,300	42	0.1	27	7	58	99.7
215	263	7,600	700	600	610	49,000	40	0.1	20	6		
216	304	5,900	520	500	690	48,700	51	0.1	ND	7		
219	311	7,800	730	700	770	49,900	44	0.0	30	7		
220	225	4,200	400	400	480	39,900	34	0.1	12	6		
221	ND	7,200	620	500	660	45,300	37	0.0	28	7	66	99.9
222	309	8,100	710	700	690	49,100	33	0.0	25	6		
223	316	5,700	530	400	460	38,800	27	0.0	20	4		
226	277	5,900	420	500	580	42,200	35	0.1	ND	7		
227	299	7,300	630	600	650	43,600	35	0.1	27	6		
228	355	7,800	760	700	790	47,000	101	0.1	25	14	61	99.8
229	310	7,600	690	600	650	30,700	64	0.1	50	10		
230	310	7,500	680	600	710	ND	88	0.1	55	12		
233	258	3,700	370	200	450	ND	96	0.1	25	12		
234	356	7,800	740	900	780	ND	101	0.1	65	12		
235	309	6,500	530	500	690	ND	68	0.1	45	10	57	99.8
236	356	6,400	560	500	800	ND	109	0.1	57	16		
237	401	8,200	740	1,100	940	ND	101	0.1	78	10		
240	308	6,400	560	500	770	ND	83	0.1	45	12		
241	402	6,700	560	500	740	ND	50	0.1	40	9		
242	351	8,100	780	600	860	ND	106	0.1	75	18	70	99.9
243	353	6,500	530	500	780	ND	100	0.1	65	17		
244	317	6,300	550	500	680	ND	76	0.1	67	15		
248	264	6,300	610	500	760	ND	76	0.1	65	13		
249	310	6,300	550	300	160	ND	120	0.1	68	15	74	99.9
250	351	6,500	600	700	730	ND	71	0.1	65	13		
251	306	6,400	550	500	730	ND	87	0.1	65	15		
254	263	6,200	570	500	720	ND	84	0.1	63	14		
255	267	4,400	380	300	450	ND	75	0.2	45	13		
256	264	4,500	440	300	530	ND	86	1.0	40	16	67	98.8
257	224	4,300	360	300	440	ND	72	2.5	60	12		
258	265	6,300	560	300	620	ND	87	1.0	63	15		
262	310	6,700	620	200	910	ND	75	0.3	55	13		
263	262	4,800	460	100	810	ND	76	0.3	35	14		
264	250	5,000	430	ND	1,020	ND	79	0.3	55	15	59	99.6
265	199	4,500	410	ND	750	ND	73	0.2	35	12		

(continued)

TABLE 6-2. (continued)

Julian date (1978)	Electrical consumption of system kWh	Natural gas consumption of boiler ft3	Water consumption of boiler (gal)	Decanted water to sewer (gal)	Water flow to tower cooler (gal)	Water flow to condenser (gal)	Solvent introduced adsorber (gal)	Solvent air emissions from adsorber (gal)	Recovered solvent (gal)	No. dry cleaning cycles (per day)	% Recovered (weekly)	Emissions reduction (weekly)
268	300	10,600	910	ND	1,500	ND	77	1.4	63	14		
269	305	4,900	390	ND	1,000	ND	67	0.8	30	8		
270	259	5,600	510	ND	810	ND	70	0.4	60	10	72	99.0
271	349	9,100	800	ND	1,170	ND	75	0.4	58	11		
272	319	5,100	470	ND	770	ND	61	0.5	40	14		
275	270	3,700	240	ND	430	31,800	76	0.4	37	15		
276	260	6,100	520	ND	660	ND	21	0.3	60	4	81	99.4
277	81	2,200	240	ND	260	ND	76	0.3	20	17		
279	308	6,300	560	ND	690	ND	57	0.3	70	11		
282	312	6,100	600	ND	680	39,800	66	0.8	50	13		
283	358	6,000	510	ND	810	37,800	75	0.5	90	14		
284	219	4,700	390	ND	680	31,900	70	0.5	40	13	91	99.2
285	260	6,100	550	ND	810	33,900	70	0.5	80	12		
286	218	4,000	360	300	560	29,600	64	0.3	53	12		
289	222	6,100	590	400	790	39,800	79	0.4	80	15		
290	263	4,400	390	300	610	29,800	33	0.1	55	6		
291	262	6,100	600	400	750	35,800	79	0.3	80	14	98	99.5
292	218	4,400	380	300	640	31,400	86	0.5	50	14		
293	215	5,900	570	400	610	34,200	85	0.6	90	13		
296	85	2,400	230	100	480	14,200	20	0.5	25	4		
297	216	4,200	410	300	760	26,200	74	0.5	45	12		
298	263	6,000	540	400	1,110	38,000	91	0.6	80	15	85	99.2
299	168	4,400	430	300	830	29,600	63	0.4	45	11		
300	263	6,100	550	400	990	35,800	78	0.6	82	15		
303	219	4,400	410	300	800	29,200	61	0.7	44	11		
304	216	6,200	640	400	930	31,600	76	0.8	69	11		
305	308	6,300	580	400	1,140	39,900	101	0.9	67	15	73	99.0
306	265	6,200	890	400	1,100	34,400	77	0.7	74	13		
307	225	4,500	390	300	810	29,000	86	0.9	37	14		
310	262	6,100	550	400	1,120	33,700	97	0.5	68	15		
311	170	4,200	370	300	770	23,900	67	0.5	50	11		
312	305	11,100	1,050	800	1,450	40,400	60	0.6	95	15	78	99.4
313	168	4,100	690	300	770	27,500	89	0.4	27	14		
314	267	5,900	510	300	870	31,000	91	0.5	75	16		
317	176	4,100	380	900	680	23,400	63	0.9	38	11		
318	219	4,100	360	200	780	26,700	79	1.2	36	14		
319	216	5,600	490	300	1,120	32,700	79	0.9	68	16	53	98.3
320	215	3,900	330	200	860	26,300	75	0.9	46	13		
321	170	3,600	390	200	640	22,600	78	2.4	48	13		
324	350	5,300	470	300	950	50,100	75	1.9	45	13		
325	220	3,900	390	300	740	27,700	89	0.9	30	15	61	97.6
326	220	5,400	490	300	820	30,900	64	2.7	63	14		
331	264	5,700	550	300	1,180	34,700	54	0.6	50	10		
332	173	4,100	450	300	760	22,900	71	2.9	42	14		
333	355	9,600	870	700	1,610	46,200	73	5.9	78	14	80	95.9
334	423	5,900	570	500	950	27,900	58	1.0	34	11		

