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Onsite Solvent Recovery

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ONSITE SOLVENT RECOVERY

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NOTICE

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, Superfund-related activities, and pollution prevention. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

Passage of the Pollution Prevention Act of 1990 marked a significant change in U.S. policies concerning the generation of hazardous and nonhazardous wastes. This bill implements the national objective of pollution prevention by establishing a source reduction program at the EPA and by assisting States in providing information and technical assistance regarding source reduction. In support of the emphasis on pollution prevention, the "Waste Reduction Innovative Technology Evaluation (WRITE) Program" has been designed to identify, evaluate, and/or demonstrate new ideas and technologies that lead to waste reduction. The WRITE Program emphasizes source reduction and onsite recycling. These methods reduce or eliminate transportation, handling, treatment, and disposal of hazardous materials in the environment. The technology evaluation project discussed in this report evaluates new technology applications by measuring performance, the release of solvents into the environment, energy use, and the associated economics.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This study evaluated the product quality, waste reduction/pollution prevention, and economic aspects of three technologies for onsite solvent recovery. The technologies were (1) atmospheric batch distillation, (2) vacuum heat-pump distillation, and (3) low-emission vapor degreasing.

The atmospheric and vacuum distillation units were tested on spent methyl ethyl ketone (MEK) and spent methylene chloride (MC), respectively. Samples of spent, recycled, and virgin solvents at two industrial sites were subjected to physical and chemical tests to determine solvent quality. The quality of the recycled solvent was found to be acceptable for use in the specific applications examined during this study. Significant waste reduction was achieved by reducing the volume of spent solvent to distillation residue needing disposal.

The low-emission vapor degreaser (LEVD) is a fully enclosed alternative to conventional, open-top vapor degreasing. It was found to reduce air emissions by more than 99%, compared to a conventional vapor degreaser of the same production capacity.

Compared to disposal, the atmospheric and vacuum distillation units reduced operating costs significantly. The estimated payback period for these units was found to be less than 2 years. The LEVD reduced operating costs by reducing solvent losses and labor costs. The estimated payback for this unit was approximately 10 years.

The cost estimates were based on a full range of considerations including hardware, engineering, installation, operation, maintenance, contingency funds, and energy use. They did not, however, include potential changes in liabilities or impacts due to regulations planned, or in the process of being implemented.

This report was submitted in partial fulfillment of Contract Number 68-C0-0003, Work Assignment 2-36, under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from May 1, 1991 to September 30, 1993, and work was completed as of September 30, 1993.

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SECTION 1
PROJECT DESCRIPTION

This study, performed under the U.S. Environmental Protection Agency's (EPA) Waste Reduction and Innovative Technology Evaluation (WRITE) Program, was a cooperative effort between EPA's Risk Reduction Engineering Laboratory (RREL) and the Washington Department of Ecology. The objective of the WRITE Program is to evaluate, in a typical workplace environment, examples of prototype or innovative commercial technologies that have potential for reducing waste. The results of the evaluation then are made available to potential users.

For each technology to be evaluated, three issues were addressed. First, it must be determined whether the technology is effective. Because waste reduction technologies usually involve recycling or reusing materials, or using substitute materials or techniques, it is important to verify that the quality of the product continues to be satisfactory for the intended purpose. Second, the wastes and releases generated by the old and new systems must be calculated and compared. Third, the economics of the new technology must be quantified and compared with the economics of the existing technology. It should be clear, however, that traditional methods of calculating economics may not be sufficiently accurate to account for a list of benefits that represent a growing impact on the cost of doing business. These benefits include worker safety, morale and the resulting productivity, reduced company liability, reduced regulatory compliance (cost of permits, testing, record keeping, and reporting), increasing costs of disposal, as well as company reputation as good citizen and steward of resources. The quantification of these benefits is more difficult. This project did not include the evaluation of these benefits.

This study evaluated three technologies for recovering and reusing waste solvent on site. They were atmospheric batch distillation, vacuum heat-pump distillation, and low-emission vapor degreasing. These technologies were selected because of their waste reduction/pollution prevention potential, potential for wide applicability, and opportunity for testing.

PROJECT OBJECTIVES

The goal of this study was to evaluate three technologies that could be used to recover and reuse waste solvents. This study had the following critical objectives:

- Evaluate the product quality resulting from use of each technology
- Evaluate the waste reduction/pollution prevention potential of each technology
- Evaluate the costs/benefits (economics) of using each technology.

Direct comparisons among the three units were not an objective of this study, but rather, the suitability of each technology to its respective application and the consequential environmental considerations were evaluated.

DESCRIPTION OF THE TECHNOLOGIES

The three technologies evaluated are described below. In each technology category, a specific unit offered by a specific manufacturer was tested. However, other variations of these units (with varying capabilities) may be available from several vendors.

Atmospheric Batch Distillation

This is the simplest technology available for recovering liquid spent solvents. Units that can distill as few as 5 gallons (gal) or as much as 55 gal per batch are available. Some of these units can be modified to operate under vacuum for higher-boiling solvents (300°F or higher). In atmospheric distillation, the spent solvent is subjected to controlled heating. The solvent boils, turns into vapor, and leaves the still. Contaminants with higher boiling points (e.g., oil, solids) are left behind in the still, as distillation residue or still bottoms, and can be collected at the end of the batch. Typically, this residue is sent out for disposal. Distillate vapors are condensed to obtain the recycled solvent. Contaminant components that have lower boiling points than the solvent or that form an azeotrope with the solvent cannot be separated (without fractionation features) and may end up in the distillate.

The atmospheric batch unit used in this study was a Model LS-55D,* manufactured by Finish Thompson, Inc.* Figure 1 describes this 55-gal capacity atmospheric unit. A disposable polymer bag lines the still, and the spent solvent is poured into it. After the unit's lid is closed and sealed, the unit is switched on. An encapsulated heating element (direct heat) distills the solvent, which condenses and collects in a clean drum. Temperature settings can be varied according to

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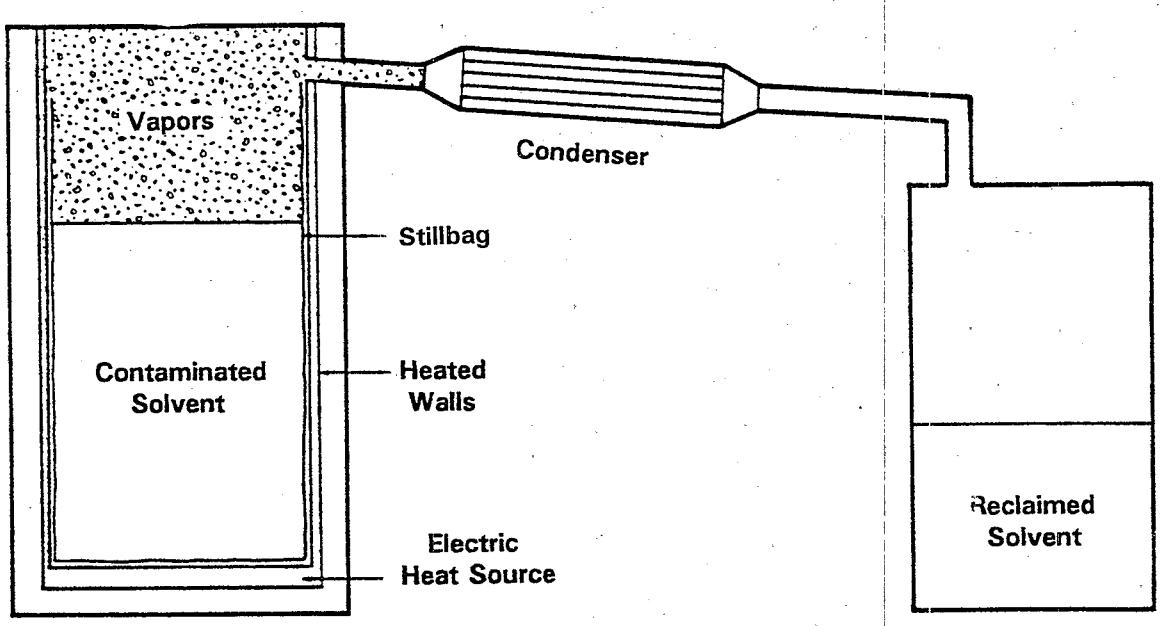

Figure 1. Atmospheric distillation unit.
(*Source*: Finish Thompson, Inc.)

the solvent. A sight glass indicates when no further distillate is available. The unit is then shut off and allowed to cool. Alternatively, a timer or a temperature controller is available as an option. The still bag containing the residue is removed and disposed of as hazardous waste.

The unit has several safety features, including explosion-proof design. Two thermostat controls ensure that the recommended heater temperature is not exceeded. A water flow switch/interlock is used to shut off the heater if water supply to the condenser is interrupted. For the configuration tested, uncondensed vapors escapes along the fill hose at the distillate drum as the drum slowly fills. Generally, solvent users have a flammable storage area that can meet the requirements of this operation. Roof vents also have been used in other, similar situations. However, additional safety requirements may be levied by insurers, such as an explosion-proof roof. Appendix A describes some variations in design and operation of atmospheric units offered by the same vendor to suit different applications.

Vacuum Heat-Pump Distillation

The unit tested, Model 040* is manufactured by Mentec AG* in Switzerland and supplied in the U.S. by Vaco-Solv Chicago, Inc.* As shown in Figure 2, the configuration is similar to that of a conventional vacuum distillation system except that the pump, in addition to drawing a vacuum, functions as a heat pump. No external heating or cooling is applied. The heat pump generates a vacuum for distillation and compresses vapors for condensation. The Model 040 used in the testing is suitable for solvents with boiling points up to 80°C.

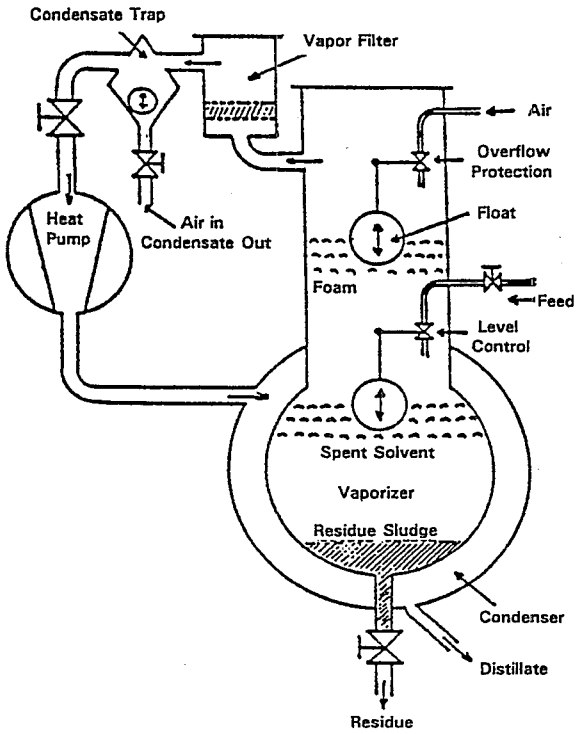

Figure 2. Vacuum heat-pump distillation unit.
(*Source*: Vaco-Solv Chicago, Inc.)

As shown in Figure 2, the spent solvent is continuously sucked into the evaporator by a filling valve. The vacuum drawn generates vapors, which are sucked into the heat pump, compressed, and sent to the condenser. Temperature stabilizes automatically according to the specific solvent characteristics and the ambient. The condenser surrounds the evaporator allowing heat exchange between the cool spent solvent and the warm condensing vapors. Because of this heat exchange, this vacuum unit uses 50 to 75% less energy than a conventional distillation unit.

* Mention of trade names or products does not constitute endorsement for use.

The energy savings estimate is based on the power ratings of the heat pump (vacuum unit) and the electric heater (atmospheric unit).

The heat pump is a single-stage rotary vacuum pump, modified to operate in a solvent atmosphere. The pump oil is a type that is insoluble in solvent. Solvent vapor entering the pump is kept free of solid and liquid impurities by a vapor filter and condensate trap. An overflow protection device guards against foaming in the evaporator by releasing the vacuum.

A continuous distillate is produced and can be collected in a clean tank or drum. The residue at the bottom of the still can be intermittently drained for spent solvents containing less than 5% solids. For spent solvents with a higher solids content, continuous draining by means of a discharge pump may be necessary.

This unit can be retrofitted into an existing operation for continuous recycling. Alternatively, it can be used in a semicontinuous mode, whereby the inlet hose is dipped into a drum containing spent solvent. The unit then draws solvent continuously out of the spent solvent drum until it is empty. The recycled solvent is collected through the outlet hose in a clean drum. The unit is offered in nonexplosion-proof as well as explosion-proof design (for flammables). Appendix A describes some variations in design and operation of vacuum units offered by the same vendor to suit different applications.

Vacuum distillation generally improves process efficiency, leaving much less solvent behind in the residue. Although most solvents have fairly good heat stability, the stabilizers in the solvent can degrade during heating. Because the solvent boils at a lower temperature under vacuum, repeated solvent recycling is less harsh on the stabilizers. Baking and incrustation of the residue due to heating also are avoided. The continuous mode of operation of this unit is especially suitable for degreasing applications, in which continuous recycling of the solvent maintains good solvent quality at all times. This results in a lower heating-energy requirements, compared to a solvent that becomes progressively contaminated. The addition of a continuous distillation unit to a degreaser, as described below, can increase the throughput of the degreaser by reducing the cleaning cycle time and reducing the frequency of the degreaser shutdown time for solvent replacement or internal distillation cycles, which is a feature of the LEVD. These benefits have to be weighed against the added costs of purchasing and operating the extra hardware.

Low-Emission Vapor Degreasing

Low-emission vapor degreasing (LEVD) is a technology currently used in Europe, where vapor degreasers are regulated as a point source. Until recently, LEVD units were not

available in the United States, where a variety of conventional open-top vapor degreasers (with or without lids) are used instead.

Conventional vapor degreasing is a common method for cleaning machined parts, and the workload is inserted in a tank containing solvent vapors. The vapors condense on the parts, and the contaminants (e.g., oil) on the parts drain out with the condensate. The condensate drops into a sump, which is heated to produce more vapors. Before reaching the sump, the condensate passes through a water separator. This process continues until the workload reaches the same temperature as the solvent vapor and no more solvent condenses on it. The workload is then withdrawn and cooled. The solvent in the sump is used until excess contaminants accumulate in the spent solvent. The spent solvent is then discarded and fresh solvent is added. The spent solvent can be distilled by conventional means and reused. Alternatively, a continuous distillation unit (discussed above) can be directly hooked up to the sump so that solvent is continuously drawn from the sump, distilled, and returned to the sump.

However, previous studies (Battelle, 1992a) on conventional open-top vapor degreasers have showed that a large part of the solvent (more than 90% in some cases) is lost through air emissions. Although vapor degreasers are required to have primary cooling coils (tapwater cooled) and a certain freeboard height (typically 0.75 times the width of the opening or higher), air emissions are considerable. Air emissions are mainly workload-related, caused either by dragout of solvent on the workload itself (and subsequent vaporization) or by disturbance in the air-vapor interface during entry and exit of the workload. Other sources of air emissions are convection and diffusion during startup, operation, idling, shutdown, and, to a small extent, equipment leaks. Air emissions are a concern for metal finishers because many of the solvents used in vapor degreasing have been targeted by the EPA in the 33/50 Program. Both EPA and Occupational Safety and Health Administration (OSHA) regulations are becoming more stringent.

Improvements available for conventional vapor degreasers include increased freeboard height, refrigerated coils, and covers that eliminate drafts and reduce diffusion.

In contrast, low-emission vapor degreasers (LEVDs) are completely enclosed, airtight units. The unit tested in this evaluation was the Model 83S (Size 1) which is manufactured in the United States by Durr Automation, Inc.*

Figure 3 shows the operation of the LEVD. Approximately 1 hour before the shift begins, a timer on the unit switches on the heat to the sump. The solvent in the sump is allowed to reach vapor temperature. At this point, the vapor is still confined to the enclosed jacket around the working chamber. The parts to be cleaned (workload) are placed in a galvanized basket, which is

* Mention of trade names or products does not constitute endorsement for use.

lowered by a hoist from an opening in the top of the unit into the working chamber. Loads can range from 330 to 1100 lb (of steel parts) in this model. The lid is shut, the unit is switched on, and compressed air from an external source hermetically seals the lid. The lid remains shut until the full cleaning cycle is completed.

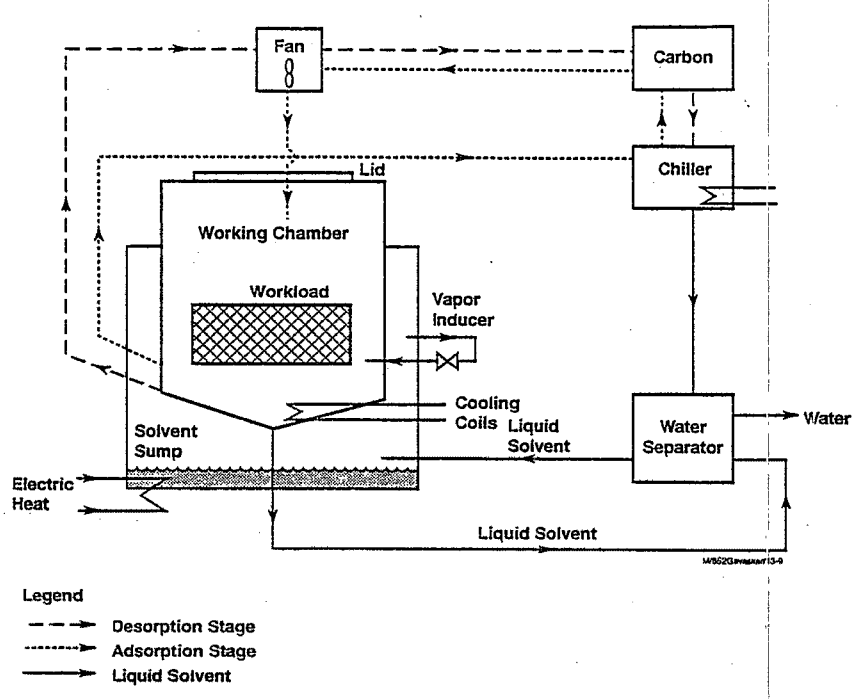

Figure 3. Low-emission vapor degreaser.
(*Source*: Durr Automation, Inc.)

Table 1 shows the various stages in a typical cleaning cycle. The table also shows typical time settings recommended by the manufacturer for each stage, as well as the actual time settings used during the testing for this evaluation.

The first stage in the cycle is an optional liquid solvent spray. This stage, which can be preset at 10 to 180 sec, is used only in certain cases when excessive contamination on the workload requires mechanical cleaning action. The second stage is the "vapor-fill" stage, during which solvent vapor is introduced into the working chamber for the first time. The vapor enters from near the bottom of the chamber and rises through the workload to a preset height, 1 ft below the lid of the chamber. Condensate from the parts is continuously drawn into a water separator and returned to the sump. This stage continues until the chamber temperature reaches 100°C. Stage time varies depending on type and mass of workload. The unit is then considered to be in its

optimum "degreasing" stage. The unit remains in this degreasing stage for a brief period (20 to 180 sec preset) for maximum cleaning.

TABLE 1. LEVD CLEANING CYCLE

Stage	Vendor-Recommended Time Settings	Times Set for this Testing
Solvent heatup (once a day)	Variable[a]	Variable[a]
Solvent spray (optional)	10-180 sec	not used
Vapor fill	Variable[b]	Variable[b]
Degreasing	20-180 sec	60 sec
Condensation	120 sec	120 sec
Air recirculation	120 sec	120 sec
Carbon heatup	Variable[c]	Variable[c]
Desorption	60 sec	60 sec
Adsorption	60-240 sec[d]	240 sec

[a] Requires approximately 1 hour on days following overnight shutdown when sump solvent temperature drops to 70°C. After weekend shutdowns, when sump solvent temperature drops to 20°C, it may take 1.5 hours for solvent to reach vapor temperature. Time on unit allows automatic heatup prior to beginning of shift.
[b] Varies depending on workload metal and mass.
[c] Carbon heatup took approximately 22.5 min during testing.
[d] At 60 sec, if monitor shows that chamber concentration is above 1 g/m^3, then the adsorption stage proceeds to the full 240-sec stage. This sequence repeats if necessary.

The unit then enters a 2-min (preset) "condensation" stage, in which the solvent vapors in the chamber are condensed out by a refrigerated cooling coil at the bottom of the chamber. The next stage is a 2-min (preset) "air recirculation" stage. In this stage, the air-solvent mixture in the chamber is recirculated continuously through a chiller to condense out more solvent, which goes to the water separator and then the sump. The unit then enters a "carbon heat-up" stage (stage time varies depending on initial carbon temperature). In this stage, the chamber air is heated by a compressor fan and passed through a carbon unit consisting of a series of activated carbon fiber mats. As the carbon mats heat up, the solvent captured during the previous cleaning cycle is released to the circulating air. The desorbed solvent is then condensed out in the chiller. This stage continues until the last (downstream) carbon mat reaches 70°C. At this point, the cycle

goes into a 1-min (preset) "desorption" stage to complete the desorption. The vendor is designing future modifications to the unit that would incorporate twin carbon beds to eliminate carbon heat-up and desorption stages.

The carbon is now ready to adsorb the solvent from the current cleaning cycle. In the "adsorption" stage, the chamber air is recirculated in the reverse direction — first through the chiller and then through the carbon. Most of the residual solvent vapor in the cold air is adsorbed on the carbon. The time for this stage can be preset to anywhere between 1 and 4 min. When this preset time is reached, a PID (photoionization detector) probe inside the working chamber verifies that the chamber air has less than 1 g/m^3 of solvent and signals the air compressor to release the seal on the lid to end the cycle. If the chamber air still has more than 1 g/m^3 of solvent, the cycle goes back to the desorption stage. The entire cleaning cycle is programmed and requires no operator attention other than for loading and unloading the workload. The LEVD system has no solvent exhaust during the entire cycle, except for a very small amount at the end, when the lid is opened.

Several safety features are built into the unit. When vapor in the outer jacket increases beyond a certain pressure, a thermostat turns off the heat to the sump to prevent more vapor from being generated. Inside the chamber, even though the lid is hermetically sealed, the vapor level is not allowed to rise above the working level (1 ft below the lid). If the vapor level rises above the working level, a thermostat signals a valve to stop any more vapor from entering the chamber.

The unit can also be operated as a distillation unit to clean the liquid solvent in the sump. In the distillation cycle, the unit is turned on without any workload in the chamber. After most of the solvent is converted to vapor, the residue in the sump is drained out. The vapors in the chamber are then condensed in the chiller to recover the solvent. The life of the solvent is thus extended without a separate liquid distillation machine. Appendix A describes some variations in design and operation of enclosed vapor degreasing units offered by the same vendor to suit different applications.

DESCRIPTION OF THE TEST SITES

The two liquid distillation units were tested at industrial sites where the units have been purchased and are being used. The LEVD unit was tested at its manufacturing site.

The Model LS-55D atmospheric unit was tested at Navistar International Transportation Corporation's Plastics Division in Columbus, Ohio. The atmospheric unit is used by Navistar to reclaim various solvents used in its paints division. For this evaluation, a test batch of spent

methyl ethyl ketone (MEK) was processed through the unit. MEK is used to clean the spray painting lines between colors. The spent solvent is collected in 55-gal drums and taken to the flammables storage area to be recycled. The recycled solvent is reused for the same purpose, and the residue is shipped off as hazardous waste.

The Model 040 vacuum unit was tested at Cooper Industries' Belden Division in Richmond, Indiana. The Belden Division manufactures wires and cables. The recovery unit was tested on spent methylene chloride (MC). The methylene chloride is used for cold (immersion) cleaning of wires and cables when markings (ink) are to be removed. Cooper has modified the Model 040 unit, by adding an air-cooled heat exchanger to allow it to operate at rates faster than those recommended by the manufacturer. When solvent is circulated through the unit at a rate higher than that recommended by the manufacturer, the distillate does not get enough chance to cool down and exits the unit at a higher temperature. This can lead to higher vapor losses at the point where the outlet hose enters the recycled solvent drum. Cooper uses a retrofitted air-cooled condenser to cool the distillate and reduce vapor losses.

LEVD technology has been in use in Europe for some time. However, this technology has only recently arrived on the U.S. market. Therefore, the 83S (Size 1) unit used in this study was tested at the manufacturing location in Davisburg, Michigan. Machined steel parts were processed several times to test the performance of the unit. Perchloroethylene (PCE) was the solvent used during this testing.

SUMMARY OF APPROACH

A Quality Assurance Project Plan (QAPP), prepared at the beginning of this study (Battelle 1992b), describes the detailed approach and scientific rationale used to evaluate the three technologies. Sections 2,3, and 4 of this report describe the actual testing conducted. Section 5 (Quality Assurance) of this report describes any deviations from the test plan in the original QAPP. For each technology, the evaluation covered issues of product quality, waste reduction/pollution prevention, and economics.

Product Quality Evaluation

The objective of this part of the evaluation for the two liquid distillation units was to show that the recycled solvent was of sufficient quality to allow its reuse. The approach was to process one 55-gal drum of spent solvent each through the batch and continuous units. Samples of the spent and recycled solvents were taken and analyzed to determine the improvement in

quality. A sample of virgin solvent also was collected at each site and subjected to the same tests as a basis for comparison.

The objective for the LEVD was to process test batches of machined parts, covered with cutting oil, through the unit and to ensure that the unit was performing its basic function — effective parts cleaning.

Waste Reduction/Pollution Prevention Evaluation

The waste reduction potential of the two distillation units was measured in terms of the amount of solvent that could be recovered and reused (current practice), rather than sent out for disposal (former practice).

The pollution prevention potential of the LEVD was measured in terms of its ability to prevent atmospheric emissions of solvent. Air emission information for conventional degreasers was obtained from previous EPA-sponsored studies (Battelle, 1992a, EPA, 1989). The overall potential for applying the technologies was estimated on the basis of annual solvent usage in the United States.

Economic Evaluation

For the two liquid distillation units, the economic evaluation consisted of a comparison between the cost of disposal versus the savings through recycling. For the LEVD, the cost of the LEVD operation was compared to the cost of operating a conventional degreaser of similar production capacity.

SECTION 2
PRODUCT QUALITY EVALUATION

This section describes the testing that was done to ensure that the new technology provides an acceptable product — clean solvent or clean parts.

ONSITE TESTING

The tests conducted at the evaluation sites are described below. All solvent samples collected were refrigerated until analysis.

Atmospheric Unit

Table 2 describes the samples collected and data gathered during the test run. Samples were collected in precleaned disposable glass tubes. The still was lined with a still bag, and the spent methyl ethyl ketone (MEK) from the test drum was pumped into it. The lid was closed and sealed, the tapwater flow was started through the condenser, and the unit was switched on. It took about 1.5 hr for the first condensate to appear through the outlet hose into the clean drum; this time is typical for the operation. The drum used to collect the recycled solvent was an empty drum that once had contained virgin MEK. The site reuses its empty drums in this fashion. The volumes obtained for the run were verified against the operator's logs to compare the test numbers with those from previous runs. The test run was determined to be typical of the operation.

Vacuum Unit

Table 2 describes the samples and data collected during the testing of the vacuum heat-pump distillation unit. It was noted that the sample collected as a "virgin" sample was actually a sample of methylene chloride (MC) that was obtained by Cooper from a solvent recycling company. The characteristics of this "virgin" solvent meet the requirements for the company's application, and this solvent has been used satisfactorily at the site in the past.

TABLE 2. ONSITE TESTING OF ATMOSPHERIC AND VACUUM UNITS

Recycling Unit	Solvent Type	Spent Solvent (gal)	Recycled Solvent (gal)	Residue (gal)	Run Time (hrs)	Samples Collected	Sample Number
Atmospheric	MEK[a]	55	39	16[c]	12	Spent Recycled[e] Virgin	MEK-S MEK-R MEK-V
Vacuum	MC[b]	55	48	3[d]	12	Spent Recycled[e] Virgin	MC-S MC-R MC-V

[a] MEK = methyl ethyl ketone
[b] MC = methylene chloride
[c] No significant losses to the atmosphere.
[d] Approximately 4 gal of solvent per 55-gal batch are lost due to air emissions.
[e] Duplicate analysis performed on recycled samples [(MEK-R Dup) and (MC-R Dup)].

To speed up the processing rate, the vacuum unit was being operated at a faster rate than that recommended by the manufacturer. The unit's built-in condenser-evaporator heat exchange was not sufficient for this rate. Cooper had therefore attached an additional air-cooled condenser at the outlet. With this extra device, the vapor loss at the outlet was restricted to approximately 4 gal per 55 gal of spent solvent. To prevent the release of this vapor into the work area, the vapor was led through a pipe to the roof of the facility and discharged at a rate within applicable State regulations. According to the manufacturer, this vapor loss can be prevented by operating the vacuum pump at a slightly lower rate.