TABLE 6-3. DEMONSTRATION PROGRAM
CONTINUOUS DATA SUMMARY

ENTIRE DEMONSTRATION PROGRAM		
Solvent into adsorber - l (gal)	22,834	(6,032)
Solvent emissions from adsorber - l (gal)	193	(51)
Solvent recovered - l (gal)	16,202	(4,280)
Natural gas consumption - m^3 (ft^3)	14,561	(514,200)
Electricity consumption - kWh	23,654	
Water consumption - l (gal)	185,712	(49,060)
Wastewater to sewer - l (gal)	156,338	(41,300)
Method 1 efficiency	99%	
Method 2 efficiency	71%	
DEMONSTRATION PROGRAM AFTER HEEL ATTAINMENT		
Solvent into adsorber - l (gal)	15,077	(3,983)
Solvent emissions from adsorber - l (gal)	174	(46)
Solvent recovered - l (gal)	11,424	(3,018)
Natural gas consumption - m^3 (ft^3)	7,660	(270,400)
Electricity consumption - kWh	13,803	
Water consumption - l (gal)	105,197	(27,790)
Wastewater to sewer - l (gal)	82,901	(21,900)
Method 1 efficiency	99%	
Method 2 efficiency	76%	

TABLE 6-4. DEMONSTRATION PROGRAM WEEKLY UTILITIES CONSUMPTION OF THE CARBON ADSORPTION UNIT

Week of (1978)	Natural gas consumption 10^9 J/wk	(10^6 Btu/wk)	Electricity consumption 10^9 J/wk	(10^6 Btu/wk)	Water consumption 10^3 l/wk	(10^3 gal/wk)	Wastewater to sewer 10^3 l/wk	(10^3 gal/wk)
July 24	61.9	(58.6)	6.1	(5.8)	ND	(ND)	16.3	(4.3)
July 31	28.1	(26.6)	ND	(ND)	9.1	(2.4)	ND	(ND)
August 7	35.9	(34.0)	ND	(ND)	11.4	(3.0)	10.2	(2.7)
August 14	39.3	(37.2)	5.6	(5.3)	12.1	(3.2)	11.4	(3.0)
August 21	35.5	(33.6)	6.0	(5.7)	11.0	(2.9)	12.1	(3.2)
August 28	37.1	(35.1)	6.2	(5.9)	11.4	(3.0)	9.8	(2.6)
September 4	27.8	(26.3)	4.4	(4.2)	8.7	(2.3)	7.6	(2.0)
September 11	28.0	(26.5)	4.6	(4.4)	8.7	(2.3)	6.4	(1.7)
September 18	22.9	(21.7)	3.7	(3.5)	7.2	(1.9)	ND	(ND)
September 25	43.3	(41.0)	5.5	(5.2)	11.7	(3.1)	ND	(ND)
October 2	20.0	(18.9)	3.3	(3.1)	6.1	(1.6)	ND	(ND)
October 9	29.2	(27.7)	5.0	(4.7)	9.1	(2.4)	ND	(ND)
October 16	29.2	(27.7)	4.2	(4.0)	9.5	(2.5)	6.8	(1.8)
October 23	25.1	(23.8)	3.6	(3.4)	8.3	(2.2)	5.7	(1.5)
October 30	30.1	(28.5)	4.4	(4.2)	11.0	(2.9)	6.8	(1.8)
November 6	34.2	(32.4)	4.2	(4.0)	12.1	(3.2)	7.9	(2.1)
November 13	23.2	(22.0)	3.6	(3.4)	7.6	(2.0)	6.8	(1.8)
November 20	10.6	(15.1)	2.9	(2.7)	5.3	(1.4)	3.4	(0.9)
November 27	27.6	(26.1)	2.9	(2.7)	9.1	(2.4)	6.8	(1.8)
Average	31.3	(29.6)	4.4	(4.2)	9.5	(2.5)	8.3	(2.2)

[a]Conversion: 1031 Btu/ft^3 natural gas.

[b]Conversion: 3414 Btu/kWh.

[c]ND - No data.

TABLE 6-5. COMPARISON OF PROCESS SOLVENT AND RECOVERED SOLVENT PROPERTIES

Week of (1978)	July 24	July 31	Aug 7	Aug 14	Aug 21	Aug 28	Sept 4	Sept 11	Sept 18	Sept 25	Oct 2	Oct 9	Oct 16	Oct 23	Oct 30	Nov 6	Nov 13
I. Distillation range difference between process solvent and recovered solvent (in ^{0}C) (% solvent evaporated)																	
0	0.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.5	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0
2	2.0	0.0	1.0	0.0	1.0	0.0	0.0	1.0	1.0	2.0	1.0	1.0	1.0	0.5	1.0	2.0	1.0
5	0.0	0.5	1.0	0.5	0.5	0.0	1.0	1.0	2.0	0.5	1.0	0.5	1.0	0.5	2.0	1.0	1.0
10	0.5	1.0	1.0	0.5	1.0	0.0	1.0	0.0	1.5	1.0	1.0	0.5	2.0	0.5	1.0	1.0	1.0
20	1.5	0.0	0.5	1.0	1.0	0.5	0.0	1.0	1.5	1.0	1.5	1.0	2.0	0.0	0.5	1.0	0.5
30	1.0	0.0	1.0	1.0	1.0	0.5	0.0	1.0	1.5	0.5	1.0	1.0	0.5	0.5	0.0	1.0	1.0
40	1.5	1.0	0.5	1.0	1.0	0.0	1.0	0.0	1.5	0.0	1.5	1.5	1.0	0.5	0.5	1.0	1.5
50	2.0	1.0	1.0	0.5	1.0	0.0	1.0	1.0	1.0	0.5	2.0	1.0	3.0	0.0	1.0	1.0	1.5
60	2.0	0.5	1.0	1.0	1.0	1.0	0.5	0.5	1.0	1.0	1.0	0.5	1.0	0.5	1.0	1.0	2.0
70	2.0	0.0	0.5	1.5	1.0	1.0	1.0	0.5	0.5	1.0	1.0	1.0	1.0	0.5	1.0	0.0	2.0
75	2.3	1.0	0.5	1.5	1.0	1.0	1.0	0.5	0.0	0.5	0.5	1.0	1.0	0.0	1.0	0.5	1.0
80	2.0	1.0	0.5	2.0	0.5	1.0	0.5	0.5	0.0	1.0	1.0	1.0	1.0	0.0	1.0	0.5	1.0
90	4.0	0.0	1.0	2.0	1.0	1.0	0.0	0.0	0.5	2.0	1.0	2.0	1.5	3.0	1.0	1.0	4.0
95	5.0	2.5	1.5	0.5	0.0	1.0	1.5	3.0	1.0	1.0	1.5	2.5	1.5	4.0	0.0	0.5	2.0
end point	6.0	4.0	5.0	3.0	0.0	1.0	0.5	4.0	0.5	1.0	0.5	3.0	3.0	3.0	1.0	0.0	3.0
II. Acidity difference between process solvent and recovered solvent (mg eq KOH/100 ml)	5.1	5.1	0.0	0.0	0.0	0.0	0.0	8.2	5.1	5.1	0.0	5.9	0.0	0.0	0.0	5.1	0.0
III. Kauri-Butanol value difference between process solvent and recovered solvent	1.0	1.0	0.5	0.5	0.5	0.5	0.2	0.0	0.0	0.5	0.2	0.0	0.0	0.0	0.4	0.0	0.5
IV. Bromine number difference between process solvent and recovered solvent	*ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.2	0.4	0.7	0.8	0.0	0.2	0.0
V. Flash point difference between process solvent and recovered solvent (^{0}C)	3	1	1	ND	ND	ND	3	3	0	4	1	1	1	1	1	2	3
VI. Solvent composition difference as determined by gas chromatograph (volume % by carbon fraction)																	
C_{12}	1.0	0.1	0.8	0.4	0.9	0.2	2.5	0.7	0.9	1.9	1.1	0.4	3.0	1.4	0.6	1.6	2.8
C_{13}	2.0	0.2	0.8	6.6	1.7	1.9	1.3	0.2	0.8	1.5	4.4	0.9	0.7	0.9	5.2	1.9	1.7
$C_{14}+C_{15}$	1.3	2.0	2.1	1.7	0.2	0.1	1.8	1.6	0.1	1.1	2.7	0.1	0.3	1.8	0.8	1.5	2.2
C_{16}	1.2	0.1	3.9	1.3	1.5	1.0	0.4	2.1	1.8	0.7	1.8	0.1	0.8	0.4	1.5	0.6	0.5
C_{17+}	1.4	2.4	2.4	0.6	1.3	3.0	0.2	0.4	0.1	0.8	5.2	0.5	2.6	4.6	2.3	1.8	2.0
VII. Solvent content of wastewater (ppm)	0.25	0.25	0.08	0.16	0.11	0.12	0.12	0.01	0.01	0.02	0.01	0.01	0.01	0.03	0.05	0.02	0.12

TABLE 6-6. TYPICAL ANALYSIS OF STODDARD SOLVENT

Distillation Range-percent	Neat Solvent °C	Recovered Solvent °C
IBP	155	154
2	157	158
5	158	160
10	160	161
20	162	162.5
30	164	164
40	165.5	166
50	167	168
60	169	170
70	172	173
75	173	174
80	175	176
90	179	178
95	182	182
EP	183	184
Acid # (mg KOH/ml)	15.3	15.3
KB Value	30.1	30.5
Br # (mg Br/ml)	0.3	0.3
Flash Point °C	34.4	33.9
Gas Chromatography		
C_{12}	13.7%	14.3%
C_{13}	23.6%	18.4%
C_{14-15}	44.7%	45.5%
C_{16}	9.4%	10.9%
C_{17+}	8.6%	10.9%
Wastewater - Solvent	0.05 ppm	

Operating Labor

The amount of labor required to operate the carbon adsorption unit designed by VIC Manufacturing was estimated on the basis of TRW operating data. For the purpose of comparison with the optimization studies, the estimated labor requirements were broken into the following four categories:

1) Start-up
2) Filter cleaning
3) Shutdown
4) Miscellaneous

The labor requirement is of a non-professional nature; however, some training is required. The non-optimized system operating labor is presented in Table 6-7.

TABLE 6-7. DEMONSTRATION PROGRAM - OPERATING LABOR

Operation	Labor hours/Days
Adsorber start-up	0.25
Boiler start-up	0.25
Filter cleaning	1.50
Shutdown	0.50
Miscellaneous	0.50
Total	3.00
Weekly total	15.00
Annual total	780.00

OPTIMIZATION STUDIES

The optimization studies ran from December 4, 1978, through March 23, 1979. The information presented in this section refers to data collected during that period.

Change of Filter System

The parameter studied during the change of the filter system test was operating labor. The object of the modification was to reduce the amount of labor required for daily operation of the system. The results of this test are shown in Table 6-8.

TABLE 6-8. OPTIMIZATION PROGRAM - OPERATING LABOR

Operation	Labor hours/day
Adsorber start-up	0.25
Boiler start-up	0.25
Filter cleaning	0.50
Shutdown	0.50
Miscellaneous	0.50
Total	2.00
Weekly total	10.00
Annual total	520.00
Percent reduction	33%

Blower Cycle Alteration

The purpose of this test was to reduce the electricity consumption of the carbon adsorption unit. Electricity usage was, therefore, monitored as explained in Section 4. Table 6-9 represents the savings which result from this modification.

TABLE 6-9. OPTIMIZATION PROGRAM
TASK 2 - BLOWER CYCLE ALTERATION ELECTRICITY CONSUMPTION

Week of (1979)	Electricity consumption 10^9 J/wk	(10^6 Btu/wk)
January 15	4.2	(4.0)
January 29	4.3	(4.1)
February 5	4.1	(3.9)
February 19	3.8	(3.6)
February 26	3.5	(3.3)
Average	4.0	(3.8)
Pre-optimization average	4.4	(4.2)
Percent reduction	10%	

TABLE 6-10. OPTIMIZATION PROGRAM
TASK 3 - ADSORPTION/DESORPTION CYCLE ALTERATION

Week of (1979)	Natural gas consumption		Water consumption		Wastewater to sewer	
	10^9 J/wk	(10^6 Btu/wk)	10^3 l/wk	(10^3 gal/wk)	10^3 l/wk	(10^3 gal/wk)
January 15	18.6	(17.6)	6.8	(1.8)	6.8	(1.8)
January 29	18.7	(17.7)	6.8	(1.8)	4.9	(1.3)
February 5	17.5	(16.6)	6.1	(1.6)	1.9	(0.5)
February 19	14.3	(13.5)	4.9	(1.3)	3.0	(0.8)
February 26	13.9	(13.2)	4.9	(1.3)	4.2	(1.1)
Average	16.6	(15.7)	5.8	(1.5)	4.2	(1.1)
Pre-optimization Average	31.3	(29.6)	9.5	(2.5)	8.3	(2.2)
Percent reduction	47%		40%		50%	

Adsorption/Desorption Cycle Alteration

As previously explained, one of the purposes of this operation modification was to reduce the consumption of water and natural gas by the boiler. Table 6-10 shows the reductions which result from this operation.