LEVD

Table 3 describes the testing conducted on the low-emission vapor degreaser (LEVD) using perchloroethylene (PCE) solvent. Runs were conducted on machined steel parts. The parts were steel ridged cylinders (approximately 2-in diameter x 5-in height) and 6-in-diameter recessed steel disks. Runs were started variously with and without cutting oil on the parts. Total cycle times were recorded for all completed runs. Runs 1, 4, and 7 were interrupted for the reasons mentioned in Table 3. Because the same batch of parts was used for each run, parts were either cold (ambient) or hot (see Table 3) depending on the cooling time allowed between runs. The total cycle time varies depending on the initial temperature of the parts. If parts are already hot, the total cycle time is reduced. In general, the runs that start out with cold parts are more reflective of actual operating conditions. The addition of oil to the parts did not greatly affect the total cycle

time. The total cycle time varied considerably depending on the workload mass. The masses of the steel parts given in Table 3 do not include the mass of the basket, which weighed 65 lb.

TABLE 3. ONSITE TESTING OF LEVD

Day No.	Run No.	Initial Parts Temperature	Weight of Steel Parts[a] (lbs)	Oil on Parts at Start	Total Cycle Time (min)
1	1[b]	Ambient	165	No	–[b]
1	2	Hot[c]	165	No	39
1	3	Ambient	900	No	67.5
1	4[c]	Hot[c]	160	No	–[d]
2	5	Ambient	165	Yes	50.5
2	6	Hot[c]	165	Yes	40
2	7[d]	Hot[c]	165	Yes	–[e]
2	8	Ambient	915	Yes	69
2	9	Hot[c]	160	No	40

[a] Not including the weight of the 65-lb basket.
[b] Run 1 was interrupted because of power outage due to stormy weather. Was continued after machine was reprogrammed.
[c] Approximately 60 to 70°C above ambient.
[d] Purpose of Run 4 was to collect liquid solvent during the condensation and desorption cycles. This run was not timed.
[e] Run 7 had to be abandoned at carbon heatup stage due to carbon overheating. Wiring problem was corrected and normal functioning was restored for the next run.

In all the runs starting with parts dipped in cutting oil, the cleaned parts were visually examined for traces of oil contamination. This was done to ensure that the unit was performing its basic function, degreasing. No oil contamination was noticed on the surface of the parts from any of these runs.

LABORATORY ANALYSIS — PHYSICAL CHARACTERIZATION

Samples collected during onsite testing of the atmospheric and vacuum units were refrigerated and sent to the laboratory for analysis. The laboratory tests performed on the solvent samples included:

- color (ASTM D1209, D2108)
- specific gravity (ASTM D891-89, D2111-85)
- absorbance (EPA Method 110.3)
- nonvolatile matter (ASTM D1353, D2109)
- conductivity (EPA 120.1)
- water content (ASTM D1364, D3401)
- acidity (ASTM D1613)
- purity (ASTM D2804).

For the MC samples, the following additional tests were conducted:

- pH (ASTM D2110)
- acid acceptance (ASTM D2942)
- corrosion (ASTM D2251).

Appendix B describes the laboratory tests conducted on the solvent samples, their significance, and the standard methods used for the analysis. Duplicate analyses were performed on the recycled samples from both sites.

Atmospheric Unit

Table 4 describes the results of the physical characterization of the atmospheric unit samples. The spent solvent appeared to have collected a lot of dissolved and sedimentitious contamination during its use as a cleaner for paint lines. The recycled samples were relatively similar in appearance and color to that of the virgin sample. The specific gravity value of the recycled samples fell between the values of the spent and virgin samples. This indicated that recycling had caused a definite improvement, although not quite to virgin grade. Absorbance measurements indicated sharp differences between the spent solvent and the recycled solvent. There was very little difference between absorbance measurements on the recycled and virgin samples. Therefore, appearance, color, specific gravity, and absorbance could serve as quick indicators of solvent quality for onsite operators.

Vacuum Unit

Table 4 describes the results of the physical characterization of the vacuum unit samples. The spent MC differed noticeably from the recycled and "virgin" samples in appearance and color. The spent solvent appeared to have collected a substantial amount of contamination, primarily in solution, during its use for removing marking ink from wires. Specific gravity and

TABLE 4. PHYSICAL CHARACTERIZATION OF SOLVENT SAMPLES

Sample	Appearance	Color[a]	Specific Gravity	Absorbance 400 nm	500 nm	600 nm
Atmospheric Unit (MEK)						
Spent	Dark gray w/sediment	— [c]	0.845	4.5	4.5	4.5
Recycled	Clear	5	0.827	0.014	0.000	0.000
Recycled Dup[b]	Clear	5	0.821	0.016	0.002	0.001
Virgin	Clear	5	0.800	0.004	0.007	0.005
Vacuum Unit (MC)						
Spent	Dirty gray-brown	— [c]	1.220	1.824	1.674	1.435
Recycled	Clear	5	1.286	0.010	0.001	0.004
Recycled Dup[b]	Clear	5	1.288	0.014	0.011	0.006
Virgin	Clear, tinge of yellow	10	1.298	0.010	0.010	0.004

[a] On a scale of 5 to 500, with 500 being the darkest color.
[b] Duplicate analysis of the same sample.
[c] Not comparable with standards. Sample was too dirty.

absorbance characteristics of the recycled samples had been restored to levels fairly close to those of the "virgin" sample.

LEVD

Other than onsite measurements made during testing of the LEVD, there were no samples or laboratory analyses.

LABORATORY ANALYSIS — CHEMICAL CHARACTERIZATION

Chemical characterization parameters and the standard methods used are described in Appendix B. Duplicate analyses were performed on the recycled samples from both sites.

Atmospheric Unit

Table 5 describes the results of the chemical characterization. Nonvolatile matter (contamination) accounted for nearly 7% of the spent MEK sample. This was reduced to approximately 0.002% in the recycled sample, a value indistinguishable from that of virgin grade. Conductivity and acidity values of the recycled samples fell between those of the spent and virgin samples, indicating some improvement in these parameters. The water content increased from approximately 1.9% in the spent sample to approximately 5.5% in the recycled samples. This indicates that water contamination present in the spent solvent transfers to the distillate. However, the fact that the volume of the distillate is roughly 30% lower than the total volume of the initial spent batch explains only about 15% of this increase in water concentration. The remaining water must have entered the recycled solvent during the recycling process itself, possibly due to a slight leakage from the water-cooled condenser.

The MEK purity of the recycled sample showed a substantial improvement from the spent sample, increasing from 78% to about 85%. The large decrease in nonvolatile matter during recycling (discussed above) accounts for most of this increase in purity. Of the 15% impurity in the recycled sample, 5% is water as discussed above. The remaining 10% impurity is probably due to the codistilling out of paint thinner solvents (proprietary blends) present in the spent solvent and having similar boiling points.

Vacuum Unit

Table 5 describes the chemical characterization of MC samples from the vacuum unit testing. Caution should be exercised in interpreting the results because the so-called "virgin" solvent was actually purchased by the site from a solvent recycling company. Over time, this "virgin" solvent grade has proved sufficient for its application — removing marking inks from wires and cables.

TABLE 5. CHEMICAL CHARACTERIZATION OF SOLVENT SAMPLES

Sample	Nonvolatile Matter (mg/100 mL)	Conductivity (μmhos/cm)	Water Content (% by wt.)	Acidity (as acetic acid wt. %)	Purity (% by wt.)
Atmospheric Unit (MEK)					
Spent	6,951	7.05	1.89	.055	78.41
Recycled	2.6	3.30	5.42	.003	85.02
Recycled Dup	2.0	3.40	5.56	.003	85.54
Virgin	2.2	1.15	0.09	.002	99.09
Vacuum Unit (MC)					
Spent	34,101 ppm	1,063	0.27	NA	NA
Recycled	20.37 ppm	137	0.25	NA	86.4
Recycled Dup	17.88 ppm	136	0.24	NA	NA
Virgin	57.16 ppm	36	0.14	NA	90.1

NA = Not Applicable

Nonvolatile matter (contamination) content dropped from 3.4% in the spent to approximately 0.002% in the recycled samples. Conductivity values of the recycled samples were indistinguishable from the value of the "virgin" solvent but were clearly lower than that of the spent solvent, indicating an improvement. Water content values of the recycled samples were between those of the spent and the "virgin," without any of the values being particularly high.

The MC purity of the recycled solvent was 86%. This compares favorably with the "virgin" sample purity of 90%, given that much of the 10% impurity in the "virgin" sample is probably volatile. Volatile impurities present in the "virgin" solvent will codistill out into the recycled solvent.

Table 6 describes some performance characteristics of MC (a halogenated solvent). The pH of the water extract of the recycled solvent was fairly close to the "virgin" value of 7. Substantial improvement is indicated from the spent sample's pH of 5. The lower pH indicates the presence of potentially corrosive components in the spent solvent. The acid acceptance for all samples was below 0.16% NaOH, the minimum level specified for vapor degreasing-grade MC. Because the "virgin" sample also was below this level, it is difficult to judge the effect of recycling on stabilizer content. The corrosion test on steel and aluminum yielded noticeable corrosion only in the case of the steel strip placed in the spent solvent sample. No such corrosion was evident due to the recycled solvent, indicating that recycling improved the quality.

TABLE 6. PERFORMANCE CHARACTERISTICS OF METHYLENE CHLORIDE

Sample	pH	Acid Acceptance[a]	Corrosion	
			Steel	Aluminum
Spent	5.0	0.032	Rust[c]	No rust
Recycled	6.7	0.004	No rust	No rust
Recycled Dup	6.6	0.005	No rust	No rust
Virgin	7.0	0.003	No rust	No rust

[a] Measured as equivalent NaOH wt%.
[b] In terms of oxidation products (rust) showing up on the metal surface.
[c] Steel strip showed a number of rust marks on both sides.

LEVD

Only onsite measurements were made during the testing of the LEVD. No samples were taken or laboratory analyses performed.

PRODUCT QUALITY ASSESSMENT

Substantial improvement in the quality of the spent MEK solvent feed was brought about by the atmospheric unit. Standard solvent quality-monitoring parameters such as specific

gravity, absorbance, and conductivity showed a relatively good agreement between recycled and virgin solvent values. Nonvolatile matter was virtually removed from the recycled solvent. The MEK purity rose from 78% in the spent solvent to 85% in the recycled solvent. The recycled value was lower than the >99%-pure virgin grade, but the impurities are expected to be mainly paint thinners (solvents), which do not interfere during reuse in cleaning spray painting lines between colors. The presence of 5% water (traced to a small leak in the water-cooled condenser) in the recycled solvent is of concern, although the site did not report any adverse effect on the painting operation. The distillation unit has been at the site for several years and its condenser coil needs to be changed.

The vacuum unit considerably improved the quality of the spent MC solvent feed. The evaluation was complicated by the fact that the "virgin" solvent was actually purchased by the site from a solvent recycling company. This "virgin" grade itself was analyzed to be 90% pure MC. Hence, a large component of the spent solvent feed to the vacuum unit was (probably volatile) impurities accumulated over several previous recycles at the site from other sources. Even then, an 86% recycled MC purity was achieved by the vacuum unit. Nonvolatile matter was virtually removed. Standard solvent quality monitoring parameters, such as specific gravity, absorbance, and conductivity, showed relatively good agreement between recycled and "virgin" values, indicating that the recycled material was a fairly close approximation of the "virgin" grade. The pH of water extracts from the spent, recycled, and virgin samples showed that both the recycled solvent and the "virgin" sample had a pH close to 7, compared to a potentially corrosive spent sample pH value of 5. The corrosion test showed that spent solvent caused corrosion of steel, whereas the recycled solvent caused no noticeable corrosion.

The performance of the LEVD enabled oily parts to be cleaned to acceptable levels. It was noted that the enclosed design has potential for reducing water contamination of solvent from at least one source. Water contamination during degreasing normally occurs either through parts (workload) coated with water-soluble machine oils or through condensation of atmospheric moisture. In open-top vapor degreasers, there is a tendency for atmospheric moisture to condense out on cooling coils (especially refrigerated coils). In the enclosed design, only a limited amount of ambient air (equal to the free volume of the loaded chamber) comes into contact with the cooling surfaces of the unit. Therefore, there is less atmospheric contribution of water to the liquid solvent in the LEVD. Lower water contamination implies lower depletion of solvent stabilizers and acid formation by hydrolysis.

SECTION 3
WASTE REDUCTION/POLLUTION PREVENTION POTENTIAL

The waste reduction/pollution prevention aspects of the three technologies are discussed in this section.

ATMOSPHERIC UNIT

Table 7 describes the waste reduction achieved at the test site by this technology. Annual solvent usage was obtained from records maintained at the site during the year prior to recycling. Annual waste generation numbers were estimated from the data in Table 2 and from site records. The site generates 880 gal/yr of spent methyl ethyl ketone (MEK). With the disposal option, this entire volume (along with its 55-gal containers) would have been disposed of as a Resource Conservation and Recovery Act (RCRA) hazardous waste through a waste disposal company. Through recycling, this waste has been reduced to 262 gal of distillation residue (plus its containers), which is disposed of as RCRA hazardous waste.

The recycled solvent leaving the outlet hose has a near-ambient temperature, and vapor losses during recycling are minimum. Previously, the manufacturer supplied an airtight outlet hose-to-drum connection and a pipe to vent vapors to the roof of the facility. However, this has been discontinued, and the outlet hose now hangs loosely into the drum. The recycling unit is operated in an area of the site reserved for flammables storage.

MEK is a hazardous chemical listed on the Toxic Releases Inventory (TRI). It is also on the EPA's list of 17 chemicals targeted for 33% reduction by 1992 and 50% reduction by 1995.

VACUUM UNIT

Table 7 describes the waste reduction achieved at the test site by this technology. The annual solvent usage was obtained from records maintained at the site during the year prior to recycling. The annual waste generation numbers were estimated from the data in Table 2 and from site records. The site generates 3,000 gal/yr of spent methylene chloride (MC). With the disposal

TABLE 7. WASTE REDUCTION BY ATMOSPHERIC AND VACUUM UNITS

-Disposal Option -		- Recycling Option -	
Wastestream	Annual Volume	Wastestream	Annual Volume
Atmospheric Unit Test Site:			
Spent MEK	880 gal	Distillation Residue	262 gal
Drums	17 drums	Still bags	17 bags
		Cooling water	18,360 gal
		Drums	5 drums
Vacuum Unit Test Site:			
Spent MC	3,000 gal	Distillation residue	136 gal
Drums	55 drums	Air emission	218 gal
		Drums	3 drums
		Used oil	1 gal

option, this entire volume (plus its 55-gal containers) would have been disposed of as a RCRA hazardous waste through a waste disposal company. Through recycling, this waste has been reduced to 136 gal of distillation residue (along with its containers), which is disposed of as RCRA hazardous waste. A very small sidestream of used oil is generated through a routine oil change on the vacuum pump. This oil is combined with other waste oil generated on the site and is disposed of according to State regulations for used oil disposal.

According to the manufacturer, air emissions due to the recycling process itself are largely avoidable, provided that the operating procedures recommended by the manufacturer are followed. However, this site has modified the unit to process faster, and this results in some air emissions (218 gal/yr based on Table 2) due to incomplete condensation of the vapors. These air emissions are vented from around the outlet hose to the roof through a temporary pipe in accordance with applicable regulations.