It was important during this task to ensure that the adsorber efficiency did not fall below the minimum acceptable level. Efficiency data for this test, therefore, are presented in Table 6-11.

TABLE 6-11. OPTIMIZATION PROGRAM ADSORBER EFFICIENCY DATA
TASK 3 - ADSORPTION/DESORPTION CYCLE ALTERATION

December 4, 1978 - January 12, 1979			
Solvent into adsorber - l (gal)	5016		(1325)
Solvent emissions from adsorber - l (gal)	208		(55)
Solvent recovered - l (gal)	3721		(983)
Method 1 efficiency		96%	
Method 2 efficiency		74%	

Carbon Bed Depth Adjustment

Two breakthrough tests were conducted to determine the depth of the mass transfer zone in the carbon beds. The first test was conducted during the week of January 22, 1979, and the second during the week of February 12, 1979. The results of both tests are presented in Table 6-12.

TABLE 6-12. OPTIMIZATION PROGRAM BREAKTHROUGH ANALYSIS RESULTS

Test 1 - January 22-24, 1979		
Total solvent into adsorber - l (gal)	587	(155)
Average solvent recovered at breakthrough - l (gal)	227	(60)
Total solvent emissions from adsorber - l (gal)	121	(32)
Total solvent recovered - l (gal)	450	(119)
Total cycles adsorbed	32	
Cycles adsorbed at breakthrough	14	
Cycles adsorbed at saturation	25	
Calculated MTZ depth - m (in)	0.7	(29.6)

(continued)

Test 2 - February 12-15, 1979

Total solvent into adsorber - l (gal)	927	(245)
Average solvent recovered at breakthrough - l (gal)	227	(60)
Total solvent emissions from adsorber - l (gal)	416	(110)
Total solvent recovered - l (gal)	447	(118)
Total cycles adsorbed	42	
Cycles adsorbed at breakthrough	14	
Cycles adsorbed at saturation	25	
Calculated MTZ depth - m (in)	0.7	(29.6)

Desorption Alteration

As described in Section 5, the steam cycle was changed during this test. Adsorber efficiency was monitored throughout the duration of the alterations to determine whether or not a reduction had occurred. As explained, adsorber efficiency was reduced and the steam cycle was returned to 60 min. The results of the 45 min and 50 min tests are shown in Table 6-13. In addition, the natural gas and water consumption rates for the tests are presented in Table 6-14. It must be noted that these gas and water consumption figures show reductions over the pre-optimization rates and the Task 3 rates. Due to the decrease in adsorber efficiency, however, these are not representative of the optimized system.

Air Cooler Reduction Test

During the period of this test, the inlet air stream and carbon bed temperatures were closely monitored to determine if the recommended maximum of 57°C (135°F) was exceeded. Table 6-15 lists the maximum temperature recorded during each day of the test.

Optimized System

Presented in Tables 6-16 and 6-17 are all continuous data collected during the optimization program. Table 6-18 is a summary of adsorber efficiency data collected during the period when the system was operated at the optimum level. Table 6-19 presents the weekly utilities consumption summary for the optimized system.

Solvent analyses were performed four times during the optimization study. The results of these analyses are presented in Table 6-20.

SPECIAL TESTS

Carbon Analysis

Carbon samples were collected four times during the test program and analyzed for carbon activity and retentivity. Carbon activity was measured using perchloroethylene adsorption at 21°C (70°F) and carbon

TABLE 6-13. OPTIMIZATION PROGRAM ADSORBER EFFICIENCY DATA
TASK 5 - DESORPTION ALTERATION

March 6, 1979 - March 23, 1979		
45-Min steam cycle		
Solvent into adsorber - l (gal)	1094	(289)
Solvent emission from adsorber - l (gal)	79	(21)
Solvent recovered - l (gal)	859	(227)
Method 1 efficiency	93%	
Method 2 efficiency	79%	
50-Min steam cycle		
Solvent into adsorber - l (gal)	2010	(531)
Solvent emissions from adsorber - l (gal)	189	(50)
Solvent recovered - l (gal)	1609	(425)
Method 1 efficiency	91%	
Method 2 efficiency	80%	

TABLE 6-14. OPTIMIZATION PROGRAM
TASK 5 - DESORPTION ALTERATION

Week of (1979)	Natural gas consumption 10^9 J/wk	(10^6 Btu/wk)	Water consumption 10^3 l/wk	(10^3 gal/wk)	Wastewater to sewer 10^3 l/wk	(10^3 gal/wk)
March 5	14.1	(13.4)	4.9	(1.3)	3.0	(0.8)
March 12	11.1	(10.5)	4.2	(1.1)	1.9	(0.5)
March 19	14.8	(14.0)	4.9	(1.3)	2.6	(0.7)
Average	13.3	(12.6)	4.7	(1.2)	2.5	(0.7)
Pre-optimization average	31.3	(29.6)	9.5	(2.5)	8.3	(2.2)
Percent reduction over pre-optimized system	57%		51%		69%	
Task 3 average	16.6	(15.7)	5.8	(1.5)	4.2	(1.1)
Percent reduction over task 3	20%		20%		38%	

TABLE 6-15 OPTIMIZATION - TASK 6
AIR COOLER REDUCTION TEST

Date (1979)	Water flow through air cooler (l/day)	(gal/day)	Daily maximum inlet temperature (^oC)	(^oF)
March 9	678	(179)	35	(95)
March 12	568	(150)	35	(95)
March 13	598	(158)	33	(91)
March 14	568	(150)	36	(97)
March 15	265	(70)	37	(98)
March 19	231	(61)	34	(93)
March 20	49	(13)	35	(95)
March 21	0	(0)	47	(117)
March 22	0	(0)	51	(124)
March 23	0	(0)	50	(122)

*Number of readings exceeding 57^oC (135^oF) = 0.

TABLE 6-16. SUMMARY OF DRY CLEANING CARBON ADSORPTION OPTIMIZATION PROGRAM OPERATING DATA (METRIC UNITS)

Julian date (1978)	Electrical consumption of system kWh	Natural gas consumption of boiler ft^3	Water consumption of boiler (l)	Decanted water to sewer (l)	Water flow to tower cooler (l)	Water flow to condenser (l)	Solvent introduced adsorber (l)	Solvent air emissions from adsorber (l)	Recovered solvent (l)	No. dry cleaning cycles (per day)	% Recovered (weekly)	Emissions reduction (weekly)
338	207	210	2687	2650	3179	79107	270	24.1	189	14		
339	267	99	1893	757	3142	133989	280	6.1	174	15		
340	311	102	1552	1136	4883	147237	241	15.5	159	15	.75	95.2
341	311	99	1287	757	4883	143830	244	11.9	193	13		
342	266	91	1363	757	4466	130960	212	2.5	216	12		
345	261	93	1211	1136	4883	127180	270	6.5	189	13		
346	312	99	1476	757	4504	136260	284	13.7	201	15		
347	217	93	1325	1136	4542	117710	226	10.1	220	12	.83	96.3
348	265	105	1628	757	4050	120740	270	12.5	220	13		
349	173	93	1363	1136	3104	87606	234	5.3	235	12		
353	223	96	1552	757	2157	215745	147	4.0	167	9	.89	96.7
354	265	93	1741	1136	4315	123310	201	7.2	144	12		
1979												
003	220	108	1476	1136	3709	93110	123	2.2	144	7		
004	215	93	1287	757	4921	127550	180	3.2	189	11	.90	97.9
005	265	99	1287	1136	3671	117710	241	5.8	155	12		
008	353	93	1325	757	3407	162380	310	23.0	233	16		
009	218	102	1400	757	2460	113550	288	15.1	243	13		
010	261	93	1211	1136	3104	100680	259	14.1	224	14	.87	94.9
011	203	93	1476	757	6737	91980	241	7.5	238	13		
012	217	91	1325	757	3407	113930	244	9.0	229	12		
015	216	109	1400	757	2990	126040	226	11.1	229	13		
016	262	112	1249	757	4012	140420	292	17.6	224	16		
017	260	106	1249	757	4126	133530	342	25.6	243	17	.90	94.0
018	215	122	1400	757	3671	126040	270	16.5	262	13		
019	219	116	1363	757	3369	103330	216	9.7	257	12		
022*	221	0	0	0	2839	107120	226	6.5	0	13		
023*	172	0	0	0	2729	96900	270	76.2	0	14		
024*	171	184	2309	2271	4201	110900	90	40.3	449	5	.83	87.0
025	263	93	1211	379	4050	129070	306	16.9	267	14		
026	260	96	1363	757	4542	136640	292	14.3	265	15		
029	264	102	1249	757	4277	140420	280	10.5	265	13		
030	259	88	1173	757	4466	162760	292	15.9	269	15		
031	260	102	1287	757	1438	140045	306	36.7	299	15	.94	92.9
032	171	99	1249	757	2271	114310	230	19.4	227	12		
033	262	96	1211	379	4693	140420	259	14.1	227	15		

(continued)

TABLE 6-16. (continued)

Julian date (1978)	Electrical consumption of system kWh	Natural gas consumption of boiler ft3	Water consumption of boiler (l)	Decanted water to sewer (l)	Water flow to tower cooler (l)	Water flow to condenser (l)	Solvent introduced adsorber (l)	Solvent air emissions from adsorber (l)	Recovered solvent (l)	No. dry cleaning cycles (per day)	% Recovered (weekly)	Emissions reduction (weekly)
036	168	91	1249	757	4769	111280	223	9.3	227	12		
037	259	96	1325	1136	5261	137400	288	8.6	223	13		
038	258	91	1022	757	2385	149510	288	8.3	227	14	.85	96.6
039	259	88	1173	379	4315	134370	288	11.5	227	13		
040	211	91	1136	1136	2233	106360	266	8.6	250	12		
043*	169	0	0	0	1211	88191	310	11.5	0	13		
044*	220	0	0	0	1060	85920	306	105.7	0	14		
045*	218	0	0	0	757	102195	313	298.8	0	15	.54	65.8
046*	123	263	3225	3028	2271	88948	0	0	448	0		
047	312	93	1211	757	1855	128690	295	2.5	213	13		
051	218	91	1249	757	1476	104088	262	5.0	244	12		
052	307	96	1173	757	1476	142695	389	21.9	254	19	.76	94.2
053	212	96	1211	757	1590	115064	356	22.6	278	16		
054	308	88	1136	379	1703	128312	367	30.2	269	17		
057	218	93	1211	757	1628	113550	377	17.3	279	14		
058	257	93	1211	757	2309	134368	356	20.5	259	15	.80	95.7
059	216	96	1173	757	1703	101817	294	9.3	270	14		
060	264	79	1363	757	1249	114307	292	9.7	252	13		
064	211	91	1249	757	3066	119228	252	10.1	237	11		
065	212	71	871	379	2914	102195	310	6.8	224	14		
066	256	71	1022	757	3104	123013	302	41.5	225	15	.83	95.8
067	216	71	984	379	1703	96139	205	4.0	210	10		
068	214	65	824	757	1855	167335	294	8.6	239	12		
071	212	62	946	379	2006	114686	292	27.0	185	14		
072	215	76	946	379	1514	119606	274	20.5	255	13	.81	91.8
073	263	74	984	379	1893	115064	266	18.7	237	14		
074	213	76	1211	757	1514	118092	256	23.4	208	13		
078	218	82	795	379	871	108630	277	12.9	220	13		
079	219	76	946	757	1022	97275	230	11.5	214	11		
080	264	82	1098	379	984	126040	288	38.9	167	15	.75	89.6
081	125	68	871	757	946	77590	198	22.3	145	10		
082	211	76	1022	379	1590	114690	220	40.7	162	12		

*Breakthrough test.