MC is a hazardous chemical listed on the Toxic Releases Inventory (TRI). It also is on the EPA's list of 17 chemicals targeted for 33% reduction by 1992 and 50% reduction by 1995.

LEVD

The pollution prevention aspect of the low-emission vapor degreaser (LEVD) was the main focus of this technology. The enclosed design of the working chamber restricts emissions to two paths. Normally emissions occur when the entire cleaning cycle is complete. At this point, the lid is opened by discontinuation of the compressed air pressure that seals the lid, and retracted to uncover the chamber. The opening releases solvent vapor that has not been evacuated from the chamber during the condensation or adsorption stages of the cycle. The other potential source of air emissions is leakage of equipment seals, valves, or piping.

Table 8 shows the emissions recorded from the LEVD. The approach used was to insert a flame ionization detector (FID) probe into the working chamber below the designated vapor level. Measurements with this FID probe were started during the adsorption stage and continued through the end of this stage, until after the lid was released and opened. The objective was to measure the concentration of any residual perchloroethylene (PCE) just before releasing the lid and after the lid is retracted. A second FID probe was used to take continuous measurements all around the unit during operation, with special emphasis around the lid to check for leaks. Both FIDs were calibrated with PCE standards (see Appendix C). The outputs from both FIDs were separately channeled to a data capture system. The measurements were recorded on both a chart recorder and a computer readout. The ambient levels in the indoor facility on the test days were consistent at around 3 to 4 ppm; this low level may be due to exhausts from forklift vehicles that were operating in the facility.

Figure 4 shows how a typical cleaning cycle ends on this unit. (See Appendix D for figures showing other runs.) Figure 4 shows the measurements taken during Run 1. The same pattern was evident in the other runs. In Figure 4, time zero corresponds to the start of measurements in the working chamber. The FID probe in the working chamber was not activated before this point to prevent large concentrations of solvent vapor from being drawn into the FID. The FID had been calibrated for accuracy in the 0 to 1,000 ppm range; particular care was taken in the range below 1 g/m^3 (approximately 150 ppm of perchloroethylene), the concentration above which the lid normally is not allowed to be opened by a programmed controller. At time zero, the chamber FID probe was in place in the working chamber, and the ambient FID probe was positioned outside the unit, near the lid seal.

TABLE 8. EMISSIONS FROM LEVD

Run No.	Final Chamber Concentration[a] (ppm)	Total PCE Emission[b] (lb/cycle)	Total Cycle Time (min)	Emission Rate (lb/hr)
1	52	0.0005	—	—
2	75	0.0007	39	0.0011
3	92	0.0008	67.5	0.0007
4	NM[d]	—	—	—
5	43	0.0004	50.5	0.0005
6	47	0.0004	40	0.0006
7	NM[d]	—	—	—
8	78	0.0007	69	0.0006
9	NM[d]	—	—	—
Target[c]	150	0.0013	60[e]	0.0013

[a] At the moment when the seal on the lid is released.
[b] Based on 150 ppm = 1g/m^3 of PCE and a chamber volume of 0.6 m^3.
[c] Normally the machine is programmed to release the lid when solvent concentration in the chamber falls below 1g/m^3 (150 ppm of PCE). This target was easily met in all the test runs.
[d] Not measured due to difficulties in completing the run as described in Table 3.
[e] Expected cycle time for 560 lb of steel parts (workload).

As seen in Figure 4, the chamber concentration began dropping sharply as the 4-min (240-sec) adsorption cycle started. Throughout the adsorption cycle, the ambient probe just outside the lid indicated concentrations between 3 and 4 ppm, which were equal to the indoor ambient concentrations in the test facility at locations far from the LEVD unit. Just before the adsorption cycle ended, the chamber FID was reading 52 ppm, well below the targeted 150 ppm. After 240 sec, the compressed air pressure sealing the lid was automatically released, but the lid remained completely in place. At this point, the chamber concentration began showing some fluctuations as the air in the chamber was disturbed, but it stayed within a 40- to 50-ppm range. A few seconds later, the lid was retracted completely to allow the chamber air full access to the

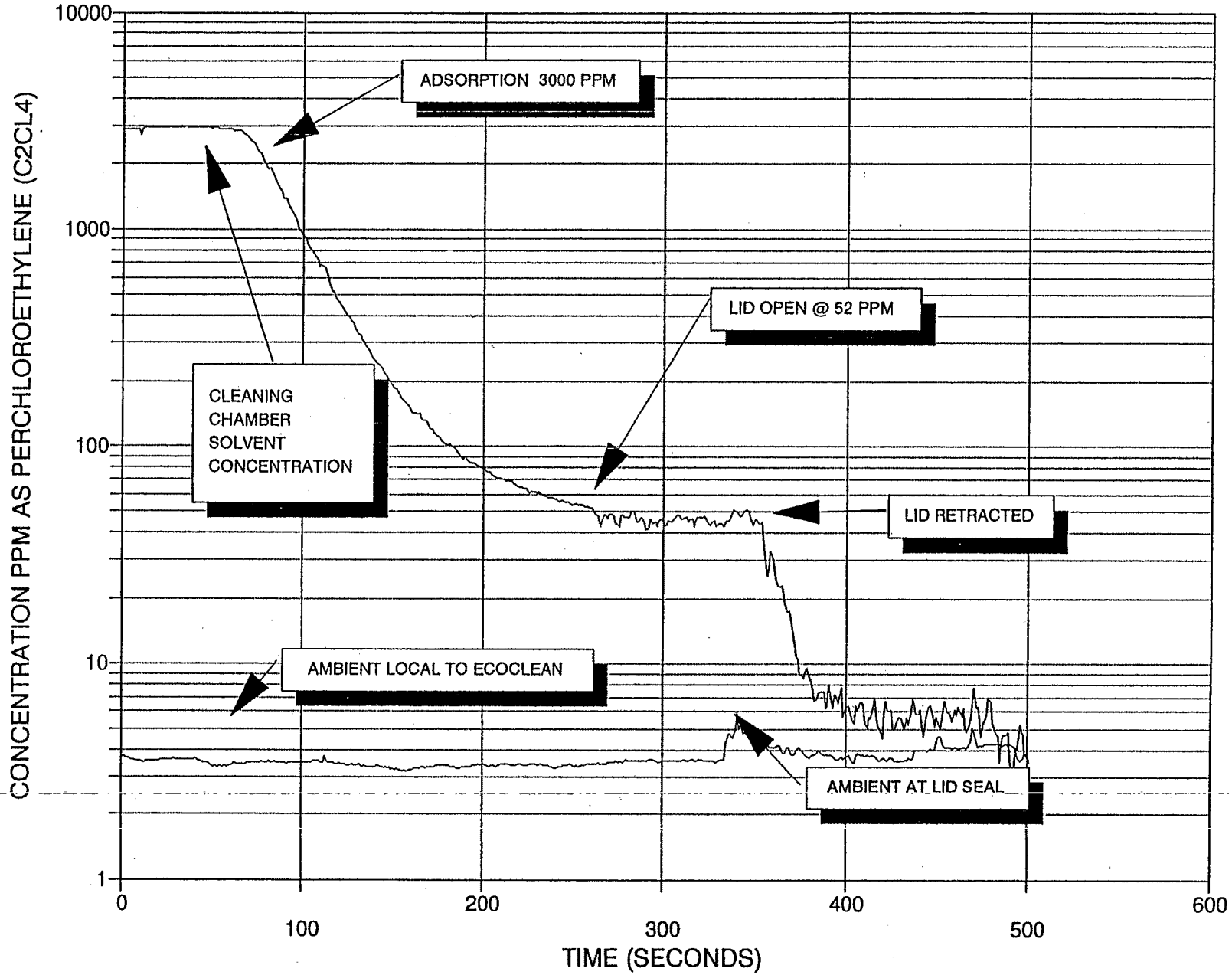

Figure 4. End of the cleaning cycle for Run 1.

ambient. At this point, the chamber concentration dropped sharply as the residual solvent vapor in the chamber dispersed. The ambient FID probe, which was near the chamber opening, showed a corresponding increase (to 6 ppm). Both FIDs soon stabilized to facility ambient levels (3 to 4 ppm).

Later, as the basket of cleaned parts was raised out of the chamber, the second FID probe was thrust into the basket and near the parts. No elevated readings above ambient were sensed near the parts, indicating that the parts were free of solvent.

During the entire operating cycle, for five of the runs (Runs 1, 5, 6, 8, and 9), a continuous perimeter survey to check for leaks was carried out around the unit. Special attention was given during the vapor-fill stage to the edges of the lid, where the top opening of the working chamber is sealed. At times during each run, the front and rear panels, which loosely surround the unit components, were removed to allow probing around the valves, piping, seals, etc.

At two points during the perimeter survey, solvent vapor was detected above facility ambient levels. The causes were identified as external to normal unit operation, and were remedied. During Run 5, a slight elevation in PCE concentration was noticed when a front panel was removed, and the second FID probe was held at the point where a temporary opening had been drilled in the chamber wall to insert the chamber FID probe for this testing. The seal around the chamber probe was tightened, and the elevated reading returned to ambient. During the vapor-fill cycle of Run 8, as the FID probe was passed around the rear of the unit near the lid, an elevated reading was noticed. It momentarily jumped to more than 100 ppm, stayed at around 30 ppm for 30 sec, and then tapered off. When the pressure gauge on the facility's compressed air supply was checked, it showed that the air compressor had malfunctioned, causing the compression seal around the lid to be released temporarily. When the compressed air supply returned to normal, the elevation in the reading dropped back to ambient.

The above testing indicates that the only significant emission from the LEVD is at the end of the cycle when the lid is opened and retracted. Table 8 shows the final chamber concentration (just before the lid is opened) for several of the test runs. In all the test runs, the solvent concentration was well below the 1 g/m^3 (150 ppm PCE) targeted. Therefore, 1 g/m^3 can be taken as the achievable concentration. The volume of the working chamber is 0.6 m^3. Assuming that all the residual solvent vapor (1 g/m^3) in the chamber has been discharged to the ambient area, the air emission through the top opening is 0.21 g (0.00132 lb). Therefore, the typical discharge of solvent through air emission is 0.00132 lb/cycle. From Section 4, if 560 lb of oiled steel parts are processed, the cleaning cycle would take 1 hour. Therefore, the air emission from this LEVD mode that processes 560 lb of steel parts/hr is 0.00132 lb of solvent/hr.

As described in Appendix E, a typical conventional open-top vapor degreaser that can clean at a similar rate (approximately 560 lb of steel parts/hr) would have a 4.5 ft^2 opening. This conventional degreaser typically would emit 0.147 lb of solvent/ft^2/hr (Appendix E), or 0.662 lb of solvent/hr, from the 4.5-ft^2 opening during continuous operation.

Therefore, the LEVD reduces air emissions by more than 99% compared with air emissions from the typical conventional open-top vapor degreaser (i.e., having a 0.75 freeboard ratio, primary cooling coil, electric hoist, and no lip exhausts) used in this calculation.

The OSHA exposure limit for PCE is 25 ppm for an 8-hr TWA (time-weighted average). Personal air sampling (in accordance with OSHA guidelines) was not conducted during this evaluation, but the 3- to 4-ppm PCE levels near the unit at all times during operation and the 6-ppm (or lower) levels at the edge of the chamber opening for about 2.5 min when the lid is retracted completely (Figure 4) are well under the OSHA exposure limit.

WASTE REDUCTION/POLLUTION PREVENTION ASSESSMENT

The atmospheric unit evaluated in this study has good solvent waste reduction potential compared to disposal. At the test site, annual hazardous solvent waste generated for disposal was reduced from 880 gal to 262 gal. A sidestream consisting of 18,360 gal/yr of cooling water (tapwater) is generated during recycling, but should not be a problem because this tapwater does not come into contact with any solvent contamination and can be reused elsewhere as process water. The user should be careful that there are no leaks in the cooling water lines, through which the water could be contaminated with solvent or vice versa.

The vacuum unit evaluated in this study has good solvent waste reduction potential compared to disposal. At the test site, annual hazardous solvent waste generated for disposal was reduced from 3,000 gal to 136 gal. At this test site, a largely avoidable sidestream of 218 gal of air emissions also was generated during recycling; the sidestream can be avoided by operating the vacuum pump at a slower rate.

The LEVD reduced air emissions by more than 99% compared with the estimated air emissions from a similarly sized conventional open-top vapor degreaser (with a 0.75 freeboard ratio, primary cooling coil, electric hoist, and no lip exhausts). Even allowing for equipment- and operation-related factors and auxiliary controls (e.g., increased freeboard ratio, refrigerated coils, covered opening, reduced room draft/lip exhaust velocities) used to reduce air emissions from a conventional degreaser, the pollution prevention performance of the completely enclosed design used in this study would be difficult to match. The perimeter ambient survey with a FID probe indicated that the OSHA exposure limit of 25 ppm (8-hr TWA) would be met by the LEVD.

The pollution prevention potential of this unit is further enhanced by its ability to perform as a liquid solvent distillation system for cleaning the sump solvent; this capability was not a part of this evaluation. The LEVD also affords greater production flexibility, when pollution prevention is an objective, because, unlike a conventional degreaser, there are no significant idling losses between loads or downtime losses during shutdown.

On the national level, the total U.S. solvent demand is approximately 160 billion gal/yr (Basta and Gilges, 1991). Approximately half this volume currently is recycled (on site or off site). There is still a large potential for recycling more. A shift from offsite to onsite recycling would prevent the transport of hazardous solvent wastes.

The largest single use for solvents in the United States is for vapor degreasing. As much as 90% of this solvent is lost through air emissions. Other leading uses are dry cleaning (for clothing) and cold cleaning (or immersion cleaning of soiled parts). The enclosed vapor degreaser has potential for significantly reducing solvent use by preventing losses through air emissions.

SECTION 4
ECONOMIC EVALUATION

The economic evaluation compares the costs of each new technology to conventional practice.

ATMOSPHERIC BATCH UNIT

The major operating costs associated with the disposal option and the atmospheric batch unit are listed in Table 9. The disposal option operating costs total $16,529/yr and include the following:

- Annual purchase of 800 gal of virgin solvent at $10.50/gal, based on plant records
- Annual disposal of 900 gal of spent solvent waste at $400/drum, based on plant records
- Seventeen 55-gal steel drums at $40 each
- Annual disposal labor estimate of 8 hr at $8/hr.