TABLE 6-17. SUMMARY OF DRY CLEANING CARBON ADSORPTION OPTIMIZATION PROGRAM OPERATING DATA (ENGLISH UNITS)

Julian date (1978)	Electrical consumption of system kWh	Natural gas consumption of boiler ft3	Water consumption of boiler (gal)	Decanted water to sewer (gal)	Water flow to tower cooler (gal)	Water flow to condenser (gal)	Solvent introduced adsorber (gal)	Solvent air emissions from adsorber (gal)	Recovered solvent (gal)	No. dry cleaning cycles (per day)	% Recovered (weekly)	Emissions reduction (weekly)
338	207	7400	710	700	840	20900	71	6.3	50	14		
339	267	3500	500	200	830	35400	74	1.6	46	15		
340	311	3600	410	300	1290	38900	64	4.1	42	15	.75	95.2
341	311	3500	340	200	1290	38000	64	3.1	51	13		
342	266	3200	360	200	1180	34600	56	0.7	57	12		
345	261	3300	320	300	1290	33600	71	1.7	50	13		
346	312	3500	390	200	1190	36000	75	3.6	53	15		
347	217	3300	350	300	1200	31100	60	2.7	58	12	.83	96.3
348	265	3700	430	200	1070	31900	71	3.3	58	13		
349	173	3300	360	300	820	23000	62	1.4	62	12		
353	223	3400	410	200	570	57000	39	1.1	44	8		
354	265	3300	460	300	1140	33900	53	1.9	38	12	.89	96.7
1979												
003	220	3800	390	300	980	24600	32	0.6	38	7		
004	215	3300	340	200	1300	33700	48	0.8	50	11	.90	97.9
005	265	3500	340	300	970	31100	64	1.5	41	12		
008	353	3300	350	200	900	42900	82	6.1	62	16		
009	218	3600	370	200	650	30000	76	4.0	64	13		
010	261	3300	320	300	820	26600	68	3.7	59	14	.87	94.9
011	203	3300	390	200	1780	24300	64	2.0	63	13		
012	217	3200	350	200	900	30100	64	2.4	61	12		
015	216	3300	370	200	790	33300	60	3.0	61	13		
016	262	3400	330	200	1060	37100	77	4.6	59	16		
017	260	3200	330	200	1090	36600	90	6.8	64	17	.90	94.0
018	215	3700	370	200	970	33300	71	4.4	69	13		
019	219	3500	360	200	890	27300	57	2.6	68	12		
022*	221	0	0	0	750	28300	60	1.7	0	13		
023*	172	0	0	0	721	25600	71	20.1	0	14		
024*	171	6500	610	600	1110	29300	24	10.6	118	5	.83	87.0
025	263	3300	320	100	1070	34100	81	4.5	71	14		
026	260	3400	360	200	1200	36100	77	3.8	70	15		
029	264	3600	330	200	1130	37100	74	2.8	70	13		
030	259	3100	310	200	1180	43000	77	4.2	71	15		
031	260	3600	340	200	380	37000	81	9.7	79	15	.94	92.9
032	171	3500	330	200	600	30200	61	5.1	60	12		
033	262	3400	320	100	1240	37100	68	3.7	60	15		
036	168	3200	330	200	1260	29400	59	2.5	60	12		
037	259	3400	350	300	1390	36300	76	2.3	59	13		
038	258	3200	270	200	630	39500	76	2.2	60	14	.85	96.6
039	259	3100	310	100	1140	35500	76	3.0	60	13		
040	211	3200	300	300	590	28100	70	2.3	66	12		

(continued)

TABLE 6-17. (continued)

Julian date (1978)	Electrical consumption of system kWh	Natural gas consumption of boiler ft3	Water consumption of boiler (gal)	Decanted water to sewer (gal)	Water flow to tower cooler (gal)	Water flow to condenser (gal)	Solvent introduced adsorber (gal)	Solvent air emissions from adsorber (gal)	Recovered solvent (gal)	No. dry cleaning cycles (per day)	% Recovered (weekly)	Emissions reduction (weekly)
043*	169	0	0	0	320	23300	82	3.0	0	13		
044*	220	0	0	0	280	22700	81	27.9	0	14		
045*	218	0	0	0	200	27000	83	78.9	0	15	.54	65.8
046*	123	9300	860	800	600	23500	0	0	118	0		
047	312	3300	320	200	490	34000	78	0.7	56	13		
051	218	3200	330	200	390	27500	69	1.3	64	12		
052	307	3400	310	200	390	37700	103	5.8	67	19		
053	212	3400	320	200	420	30400	94	6.0	73	16	.76	94.2
054	308	3100	300	100	450	33900	97	8.0	71	17		
057	218	3300	320	200	430	30000	100	4.6	74	14		
058	257	3300	320	200	610	35500	94	5.4	68	15		
059	216	3400	310	200	450	26900	78	2.5	71	14	.80	95.7
060	264	2800	360	200	330	30200	77	2.6	67	13		
064	211	3200	330	200	810	31500	67	2.7	63	11		
065	212	2500	230	100	770	27000	82	1.8	59	14		
066	256	2500	270	200	820	32500	80	11.0	59	15	.83	95.8
067	216	2500	260	100	450	25400	54	1.1	55	10		
068	214	2300	220	200	490	31000	78	2.3	61	12		
071	212	2200	250	100	530	30300	77	7.1	48.9	14	.81	91.8
072	215	2700	250	100	400	31600	72	5.4	67.3	13		
073	263	2600	260	100	500	30400	70	5.0	62.6	14		
074	213	2700	320	200	400	31200	68	6.2	55.0	13		
078	218	2900	210	100	230	28700	73	3.4	58.1	13		
079	219	2700	250	200	270	25700	61	3.0	56.5	11	.75	89.6
080	264	2900	290	100	260	33300	76	10.2	44.1	15		
081	125	2400	230	200	250	20500	52	5.9	38.3	10		
082	211	2700	270	100	420	30300	58	10.8	42.8	12		

*Breakthrough test.

TABLE 6-18. OPTIMIZATION PROGRAM - TASKS 2 AND 3
ADSORBER EFFICIENCY DATA

January 15, 1979 - March 6, 1979 (minus breakthrough tests)		
Solvent into adsorber - 1 (gal)	7336	(1938)
Solvent emissions from adsorber - 1 (gal)	379	(100)
Solvent recovered - 1 (gal)	6462	(1707)
Method 1 efficiency	95%	
Method 2 efficiency	88%	

TABLE 6-19. OPTIMIZATION PROGRAM - WEEKLY UTILITIES CONSUMPTION

Week of (1979)	Natural gas consumption		Electricity consumption		Water consumption		Wastewater to sewer	
	10^9 J/wk	(10^6 Btu/wk)	10^9 J/wk	(10^6 Btu/wk)	10^3 l/wk	(10^3gal/wk)	10^3 l/wk	(10^3gal/wk)
January 15	18.6	(17.6)	4.2	(4.0)	6.8	(1.8)	6.8	(1.8)
January 29	18.7	(17.7)	4.3	(4.1)	6.1	(1.6)	4.9	(1.3)
February 5	17.5	(16.6)	4.1	(3.9)	6.1	(1.6)	1.9	(0.5)
February 19	14.3	(13.5)	3.8	(3.6)	4.9	(1.3)	3.0	(0.8)
February 26	13.9	(13.2)	3.5	(3.3)	4.9	(1.3)	4.2	(1.1)
Average	16.6	(15.7)	4.0	(3.8)	5.8	(1.5)	4.2	(1.1)
Pre-optimization average	31.3	(29.6)	4.4	(4.2)	9.5	(2.5)	8.3	(2.2)
Percent reduction	47%		10%		40%		50%	