The operating costs for recycling with the atmospheric unit total $6,518/yr and include the following:

- Virgin solvent purchase of 245 gal/yr at $10.50/gal to make up for processing losses (during normal solvent use at the plant) and recycling losses (solvent lost to distillation residue), based on Table 7
- Recycling operation labor at $8/hr based on 1 hr of operator involvement per batch and 17 batches per year
- Routine maintenance suggested by the vendor include (1) lid gasket replacement once a year ($86/gasket); (2) checking the condenser for deposits and cleaning if required once a year; and (3) periodic (monthly in this case) checks of the flow switch to ensure that heating shuts off when water flow to the condenser stops. Estimated labor for the above maintenance is 12 hr/yr
- Energy costs based on 6.2-kW heater operating 12 hr/batch at $0.04/kWh

TABLE 9. MAJOR OPERATING COSTS FOR ATMOSPHERIC UNIT

Item	Annual Usage	Unit Cost	Annual Cost
Disposal Option			
Virgin solvent	880 gal	$10.50/gal	$ 9,240
Disposal			
– labor	8 hr	$8/hr	$ 64
– drums	17	$40/drum	$ 680
– disposal fee	900 gal	$400/55 gal	$ 6,545
		Total	$16,529
Atmospheric Unit			
Virgin solvent	$245 gal	$10.50/gal	$ 2,573
Operating labor	17 hr	$8/hr	$ 136
Routine maintenance			
– spare parts	1	$86/each	$ 86
– labor	12 hr	$8/hr	$ 96
Energy	1,265 kWh	$0.04/kWh	$ 51
Cooling water	18,360 gal	$1/1,000 gal	$ 18
Disposal			
– labor	3	$8/hr	$ 24
– drums	5	$40/drum	$ 200
– residue disposal	262 gal	$675/55 gal	$ 3,215
– still bags	17	$84/12 bags	$ 119
		Total	$ 6,518

- Water supply costs based on 1.5 gal/min to condenser for 12 hr/batch at $1/1,000 gal
- Distillation residue disposal costs based on 262 gal/yr of residue (Table 7) at $675/55-gal drum; still bags at $84/doz; 5 drums at $40/drum; and an estimated disposal labor requirement of 3 hr/yr at $8/hr.

Recycling, therefore, results in savings of $10,011/yr.

The purchase price of the atmospheric batch unit is $12,995. A simple payback period can be calculated as follows:

$$\text{payback, years} = \frac{\text{purchase price}}{\text{savings in annual operating costs}} \quad (1)$$

This result is a payback period of less than 2 years. This simple calculation does not include factors such as taxes, inflation, installation, etc. A more detailed payback period calculation based on worksheets provided in the *Facility Pollution Prevention Guide* (EPA, 1992) is given in Appendix F. The worksheets calculate the return on investment (ROI) each year after the purchase. The payback period (i.e., the year when the ROI exceeds 15%, which is the cost of capital) by this calculation is less than 2 years.

VACUUM UNIT

The major operating costs of the vacuum unit are listed in Table 10. Also included in this table are the costs associated with the disposal option. The disposal option operating costs total $20,538/yr and include the following:

- Annual purchase of 3,000 gal of virgin solvent at $3.57/gal, based on plant records
- Annual disposal of 3,000 gal of spent solvent waste at $2.50/gal, based on plant records
- 55 steel drums costing $40/drum
- Annual disposal labor estimate of 28 hrs at $8/hr.

The operating costs for recycling total $2,255/yr and include the following:

- Virgin solvent purchase of 246 gal/yr at $3.57/gal to make up for processing losses (during normal solvent use at the plant) and recycling losses (solvent lost to distillation residue and air emissions) based on Table 2
- Recycling operation labor at $8/hr based on 1 hr of operator involvement per batch and 55 batches per year

TABLE 10. MAJOR OPERATING COSTS FOR VACUUM UNIT

Item	Annual Usage	Unit Cost	Annual Cost
Disposal Option			
"Virgin" solvent	3,000 gal	$3.57/gal	$10,710
Disposal			
- labor	16 hrs	$8/hr	$ 128
- drums	55	$40	$ 2,200
- disposal fee	3,000 gal	$2.50/gal	$ 7,500
		Total	$20,538
Recycling			
"Virgin" solvent	246 gal	3.57/gal	$ 878
Operating labor	55 hrs	$8/hr	$ 220
Energy	985 kWh	$0.04/kWh	$ 39
Disposal			
- still bottoms	136 gal	$2.50	$ 340
- used oil[a]	4 quarts	$3.00/quart	$ 12
- labor	3 hrs	$8/hr	$ 24
- drums	3	$40/drum	$ 120
Routine Maintenance			
- oil[a]	4 quarts	$3.50/quart	$ 14
- spare parts	-[b]	$480 (max)[b]	$ 480
- labor	16 hrs	$8/hr	$ 128
		Total	$ 2,255

[a] The used oil wastestream can be minimized by changing the oil filter strictly in accordance with the manufacturer's recommendations.

[b] The $480 cost for spare parts is a maximum, which assumes that the maximum number of parts will be replaced as per the manufacturer's recommendations during each overhaul. Actual maintenance costs could be lower. Appendix G summarizes the estimate.

- Routine maintenance, as described in Appendix G
- Energy costs based on the 2-hp vacuum pump operating 12 hr/batch at $0.04/kWh
- Distillation residue disposal costs based on 136 gal/yr of residue (Table 7) at $2.50/gal; used oil disposal at $3/quart (can be minimized by changing the oil filter regularly); 3 drums at $40/drum; and an estimated disposal labor requirement of 3 hr/yr at $8/hr.

The savings due to recycling, therefore, amount to $18,283/yr.

The purchase price of the vacuum unit is $23,500 for the explosion-proof model. A simple payback period can be calculated as follows:

$$\text{payback, years} = \frac{\text{purchase price}}{\text{savings in annual operating costs}} \qquad (2)$$

This results in a payback period of less than 2 years. This simple calculation does not include factors such as taxes, inflation, installation, etc. A more detailed payback period calculation based on worksheets provided in the *Facility Pollution Prevention Guide* is given in Appendix H.

LEVD

The economic evaluation involved a comparison between the operating costs of the low-emission vapor degreaser (LEVD) and a conventional open-top vapor degreaser with the same production capacity as the LEVD. The production rate of the LEVD was determined during testing by measuring the stage times that make up a cleaning cycle for the various runs.

Table 11 describes the time measurements performed during testing. For the degreasing, condensation, air recirculation, desorption, and adsorption stages, stage time was preset and is not expected to vary much based on operational factors. Carbon heatup stage time was not preset but remained fairly constant over varying operational factors. The only real variability, as seen in Table 11, is in vapor-fill (chamber heatup) times, which varied proportionately with the mass of the workload (steel parts). Most important are Runs 5 and 8, which started with parts that were cold and had oil on them, a situation typical of normal operation. Despite the widely varying workload masses, the two runs had identical carbon heatup times. For each of Runs 5 and 8, if all the stage times except vapor-fill time are added up, a 32.5-min period is obtained that is relatively constant for all runs. In addition, prior tests done by the vendor with an empty basket showed a vapor-fill time of 7.5 min, which would be the minimum vapor-fill time for any workload.

TABLE 11. LEVD CYCLE TIME BREAKDOWN FOR TEST RUNS

Run No.	Weight of Steel Parts (lbs)	Vapor fill[a]	Degreasing (preset)	Condensation (preset)	Air Recirculation (preset)	Carbon heat up	Desorption (preset)	Adsorption (preset)	Total Cycle Time[b] (min)
		- STAGE TIMES IN MINUTES -							
First Day (No oil on parts)									
1	165	8.5	1	—	—	—	—	—	—
2	165[c]	8.5	1	2	2	20.5	1	4	39
3	900	36	1	2	2	21.5	1	4	67.5
Second Day (Oil on parts, except Run 9)									
5	165	18	1	2	2	22.5	1	4	50.5
6	165[c]	12.5	1	2	2	17.5	1	4	40
8	915	36.5	1	2	2	22.5	1	4	69
9	160[c]	9	1	2	2	21	1	4	40

[a] Vapor fill times during this testing were slightly higher than they normally would be. Because of a wiring problem, only 2 of the 3 heaters (18 of the 27 kW) were functioning during the test.

[b] At the beginning of each day, additional 50 minutes are required to heat the liquid perchloroethylene from stand-by to vapor temperature. Also, cycle times were not measured for Runs 4 and 7.

[c] Parts were already somewhat hot from being used in previous runs.

Run 5, with 165 lb, had a vapor-fill time of 18 min and a total cycle time of 50.5 min; Run 8, with 915 lb, had a vapor-fill time of 36.5 min and a total cycle time of 69 min. This relationship between time and mass for steel parts is plotted in Figure 5, based on the data for Runs 5 and 8. By intrapolating between these two runs, the workload mass that gives a total cycle time of 60 min is determined to be 560 lb. Note that when the workload is 0.0 lb (empty basket), total cycle time is approximately 40 min (32.5-min fixed component plus 7.5-min minimum vapor-fill time) to 45 min.

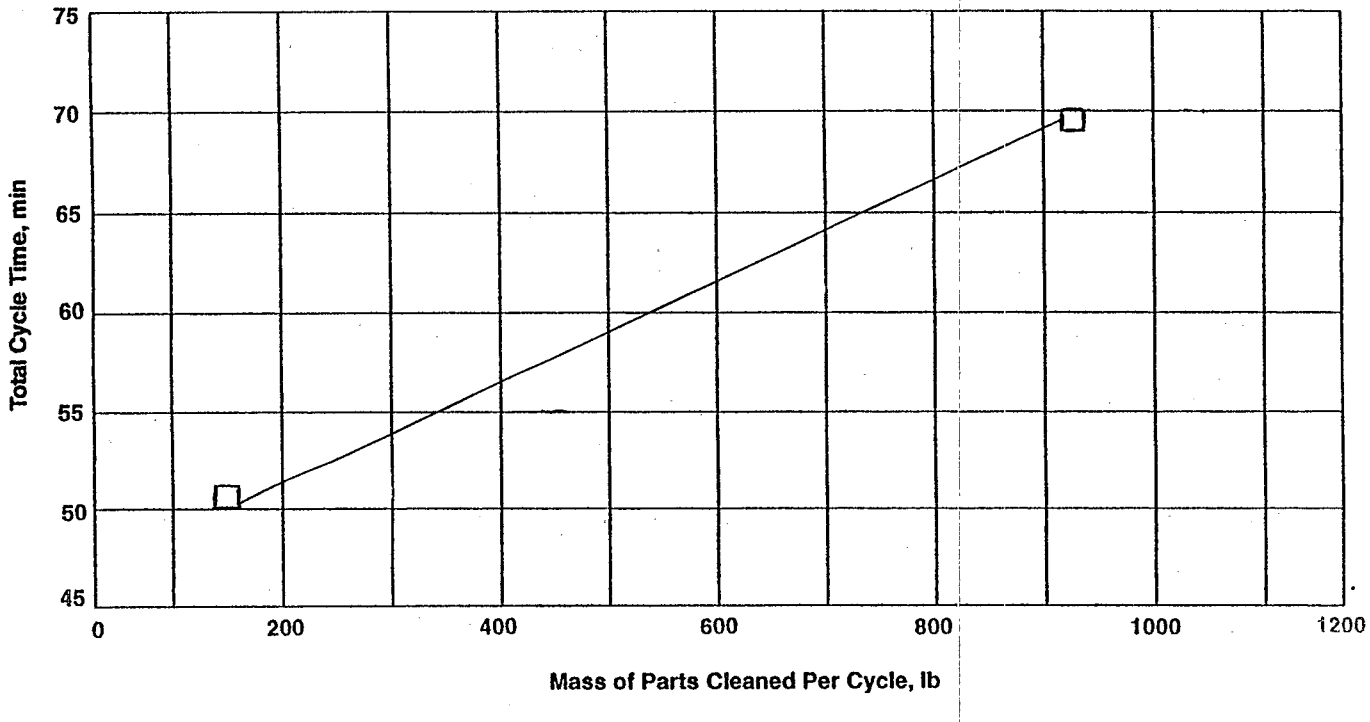

Figure 5. Variation of LEVD cycle time for steel.

Therefore, the conventional degreaser selected for comparison has a production rate of 560 lb of steel parts per hour. Based on information obtained from several vendors, Appendix E describes the features of a typical vapor degreaser that can be expected to have a similar production rate.

The major operating costs of the LEVD are listed in Table 12. Also included in this table are the operating costs for a conventional open-top vapor degreaser with a similar production capacity, as described in Appendix E. Vendor-quoted purchase price for the LEVD was $210,000.

TABLE 12. OPERATING COSTS FOR VAPOR DEGREASING

Item	Annual Volume	Unit Cost	Total Cost
Conventional Degreaser			
Operating labor	$4,000 hr	$8/hr	$32,000
Electricity	25,500 kWh	$0.04/kWh	$ 1,020
Cooling water	480,000 gal	$1/1,000 gal	$ 480
Maintenance			
– labor	22 hr	$8/hr	$ 176
– materials	–	–	$ 88
Net solvent loss	2,642 lb	$0.71/lb	$ 1,876
		Total	$35,640
LEVD			
Operating labor	333 hr	$8/hr	$2,664
Electricity	93,725 kWh	$0.04/kWh	$ 3,749
Maintenance			
– labor	262.5 hr	$8/hr	$ 2,100
– materials	–	–	$ 2,100
		Total	$10,613

The annual operating cost of the conventional degreaser totals $35,640 and includes the following:

- Operating labor is the actual operator involvement in the process. Compared to the LEVD, a conventional machine having the same production capacity is much smaller in size and runs much smaller batches. Although the LEVD runs 560 lb/batch/hr, the conventional degreaser can attain this rate only by running several small batches (cycles) per hour. This means that, over a period of 1 hour, operator involvement is almost continuous, especially if each workload has to be raised, allowed to drain, and then pulled out. Annual operator involvement for the conventional machine therefore is 16 hr/day, 5 days/week, and 50 weeks/yr at $8/hr.

- Electric heat required is 6 kW, 17 hours/day (16 hr operation and 1 hr startup), 5 days/week, and 50 weeks/yr at $0.04/kWh.

- Primary cooling coil water consumption is 2 gal/min at $1/1,000 gal.

- Annual maintenance labor cost was estimated as 2% of the unit's purchase price, and maintenance materials cost was estimated as 1% of the purchase price. The capital cost of the conventional unit was estimated at $8,500, based on information from vendors.

- Net solvent loss cost is the additional solvent that has to be purchased to make up for air emissions. The net annual solvent loss is the difference in annual emissions of the conventional unit (approximately 2,646 lb/yr per Appendix E) and the LEVD (approximately 4 lb/yr per Section 3). Solvent price was based on a current market price of $0.71/lb of perchloroethylene (PCE).

The annual operating cost of the LEVD is $10,613 and includes the following:

- Operator time of 5 min/cycle. Operator involvement is required only for unloading and loading a basket of parts at the end of each cycle (batch). At 1 cycle/hr (for 560 lb of steel parts), operating labor was based on 16 cycles/day, 5 days/week, and 50 weeks/yr.

- Electricity costs were based on the energy requirement of 93,725 kWh/yr as described in Appendix I.

- Annual maintenance labor costs were based on 1% of the LEVD purchase price and maintenance materials costs were based on 1% of purchase price. The purchase price of the LEVD is quoted by the vendor as $210,000.

The LEVD thus results in a savings in annual total operating costs of $25,027. The savings are mainly due to reduced labor costs (due to larger batch size) and lower solvent requirement (due to solvent recovery).

A simple payback period can be calculated according to the following formula:

$$\text{payback, years} = \frac{\text{purchase price}}{\text{savings in annual operating costs}} \qquad (3)$$

With a purchase price of $210,000 and an annual savings of $25,027 the LEVD pays for itself in approximately 9 years. A more detailed economic analysis based on the worksheets in the *Facility Pollution Prevention Guide* (EPA, 1992), is given in Appendix J. Although the above is a straightforward cost comparison between the LEVD and a conventional vapor degreaser of similar production capacity, some other cost-benefit factors must be taken into account while making economic decisions. One major consideration is that the LEVD does not require much of the auxiliary equipment that may be required for a standard conventional vapor degreaser, if the user is aiming to reduce workplace emissions to meet or anticipate increasingly stringent environmental and worker safety regulations. Additional control devices for standard conventional degreasers (e.g., increased freeboard ratio, refrigerated coils, lip exhausts, room ventilation) would add

considerably to capital and operating costs. In contrast, the LEVD is a self-contained unit that would require no additional facility modifications to achieve significant emission reduction.

Another consideration is the production rate of the LEVD. The above calculation was performed for a production rate of 560 lb/hr of steel parts (workload) because it is standard practice with most vendors of conventional degreasers to quote capacities based on steel parts. However, production capacity on the same machine can vary depending on the metal processed. For example, many vendors of conventional equipment quote half the capacity of steel for similarly shaped aluminum parts. This is ostensibly because the density of aluminum is half that of steel. Thus, for the same basket or chamber volume, only half as many similarly shaped parts can be processed per batch.

For the LEVD, variation in cycle time due to various workload metals can be estimated based on the times measured for steel (Figure 5). The governing factor is the thermal diffusivity of the metal. Thermal diffusivity (α) is the factor that ties in the heat conductivity (k), specific heat (c_p), and density (d) of the metal by the following relationship:

$$\alpha = \frac{k}{d \cdot c_p} \tag{4}$$

For the same shape and size of parts, the times required for different metals to reach vapor temperature are inversely related to their respective thermal diffusivities.

$$\alpha_{metal} \cdot t_{metal} = \alpha_{steel} \cdot t_{steel} \tag{5}$$

Therefore, Appendix K lists the k, c_p, and d values for steel, aluminum, brass, and copper. Appendix K also calculates the total cycle times for the various metals in the LEVD. Note that, regardless of the metal or workload mass, the total cycle time has a fixed component of 32.5 min (discussed earlier in this section) and a minimum vapor-fill time of 7.5 min. Only the variable component, the vapor-fill stage time, is affected by the metal and mass. Based on Appendix K, the total cycle times for various metals versus production rates are plotted in Figure 6. Thus, brass and copper can be processed faster than steel in the LEVD. Aluminum can be processed faster up to a point. This point is determined, for a certain shape of parts, by the maximum mass of aluminum parts that can fit into the basket and be processed per cycle. For the 915 lb of steel parts processed in Run 8 of this testing, the basket was nearly full. The vendor literature lists the maximum capacity of this LEVD model as 1,100 lb of steel parts/cycle. A full batch (basketful) of aluminum parts (of the same shape and size as steel) would weigh only 380 lb. Above 380 lb, the parts would have to be processed in the next cycle. Hence, the production rate for aluminum is restricted to 44.5-min cycles containing 380 lb/cycle. In Figure 6, the line for aluminum rises

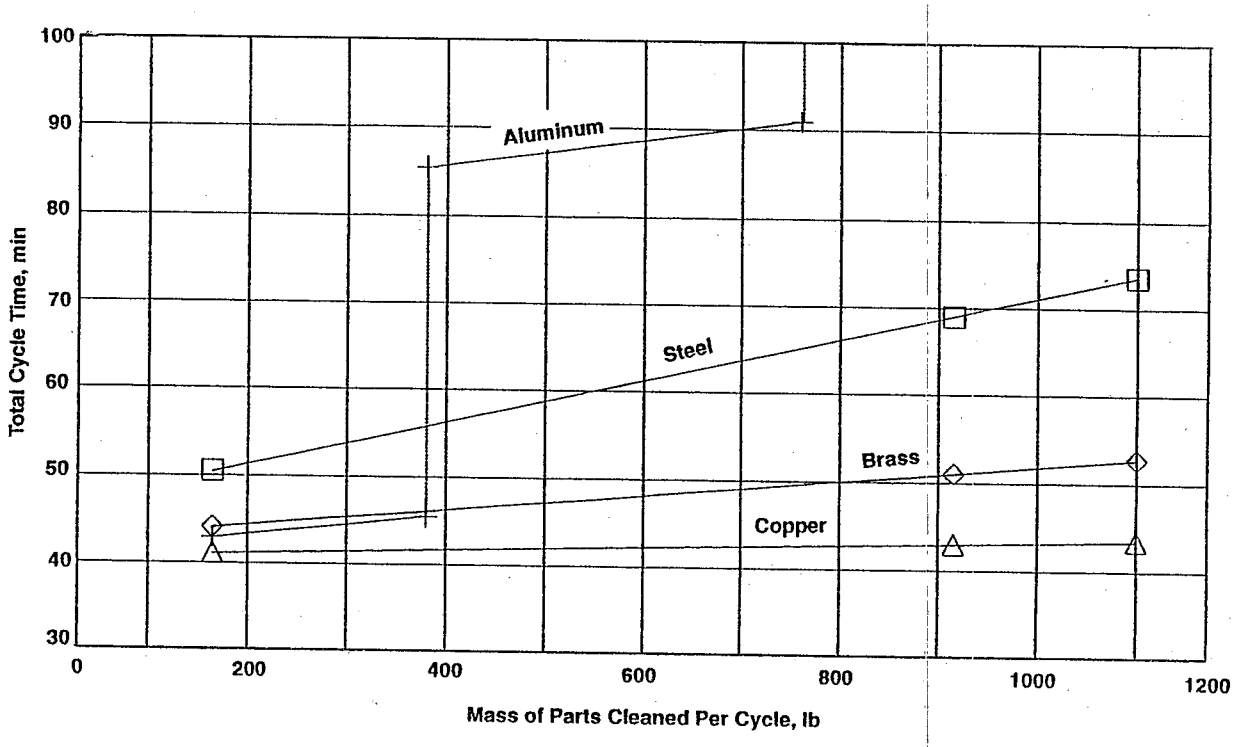

Figure 6. Variation of LEVD cycle time for various metals.

sharply (by 32.5 plus 7.5 min) at 380 lb to 84.5 min and continues with the same slope. With 44.5-min cycles, the average processing rate over a 16-hr day for aluminum on this machine is 497 lb/hr. Brass and copper, however, can be processed faster than steel. The closer to maximum load that a user can run in each cycle, the better is the time efficiency.

Another factor that may affect cycle time is the shape of the parts. Parts that have recesses where solvent could get trapped should be arranged in the basket in such a way that the solvent liquid drains out rather than stays in. Alternatively, other features offered by the vendor, such as oscillating or rotating baskets, should be used. If this is not done, either the air recirculation stage time will have to be increased, or the unit will go into a loop of several adsorption cycles until the chamber concentration falls below 1 g/m^3.

SECTION 5
QUALITY ASSURANCE

A Quality Assurance Project Plan (Battelle, 1992b) was prepared and reviewed by EPA before testing began. This QAPP contains a detailed design for conducting this study. The experimental design, field testing procedures, and laboratory analytical procedures are described. The QA objectives outlined in the QAPP are discussed below.

Onsite TESTING

Onsite testing was conducted as planned, except for the following. The plan was to evaluate the vacuum unit on both methylene chloride (MC) and methyl ethyl ketone (MEK). However, on reaching the site, the contact at the plant discovered that, a few weeks earlier, shop floor workers had already substituted the MEK used in the marking operation with a less hazardous solvent. Hence, the vacuum unit could be tested only on MC.

For the low-emission vapor degreasing (LEVD) unit, it should be noted that the extended desorption cycle required at the end of the day to regenerate the carbon had been eliminated by the manufacturer by the time of the testing.In the new design, a cooling coil has been added at the bottom of the working chamber to condense out most of the solvent before it gets to the carbon. The improved desorption stage during each normal cleaning cycle is sufficient to regenerate the carbon.

For the LEVD testing, one of the efforts planned was isolation and volume measurement of the condensed solvent recovered during a cycle, especially during the extended desorption stage. The objective was a double verification that solvent prevented from ambient release during a cycle (as indicated by the FID measurements) is captured on the carbon and recovered. With the extended desorption cycle eliminated, this aspect of the testing could not be done quite as planned. Piping was changed to collect the condensate from the newly added cooling coil. Condensate was collected in glass containers packed in dry ice to avoid evaporative losses of the hot liquid. The volume obtained was 1,500 mL during the condensation stage. Another 100 mL was collected during the desorption stage (left over from the previous run, approximately equal in volume to solvent adsorbed in the current run). The recovery of the solvent thus was verified. On the previous day, 88 L (approximately 23 gal) of solvent had been filled into the sump. The volume of

solvent remaining in the sump after completion of the run was not measured because the solvent in the sump remains hot for several hours (overnight the solvent cools only to 70°C) due to the enclosed design, and further testing had to be continued.

The QAPP stated that intermittent ambient air measurements would be made outside the unit with a FID probe. This was improved upon because of an added data-capture system on the FID and because the relatively operator-free cycle of the LEVD made possible continuous measurements all around the unit for several of the runs.

LABORATORY ANALYSIS

Laboratory analysis was performed as planned. The MEK acidity measurements (ASTM D1613) reported in Table 5 were not mentioned in the QAPP but were conducted as part of the purity analysis (ASTM D2804); there was some interpretive benefit in reporting them separately. Because of the interpretive success of the MEK purity analysis, a similar analysis (not mentioned in the QAPP) was performed on a recycled sample and the "virgin" sample of MC. No purity analysis was done on the spent MC sample because it was too viscous and contaminated to be analyzed without extensive additional steps. Absorbance measurements (UV VIS) were conducted on the solvent samples as another simple indicator of solvent quality.

Table 13 describes the detection limits and precision of the duplicate analysis on the solvent samples as per the QAPP. Except for the analysis of nonvolatiles on MEK, all other parameters had acceptable precision, within the range specified in the QAPP. The analysis of nonvolatiles on MEK exceeded the range by 1% in sample values close to the detection limit (recycled sample). This small deviation should not have had a significant effect on the results because the difference between spent and recycled values is several orders of magnitude greater than the relative difference between the duplicates. For consistency, all duplicate analyses were performed on the recycled sample for both MEK and MC. In most of the preceding tables in this report, results for both duplicates have been reported.

LIMITATIONS AND QUALIFICATIONS

The above QA data indicate that the results of the onsite and laboratory testing can be considered a valid basis for drawing conclusions about product quality, pollution prevention potential, and economics. Site-specific economic and waste generation information for the atmospheric and vacuum units was obtained from plant records going back to the year before each new technology was installed. For the LEVD pollution prevention and economic evaluation,

TABLE 13. PRECISION OF SOLVENT ANALYSIS

Parameter	Analytical Method	Sample Value[a]	Duplicate Value[a]	Precision (% RPD)	Detection Limit
Color	ASTM D1209[b]	5	5	—[d]	NA[e]
	ASTM D2108[c]	5	5	—[d]	NA
Nonvolatiles	ASTM D1353[b]	2.6	2.0	26.1	1 mg/100 mL
	ASTM D2109[c]	20.37	17.88	13.0	1 ppm
Specific gravity	ASTM D891[b]	0.827	0.821	0.7	0.001
	ASTM D2111[c]	1.286	1.287	0.0	0.001
Water content	ASTM D1364[b]	5.42	5.56	2.6	0.01%
	ASTM D3401[c]	0.25	0.24	4.1	0.01%
pH	ASTM D2110[c]	6.7	6.6	1.5	0.1
Acid acceptance	ASTM D2942[c]	0.004	0.005	22	0.001%
Purity	ASTM D2804[b]	85.02	85.54	−0.6	0.01%
Conductivity	EPA 120.1[b]	3.30	3.40	−0.0	1 μmho/cm
	EPA 120.1[c]	137	136	0.7	1 μmho/cm

[a] Measurement units are given in "Detection Limit" column.
[b] MEK.
[c] MC.
[d] Duplicates target same color standard number. Precision acceptable.
[e] NA = Not acceptable.

baseline information for a conventional open-top vapor degreaser was taken from (1) information provided by several vendors of conventional equipment contacted during the study, (2) a previous study conducted for the WRITE Program (Battelle, 1992a), and (3) a previous EPA study (EPA, 1989) of several varieties of vapor degreasers.

For the vacuum unit, the product quality evaluation was somewhat affected by the fact that the "virgin" solvent was actually a commercially recycled solvent. Therefore, the vacuum unit was tested on an unusually severe matrix, in that existing volatile impurities in the purchased "virgin" solvent had accumulated in the spent solvent over several months of use and repeated on-site recycling. Better recycled MC purity test results probably could have been obtained if the spent solvent had not contained volatile impurities from external sources. This underscores the need for users of more than one solvent to segregate solvent wastes before onsite recycling.

Repetitions of the runs on the atmospheric and vacuum units were not possible because of the low availability of spent solvent at the sites during testing. Hence, the results are for a single test run on each unit. However, it is to be noted that the sites have been using these units for a long time without experiencing major difficulties. The test runs at both sites were considered by the sites to be typical of the past several runs in recycled solvent quantity and quality.

SECTION 6
CONCLUSIONS AND DISCUSSION

The three technologies evaluated in this study were (1) an atmospheric batch distillation unit, (2) a vacuum heat-pump distillation unit, and (3) a low-emission vapor degreaser. The objective was to determine the suitability of each unit to its respective application, rather than to compare among the three units. All three units performed satisfactorily during the testing and were able to recover significant quantities of solvent. A large portion of the approximately 160 billion gal/yr of solvent consumed annually in the United States could be recycled. Between offsite and onsite recycling, onsite recycling is preferable because transportation hazards are reduced. The largest single use for solvent in the United States is for vapor degreasing, followed by dry cleaning and cold cleaning (immersion cleaning of parts). The LEVD has great potential for reducing solvent loss in vapor degreasing through air emissions.