TABLE 6-20. OPTIMIZATION PROGRAM
COMPARISON OF PROCESS SOLVENT AND RECOVERED SOLVENT PROPERTIES

Week of	1978 Nov 27	1978 Dec 4	1979 Dec 11	1979 Feb 26
I. Distillation range difference between process solvent and recovered solvent (in ^oC) (% solvent evaporated)				
0	1	1	1	3
2	0.5	1	0.5	2
5	1	1	0	1
10	1	2	0	1
20	1	2	0.5	0
30	0.5	2	1	0
40	0.5	2	0.5	0.5
50	1	2	0.5	1
60	1	2	0	2.5
70	1	2	0	2
75	1	2	0	2
80	1	1.5	0.5	3.5
90	0	3	1	3
95	0.5	2	1.5	2
end point	2.5	2	0	2
II. Acidity difference between process solvent and recovered solvent (mg eq KOH/100 ml)	1.1	5.1	5.2	5.0
III. Kauri-Butanol value difference between process solvent and recovered solvent	1.1	0.2	1.5	1.5
IV. Bromine number difference between process solvent and recovered solvent (% Br Adsorbed)	0	0	0	0
V. Flash point difference between process solvent and recovered solvent (^oC)	2	3	5	3
VI. Solvent composition difference as determined by gas chromatograph (volume % by carbon fraction)				
C_{12}	4.6	1.3	2.0	4.5
C_{13}	1.6	1.4	4.3	2.0
$C_{14 + 15}$	1.3	2.3	1.0	1.0
C_{16}	1.6	2.2	2.2	1.5
C_{17}	0.1	1.8	1.0	1.4

retentivity was measured by air desorption at 21°C (70°F). All measurements were compared to a standard consisting of carbon collected from the beds prior to being exposed to solvent vapors.

All samples taken were judged to be acceptable in terms of activity and retentivity. No significant changes were observed over the period of the study, indicating that the life span of the carbon is acceptable for use with Stoddard solvent. The results of the carbon tests are presented in Table 6-20.

Inlet Measurement Verification

Throughout the test program, the amount of solvent entering the adsorber was estimated by Valley personnel by weighing the clothes before and after drying with the difference being assumed equal to the amount of solvent evaporated. This value exceeded the inlet quantity measured by TRW by approximately 14 percent on the average. The weight difference method, however, included water evaporation which was not measured by TRW.

In order to evaluate the validity of the TRW measurements, five tests were run in which loads of clothes were washed in solvent only (no water or detergent added) and dried. The weight loss measurements, therefore, represent only solvent emissions and can be easily compared to the TRW inlet measurements. The results of these tests are presented in Table 6-21. The average difference between the weight loss measurements for solvent-only loads and the TRW inlet measurements is 6.5 percent. This indicates that the average 14 percent difference previously mentioned is partially due to the water content of the clothes.

It must be noted that the weight loss measurements should only be used as approximations. Variations in the tare weight of the containers and in the weighing procedure itself result in a significant uncertainty. Two examples of this uncertainty are measurements made on December 27 and 29, 1978, where specific loads of clothes are reported to have weighed 6.8 and 17 kg (15 and 38 lbs) more, respectively, after cleaning than they did before dry cleaning. Although these are isolated cases, they do illustrate the problems associated with making this type of measurement.

TABLE 6-21. DEMONSTRATION PROGRAM - CARBON TEST RESULTS

Sample date	Sample	Activity	Retentivity	Density
August 7, 1978	Standard	69.6%	45.5%	
	Top	61.3%	45.7%	
	Middle	54.7%	22.2%	
	Bottom	53.5%	23.7%	
October 3, 1978	Standard	72.7%	48.2%	0.485 g/cm^3
	Top	51.3%	22.9%	0.584 g/cm^3
	Middle	42.9%	22.0%	0.541 g/cm^3
	Bottom	44.7%	23.1%	0.568 g/cm^3
November 16, 1978	Standard	69.4%	45.7%	0.479 g/cm^3
	Top	67.2%	38.5%	0.483 g/cm^3
	Middle	74.4%	42.6%	0.448 g/cm^3
	Bottom	69.3%	40.3%	0.515 g/cm^3
February 7, 1979	Standard	68.9%	45.5%	0.469 g/cm^3
	Top	46.9%	22.6%	0.537 g/cm^3
	Middle	66.1%	38.7%	0.466 g/cm^3
	Bottom	71.6%	42.6%	0.485 g/cm^3

TABLE 6-22. WEIGHT LOSS VERSUS SOLVENT INLET MEASUREMENTS

Date (1979)	Weight loss measurement kg (lb)	FID inlet measurement kg (lb)	% Difference
January 17	34.9 (77)	33.1 (93)	5.2
January 25	37.6 (83)	36.7 (81)	2.4
January 30	35.4 (78)	31.3 (69)	11.6
January 31	32.7 (72)	33.1 (73)	1.2
February 28	32.7 (72)	36.7 (81)	12.2
Average			6.5

SECTION 7

ERROR ANALYSIS

In order to effectively evaluate the technical and economic feasibility of using carbon adsorption as a hydrocarbon emissions control technique, it is necessary to determine the error band(s) associated with each relevant operating parameter.

This is accomplished by using the reported accuracies of each measurement device (as given by the corresponding manufacturer or estimated from the literature) and from these accuracies, calculating the maximum expected error, assuming all the associated errors are in the same direction.

Calculation of the maximum expected error for each process operating parameter (such as mass flow rate of hydrocarbons into the carbon adsorption unit) requires that all component errors be taken into account. Thus, for example, in the case of inlet hydrocarbon mass flow rate, the following elements affect the overall error: inlet hydrocarbon concentration measurement errors, errors related to measurement of the inlet flow rate (composed of the measurement device error and errors associated with calibration of the measurement device; errors associated with calibration of zero and span gas; errors associated with temperature measurement of the inlet gas stream to carbon adsorber; and errors associated with recorders used (both the strip chart recorder and the data logger). A table (Table 7-1) of each applicable process operating parameter and the component errors making up the maximum expected error is given; in addition, the maximum expected error for each process operating parameter is also given (Table 7-2).