ATMOSPHERIC BATCH UNIT

The atmospheric unit greatly improved the quality of the spent methyl ethyl ketone (MEK) solvent feed. The quality improvement was immediately apparent from the appearance and colorlessness of the recycled solvent and was confirmed by the laboratory analysis. Standard solvent quality-monitoring parameters such as specific gravity, absorbance, and conductivity showed good agreement between recycled and virgin solvent values. Nonvolatile matter was virtually removed from the spent solvent. MEK purity rose from 78% in the spent solvent to 85% in the recycled solvent. The recycled value was lower than the >99% pure virgin grade. However, because the impurities are believed to be mainly paint thinners (solvents), they should not cause any problem when reused to clean spray painting lines between colors. The presence in the recycled solvent of 5% water (possibly due to a small leak in the water-cooled condenser) is of some concern, although the site did not report any adverse effect on the painting operation.

Compared to disposal, the atmospheric unit evaluated in this study has good solvent waste reduction potential. At the test site, annual hazardous solvent waste generated for disposal was reduced from 880 gal to 262 gal. A sidestream of 18,360 gal/yr of cooling water (tapwater) is generated during recycling, but this should not be a problem because the water does not come

into contact with any contamination and can be reused elsewhere as process water. The recycling unit is easy to install and operate safely.

The economic benefits of the atmospheric unit include reduced operating costs and a payback period of less than 2 years. One economic benefit that is difficult to quantify is the reduction in potential liability as a result of eliminating the transport of large volumes of hazardous solvent waste.

VACUUM HEAT-PUMP UNIT

The vacuum unit considerably improved the quality of the spent methylene chloride (MC) solvent. This was apparent from the visual appearance of the solvent and was confirmed by the laboratory analysis. The evaluation was complicated by the fact that the "virgin" solvent was actually a commercially recycled solvent. This "virgin" grade itself was analyzed to be 90% pure MC. Hence, the spent solvent fed to the vacuum unit probably contained significant amounts of volatile impurities accumulated over several previous recycles at the site. Even then, an 86% MC purity was achieved by the vacuum unit; the 14% impurities are likely to have been other volatile solvents. Nonvolatile matter was virtually removed. Standard solvent quality-monitoring parameters, such as specific gravity, absorbance, and conductivity, showed good agreement between recycled and "virgin" values, indicating that the recycled material was a fairly close approximation of the "virgin" grade. The pH of water extracts of the spent, recycled, and virgin samples showed that the recycled solvent had a pH close to 7 (the "virgin" sample pH), compared to a potentially corrosive spent sample pH value of 5. The corrosion test showed that spent solvent caused corrosion of steel, but that the recycled solvent caused no noticeable corrosion.

The vacuum unit evaluated in this study has good solvent waste reduction potential compared to disposal. At the test site, annual hazardous solvent waste generated for disposal was reduced from 3,000 gal to 136 gal. At this test site, a largely avoidable sidestream of 218 gal/yr of air emission also was generated during recycling but can be avoided by operating the vacuum pump at a slower rate. The recycling unit is easy to install and operate safely.

The economic benefits of the vacuum unit include reduced operating costs and a payback period of less than 2 years. One economic benefit that is difficult to quantify is the reduction in potential liability as a result of eliminating the transport of large volumes of hazardous solvent waste.

LOW-EMISSION VAPOR DEGREASER

Several runs with well-oiled steel parts verified that the low-emission vapor degreaser (LEVD) was performing its basic function. One aspect of the enclosed design that was noted was its potential for reducing water contamination of the solvent. In the enclosed design, only a limited amount of ambient air (equal to the free volume of the loaded chamber) comes into contact with the cooling surfaces of the unit. Hence, there is lower atmospheric contribution of water to the liquid solvent in the LEVD. Lower water contamination implies lower depletion of solvent stabilizers and acid formation by hydrolysis.

The LEVD reduced air emissions by more than 99% compared to the estimated air emissions from a typical conventional open-top vapor degreaser (560 lb of steel parts/hr capacity, with a 0.75 freeboard ratio, primary cooling coil, electric hoist, and no lip exhausts). It is true that air emissions from conventional degreasers can be reduced by improved operating practices and by modifications in the equipment (e.g., increased freeboard ratio, refrigerated coils, covered opening, reduced room draft/lip exhaust velocities). However, it would be difficult for any conventional degreaser to match the pollution prevention performance of the completely enclosed design used in this study. The perimeter ambient survey indicated that the OSHA exposure limit of 25 ppm (8-hr TWA) would be met by the LEVD. The pollution prevention potential of this unit is further enhanced by its ability to perform as a liquid solvent distillation system for cleaning the sump solvent; this capability was not a part of this evaluation. When pollution prevention is an objective, the LEVD also affords greater production flexibility because, unlike a conventional degreaser, the LEVD has no significant idling losses between loads or downtime losses during shutdown.

The economic benefits of the LEVD include reduced operating costs and a payback period of approximately 10 years. If the objective is to meet current or anticipated stringent environmental and occupational safety regulations, the LEVD is a self-contained piece of equipment that will meet this objective.

SECTION 7

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APPENDIX A

ADDITIONAL FEATURES OF THE THREE TECHNOLOGIES

The vendors of the three technologies described in Section 1 of this report offer additional features to suit individual users. These features are discussed here.

ATMOSPHERIC DISTILLATION

In addition to the unit described in Section 1, other standard models of 5 and 15 gal per batch capacity are available and larger units can be designed. Vacuum attachments can be retrofitted on many of the models for higher boiling solvents. Air-cooled condensers are offered as an option on some of the models. Another model incorporates a cooling system consisting of a water/glycol reservoir with fan. This water/glycol cooling system is designed for solvents that boil above 150°F and comes in a weather-proof enclosure. Potential applications include chlorinated solvents, alcohols, aliphatic petroleum hydrocarbons, aromatics, esters, chlorofluorocarbons (CFCs), ketones, terpenes, and new replacement solvents such as N-methyl-2-pyrrolidone (NMP), etc.

VACUUM HEAT-PUMP DISTILLATION

The vendor offers six continuous models varying in distilling capacity. Lower capacity models have a horizontal heat exchanger with one pump, and the higher capacity models have a vertical heat exchanger with two pumps. The same heat-pump concept also is offered in batch design. The batch heat-pump models are designed to further concentrate distillation residues from the continuous models or other atmospheric batch distillation units. The performance claimed for these second-stage stills is to concentrate feed material containing 50% solvent to still bottoms with 5% solvent.

LOW-EMISSION VAPOR DEGREASER

The unit described in Section 1 is intended mainly for medium to large parts. The vendor offers larger models with capacities of 2,200 lb and 3,300 lb of steel parts (or higher) per

cleaning cycle (or per batch). Features such as rotating baskets or basket oscillators are available for cleaning small parts. Other optional features include cold dip, hot immersion, ultrasonic cleaning, side tray loading of parts, and conveyorized loading. Future modifications are aimed at cutting down the cycle time by eliminating the carbon heatup and desorption stages through the design of twin carbon beds, so that one bed can be desorbed while the other is adsorbing.

APPENDIX B

ANALYTICAL TESTING OF SPENT, RECYCLED, AND VIRGIN SOLVENTS

The samples of spent, recycled, and virgin samples collected during the evaluation of the batch distillation and vacuum units were analyzed by standard ASTM methods (and one EPA method). The objective was to compare the quality of the recycled and virgin solvents on the one hand, and of the recycled and spent solvents on the other. The recycled versus virgin comparison indicates how closely the recycled sample resembles virgin grade; the recycled versus spent comparison indicates the improvement in quality brought about by recycling. The following parameters were used as the basis for this comparison. Table B-1 lists the titles of the standard methods used in this study. In the following description, it should be noted that the same parameter may be measured by slightly different methods depending on whether the solvent is a volatile organic solvent (e.g., methyl ethyl ketone [MEK]) or a halogenated organic solvent (e.g. methylene chloride [MC]).

Appearance: Visual appearance of a solvent often is used as an initial indicator of quality. Because most industrial solvents are transparent, any suspended or floating matter, sediment, turbidity, or free water is easily seen. ASTM D3741 covers the procedure for this visual determination.

Color: Color often is one of the first indicators of contamination of essentially clear organic solvents. The greater the color, the greater is the potential for interference with solvent functions such as cleaning and degreasing. ASTM D1209 (for clear organic liquids) and ASTM D2108 (for halogenated organic solvents) cover the visual measurement of color on a standard platinum-cobalt scale.

Nonvolatile Matter: Volatile solvents are used in paint, varnish, lacquer, and other related products in which the presence of residue may compromise quality. Residue also can affect the cleaning effectiveness of halogenated solvents in degreasing operations. The ability of the recycling processes to remove such residue from spent solvent is tested by ASTM D1353 (for volatile solvents) and ASTM D2109 (for halogenated organic solvents).

TABLE B-1. STANDARD TEST METHODS FOR SOLVENT ANALYSIS

Test Designation	Title
ASTM D3741-85 (91)	Appearance of Admixtures Containing Halogenated Organic Solvents
ASTM D1209-84 (88)	Color of Clear Liquids (Platinum-Cobalt Scale)
ASTM D2108-85	Color of Halogenated Organic Solvents and their Admixtures (Platinum-Cobalt Scale)
ASTM D1353-90	Nonvolatile Matter in Volatile Solvents for Use in Paint, Varnish, Lacquer, and Related Products
ASTM D2109-85	Nonvolatile Matter in Halogenated Organic Solvents and their Admixtures
ASTM D891-89	Specific Gravity, Apparent, of Liquid Industrial Chemicals
ASTM D2111-85	Specific Gravity of Halogenated Organic Solvents and their Admixtures
ASTM D1364-90	Water in Volatile Solvents (Fischer Reagent Titration Method)
ASTM D3401-85	Water in Halogenated Organic Solvents and their Admixtures
ASTM D2110-85	pH of Water Extractions of Halogenated Organic Solvents and their Admixtures
ASTM D2942-86	Total Acid Acceptance of Halogenated Organic Solvents (Nonreflux Methods)
ASTM D2251-85	Metal Corrosion by Halogenated Organic Solvents and their Admixtures
ASTM D2804-88	Purity of Methyl Ethyl Ketone Using Gas Chromatography
EPA 120.1	Conductance
ASTM D1613-91	Acidity in Volatile Solvents and Chemical Intermediates Used in Paint, Varnish, Lacquer, and Related Products
EPA Method 110.3	Absorbance

Specific Gravity: The specific gravity of each organic solvent is used in industry to determine the identity and purity of the solvent being used. Specific gravity change also is measured by users to monitor deterioration of solvent performance and cleanliness. This parameter is a simple hydrometer measurement that is described in ASTM D891 (for liquid chemicals in general) and in ASTM D2111 (for halogenated solvents in particular).

Water Content: Solvents are used under a variety of conditions that may be adversely affected by the presence of water. Spent solvent may contain water due to contamination during operation or simply due to atmospheric condensation. The ability of the recycling process to

eliminate water from the spent solvent will be measured by ASTM D1364 (for volatile solvents) and ASTM D3401 (for halogenated organic solvents).

pH: Halogenated solvents with alkaline stabilizers (amine-types) generally have a pH ranging from 7 to 11. Virgin and recycled solvents should fall within these ranges. Halogenated solvents are prone to a lowering of these values during use due to the formation of acids (e.g., HCl). An acidic environment is more corrosive. In ASTM D2110, the solvent sample is shaken with distilled water and the pH of the water extract is measured.

Total Acid Acceptance: The tendency of halogenated solvents to form acidic conditions is curtailed by adding stabilizers as described above. The question during recycling by distillation is whether the stabilizers are distilled with the solvent or decompose. ASTM D2942 measures the total acid acceptance properties of virgin and recycled solvents for both alkaline and neutral stabilizers.

Metal Corrosion; Corrosion is an important consideration for halogenated solvents used in degreasing and cleaning metal parts. This test (ASTM D2251) often is used as a guide in selecting or eliminating solvents used for degreasing or cleaning. For this test, polished strips of metal (steel and aluminum were used in this study) are immersed in the solvent and heated at reflux for 60 minutes. Similar strips also are kept immersed in solvent in closed containers for 10 days. At the end of this period, the strips are removed and examined visually for evidence of tarnish or corrosion.

Purity: ASTM D2804 describes the determination of the purity of MEK by gas chromatography. This method provides a quantitative indication of impurities. Although not planned in the QAPP, a similar analysis was performed on the MC recycled and "virgin" samples.

Conductivity: Liquid conductivity, as determined by Standard Method EPA 120.1 for industrial wastes, often is measured by solvent users as a quick test for contaminants. It provides a measure of any dissolved ionic impurities.

Acidity: This parameter was not planned in the QAPP as a stand-alone analysis but was part of the purity determination. However, it is reported separately in the report for its interpretive value. This parameter (ASTM D1613-91) measures total acidity as acetic acid. Acidity may be present in the spent solvent as a result of contamination during use or decomposition during storage.

Absorbance: The absorbance of the solvent in the 400 to 600 nm wavelength range was measured as a quick check on the degree of contamination. Contamination in solvent affects the transmittivity of light though the solvent. The UV-VIS absorbance meter was zeroed out using clear reagent-grade solvent (MEK or MC), and the test samples were measured with respect to this baseline. This test is based on EPA Method 110.3.

APPENDIX C
CALIBRATION OF FID INSTRUMENTS

The two flame ionization detectors (FIDs) used in the testing — the "chamber FID" and the "ambient FID" — were calibrated with propane as well as perchloroethylene(PCE)-in-air standards. The PCE standards were verified with a second standard obtained from a different source. Instruments were zero-adjusted with a zero gas (hydrocarbon-free air). The main objective of the chamber FID measurements was to ensure that chamber concentration at the end of each cycle (when the lid is opened) was <150 ppm. The main objective of the ambient FID measurements was to ensure that at locations close to the LEVD, readings did not rise significantly above the facility ambient levels. The procedures used were as follows.

At the beginning of each test day, the instruments were first zeroed out with the zero gas. The instrument was then calibrated to three propane standards — 945.5 ppm, 94.28 ppm, and 9.616 ppm.

On Day 1 the following sequence of PCE standards was run to adjust the response:

ppm of PCE Standard	Initial Chamber FID Readout	Initial Ambient FID Readout	Final - Readout Adjusted to - Chamber FID	Final - Readout Adjusted to - Ambient FID
Beginning of Day 1:				
94.28 (propane recheck)	95	95	NA[a]	NA
733	870	865	732	732
zero gas (recheck)	0.01	0.01	NA	NA
9.85	6.9	6.9	9.85	9.85
zero gas (recheck)	0.01	0.02	NA	NA
95.7	97.0	95.0	95.7	95.7
733	985	1,000	NA	NA
Noon:				
95.7	95.5	95.5	NA	NA
End of Day:				
9.85	9.83	9.82	NA	NA

[a] No adjustment performed.