For purposes of calculating the maximum expected error of the mass flow rate of hydrocarbons into and out of the carbon adsorber, the following mean hydrocarbon concentrations (based on weighted averages obtained during each respective test period) were used:

1. Mean hydrocarbon concentration into the carbon adsorber (both during the Demonstration test and Optimization test) - 2,100 ppm.

2. Mean hydrocarbon concentration out of the carbon adsorber (during the Demonstration test) - 15 ppm.

TABLE 7-1. COMPONENT ERRORS COMPRISING EACH PROCESS OPERATING PARAMETER

Process operating parameter	Component error	Rated accuracy	Reference
Mass flow rate of hydrocarbons	1) Hydrocarbon concentration	±1% f.s.	Beckman Instruments
	a. measurement device	±1% f.s.	Beckman Instruments
	b. instrument calibration	±2%	Air Products
	2) Inlet flow		
	a. measurement device	±2%	Thermo Systems
	b. instrument calibration	±10%	*
	3) Inlet temperature	±1%	+
	4) Recorder		
	a. strip chart recorder	±0.2% f.s.	Hewlett-Packard
	b. data logger	±0.3%	Fluke Manufacturing
Boiler operating costs	1) Natural gas flow rate to boiler	±0.8%	Public Service Co. of NC
	2) Water consumption of boiler	±1%	Durham City (NC) Water Department
Water consumption of condensers	1) Water usage of system condensers	±1%	Durham City (NC) Water Department
Electrical consumption of carbon adsorption system	1) Electric power requirements of system	±0.5%	Duke Power Company of NC
Solvent recovery rate	1) Measured solvent during Demonstration test	±15%	Estimated
	2) Solvent meter during Optimization test	±1%	Estimated
Operating labor	1) Labor necessary to operate and maintain carbon adsorption system	±20%	Estimated

*"Stack Sampling Technical Information, A Collection of Monographs and Papers (Volume II)", EPA-450/2-78-042b, U.S., EPA. Research Triangle Park, NC, October 1978.

+Leland, B. J. Correction of S-Type Pitot-static Tube Coefficients when used for Isokinetic Sampling from Stationary Sources. Environ. Sci. and Tech., 11:694, 1977.

TABLE 7-2. MAXIMUM EXPECTED ERROR FOR EACH PROCESS OPERATING PARAMETER

Process operating parameter	Maximum expected error
Mass flow rate of hydrocarbons into the carbon adsorber (both during Demonstration test and Optimization test)	-20% to +23%
Mass flow rate of hydrocarbons out of adsorber (during Demonstration test)	-79% to +126%
Mass flow rate of hydrocarbons out of carbon adsorber (during Optimization test)	-23% to +31%
Solvent recovery efficiency (during Demonstration test)	-23% to +41%
Solvent recovery efficiency (during Optimization test)	-21% to +24%
Steam utilization of carbon adsorption system	±2%
Water consumption of condensers	±1%
Quantity of recovered solvent (during Demonstration test)	±15%
Quantity of recovered solvent (during Optimization test)	±1%
Operating labor	±20%

3. Mean hydrocarbon concentration out of the carbon adsorber (during the Optimization test) - 100 ppm.

The maximum expected error in the amount of labor necessary for the proper operation and maintenance of the carbon adsorption system is estimated to be 20 percent. However, it should be noted that this operating parameter varies considerably on a day-to-day basis. This is due to some maintenance procedures required on an "as needed" basis (such as cleaning of the adsorption system filter).

A sample calculation employed to determine the maximum expected error in the inlet mass rate of hydrocarbons is given in Appendix A.

In the mass flow rate calculations of hydrocarbons into and out of the carbon adsorption system, it is assumed that the gas flow rate did not vary across the carbon adsorber. Thus, when determining the maximum expected error in the solvent removal efficiency of the carbon adsorption system, the errors associated with the flow rate would cancel. With this assumption, the maximum expected range of the emission reduction efficiency is calculated to be 98.4 percent to 99.8 percent for the Demonstration test and 93.9 percent to 96.3 percent for the Optimization study.

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1. Telecon. Nunn, A. B. Methods of Calculating the Mass Transfer Zone Depth in a carbon Bed. TRW Environmental Engineering Division, with Don Lee, VIC Manufacturing Co., February 22, 1979.

2. Telecon. Lutz, S. J. Inlet Gas Temperatures at Which Carbon Oxidation Begins to Occur. TRW Environmental Engineering Division, with J. W. Barber, VIC Manufacturing Co., September 5, 1978.

APPENDIX A

SAMPLE CALCULATION TO DETERMINE MAXIMUM EXPECTED ERROR BAND IN THE INLET MASS RATE OF HYDROCARBONS

RELEVANT COMPONENT ERRORS

1) Hydrocarbon analyzer: ±1 percent of full scale.
2) Hydrocarbon analyzer calibration gas: ±2 percent.
3) Flow rate measurement device: ±2 percent.
4) Flow rate measurement device calibration (velocity traverse): ±10 percent.
5) Inlet temperature measurement (thermocouple): ±1 percent.
6) Strip chart recorder: ±0.2 percent of full scale.
7) Data logger: ±0.3 percent.

Full scale calibration gas: 11,000 ppm

Expected component error from hydrocarbon analyzer (assuming average inlet concentration of 2,100 ppm):

$$\frac{(0.01)\ (11{,}000\ \text{ppm})}{2{,}100\ \text{ppm}} = \pm 5\%$$

Expected component error from strip chart recorder (assuming average inlet concentration of 2,100 ppm):

$$\frac{(0.002)\ (11{,}000)}{2{,}100\ \text{ppm}} = \pm 1\%$$

Low range expected error in inlet mass rate of hydrocarbons:

$1 - \{(.95)\ (.98)\ (.98)\ (.90)\ (.99)\ (.99)\ (.997)\}$ = 20 percent

Upper range expected error in inlet mass rate of hydrocarbons:

$1 - \{(1.05)\ (1.02)\ (1.02)\ (1.10)\ (1.01)\ (1.01)\ (1.003)\}$ = 23 percent.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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16. ABSTRACT

A carbon adsorption system was designed and installed on the exhaust outlet from a dryer at an industrial dry cleaning plant utilizing Stoddard solvent for cleaning purposes. Selected design and operating parameters were varied to determine their effect on annualized operating costs and system performance. After optimization, the carbon adsorber achieved a demonstrated efficiency in reducing hydrocarbon emissions of 95 percent.

17. KEY WORDS AND DOCUMENT ANALYSIS

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