As seen in the preceding table, the instrument was first rechecked with propane. Then the 733 ppm PCE standard was run, and the readouts showed 870 and 860 ppm. The readout was adjusted (with adjust knob) to read 732 and 732 ppm. This was a convenient, direct way of reading the instrument for PCE rather than leaving it at the propane adjustment and having to multiply each reading with a relative response factor.

Zero gas was run again as a check. The 9.85 ppm PCE standard was run next. The FIDs initially read 6.9 and 6.9 ppm. FIDs were then adjusted to read 9.85 and 9.85. After another zero check, the 95.7 PCE was run. The instrument read 97 and 95 ppm. Both FIDs were adjusted to read 95.7. All adjustments (with the adjust knob) were stopped at this point because maximum accuracy was required in the 0 to 100 ppm range. This is because the chamber concentration (at the end of the cleaning cycle) was expected to be in the higher part of this range and because ambient concentrations were expected to be in the lower part of this range.

The 733 ppm standard was run to verify linearity at higher levels. The FID readings were 985 and 1,000 ppm. This indicated that, at very high levels, some linearity had been lost. No attempt was made to readjust the instruments, in order to leave the accurate settings at 95.7 and 9.85 intact.

At noon, a single-point check was run with 95.7 ppm PCE standard and both FIDs were found to be holding well. At the end of the day, a check was run on the 9.85 ppm range, and both FIDs again were found to be holding well.

On the second day, calibration was repeated, first for instrument calibration with 945.5, 94.28, and 9.616 ppm propane standards, then with the PCE standards.

ppm of PCE Standard	Initial Chamber FID Readout	Initial Ambient FID Readout	Final - Readout Adjusted to - Chamber FID	Ambient FID
Beginning of Day 2:				
9.85	9.1	8.4	NA[a]	NA
733	745	780	NA	NA
Noon:				
733	741	740	NA	NA
zero gas (recheck)	0.01	0.01	NA	NA
9.85	10.1	10.0	9.85	9.85
End of Day:				
733	725	862	NA	NA

[a] No adjustment performed.

On the second day, the FIDs were calibrated mainly at 9.85 ppm. The 733 ppm standard was run to check linearity at this high level. On this day, response appeared to be somewhat more linear at the higher level also. At noon, a calibration check was conducted at 733 ppm and 9.85 ppm PCE, and the FIDs were found to be holding fairly well. The end-of-the-day check was run on 733 ppm PCE. In general, the objective was for the calibration checks to be within ±15% of the standard. For the end-of-the-day check on 733 ppm standard, however, the ambient FID readout showed 862 ppm (17.6% deviation from standard). This slight deviation is not expected to affect the results significantly.

APPENDIX D

LEVD CHAMBER CONCENTRATIONS AT END OF CYCLE

For Runs 1, 3, 5, and 6 of this testing, the chamber concentrations at the end of the cleaning cycle were tracked with a flame ionization detector (FID) probe. The resulting data were directed to a computer data capture system to generate the following charts. Normally, a photoionization detector (PID) monitor on the unit checks the concentration in the chamber 60 sec into the adsorption stage. If the concentration is less than 1 g/m^3 (150 ppm of PCE), the lid opens and the cycle ends. If not, the unit continues the adsorption stage up to 240 sec and rechecks the concentration. This is repeated until the desired concentration is achieved. However, for this testing the unit was programmed to run the full 240-sec adsorption stage and release the lid.

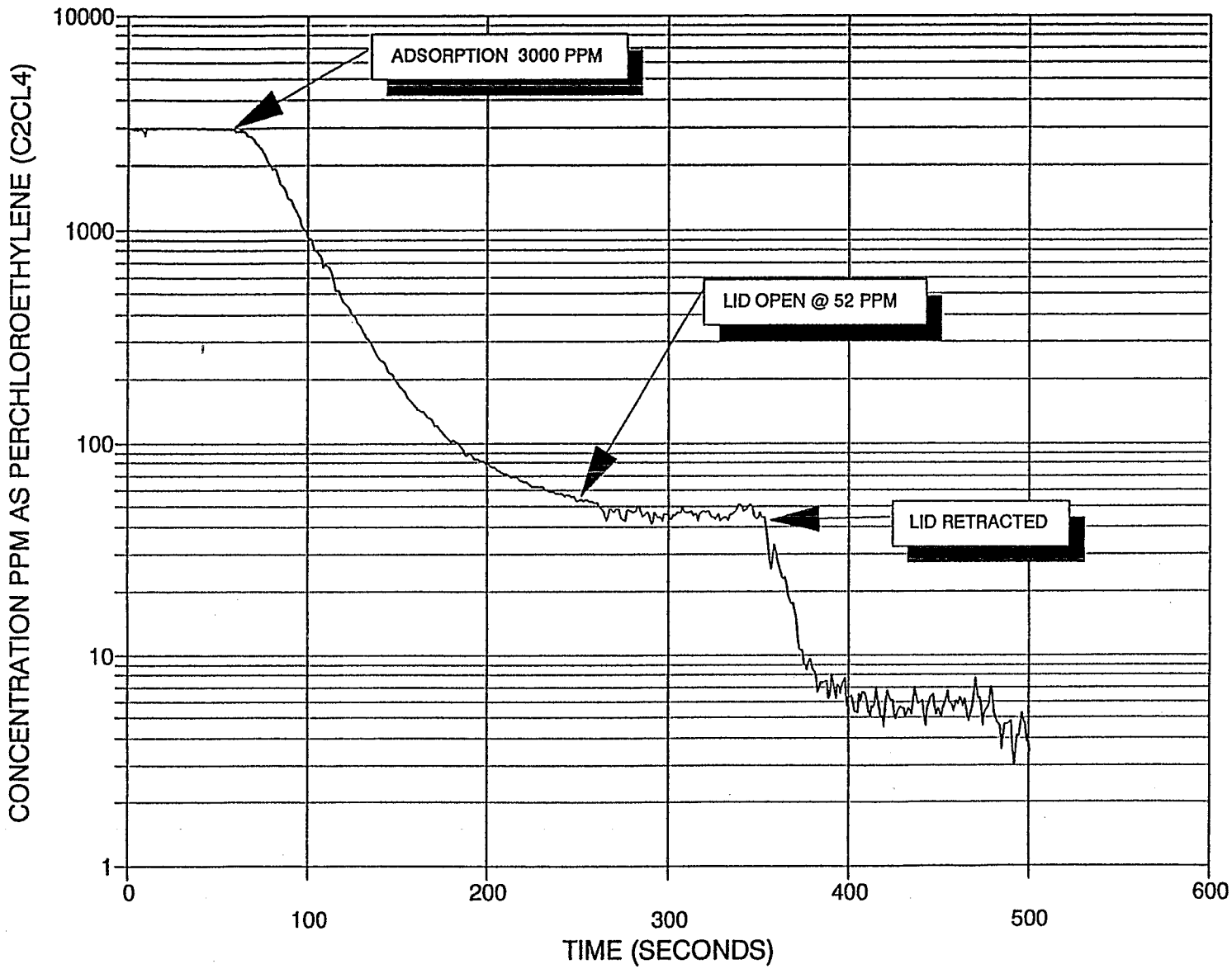

Figure D-1. Durr Ecoclean 83S, Battelle Run #1: Cleaning Chamber Solvent Concentration.

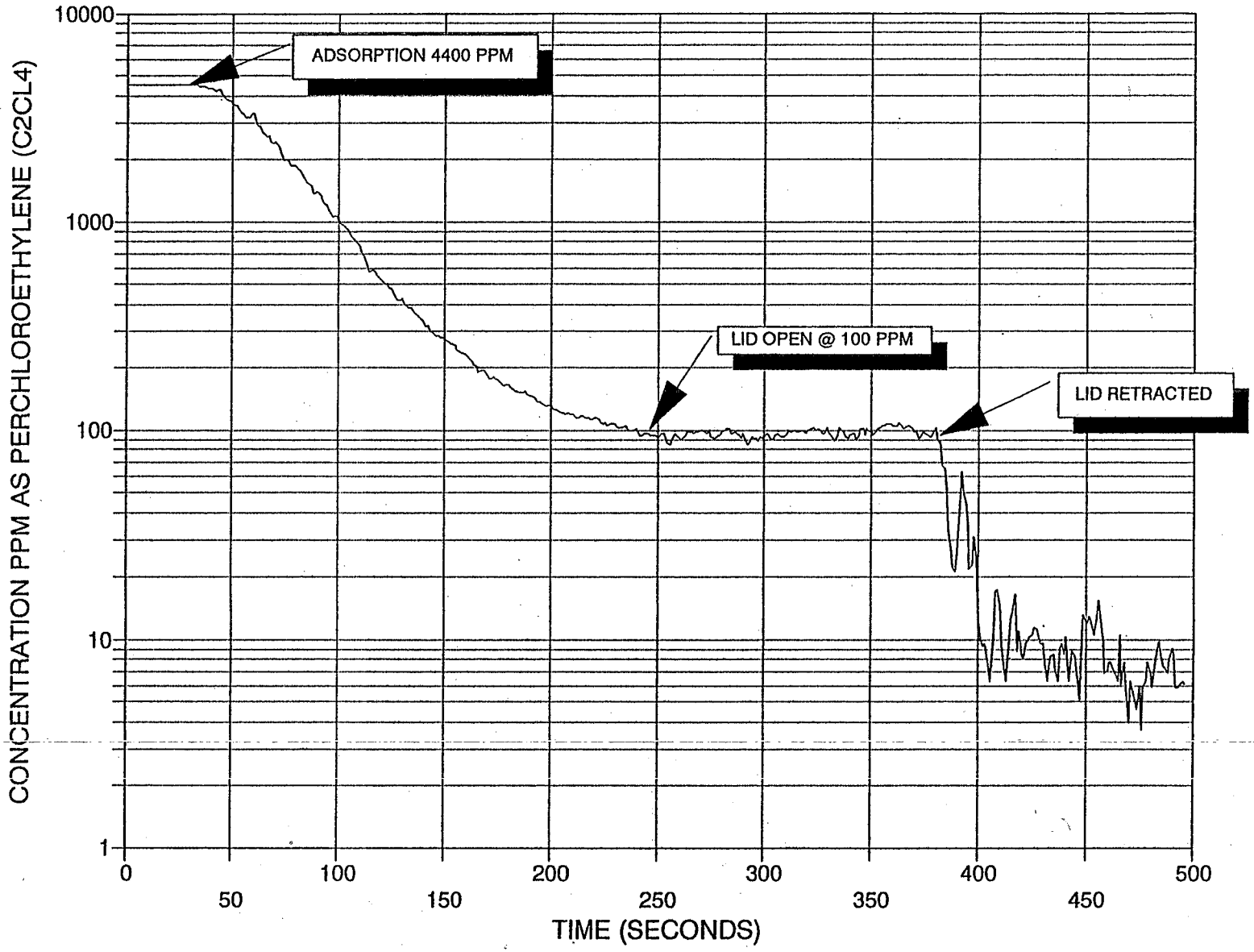

Figure D-2. Durr Ecoclean 83S, Battelle Run #3: Cleaning Chamber Solvent Concentration.

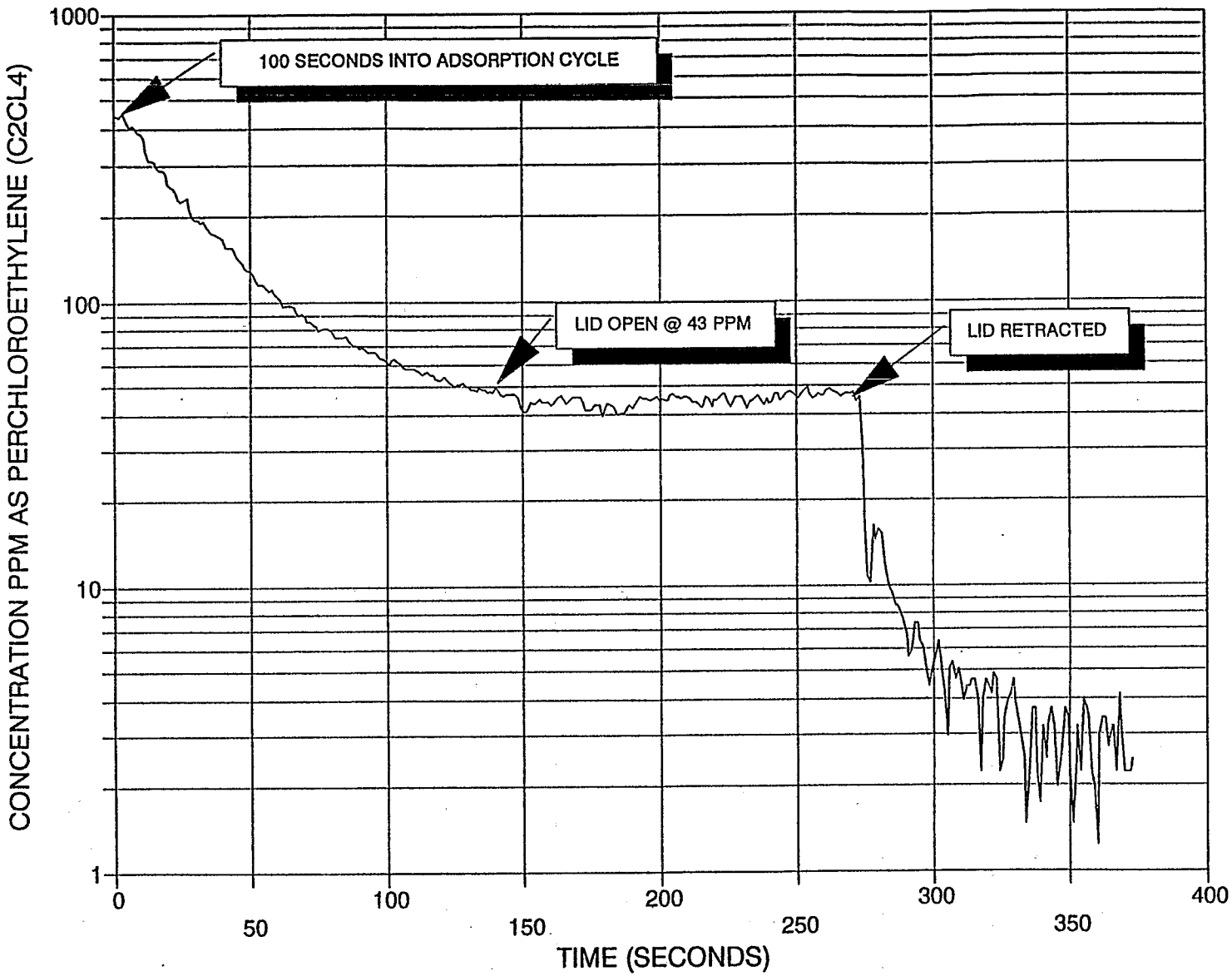

Figure D-3. Durr Ecoclean 83S, Battelle Run #5: Cleaning Chamber Solvent Concentration.

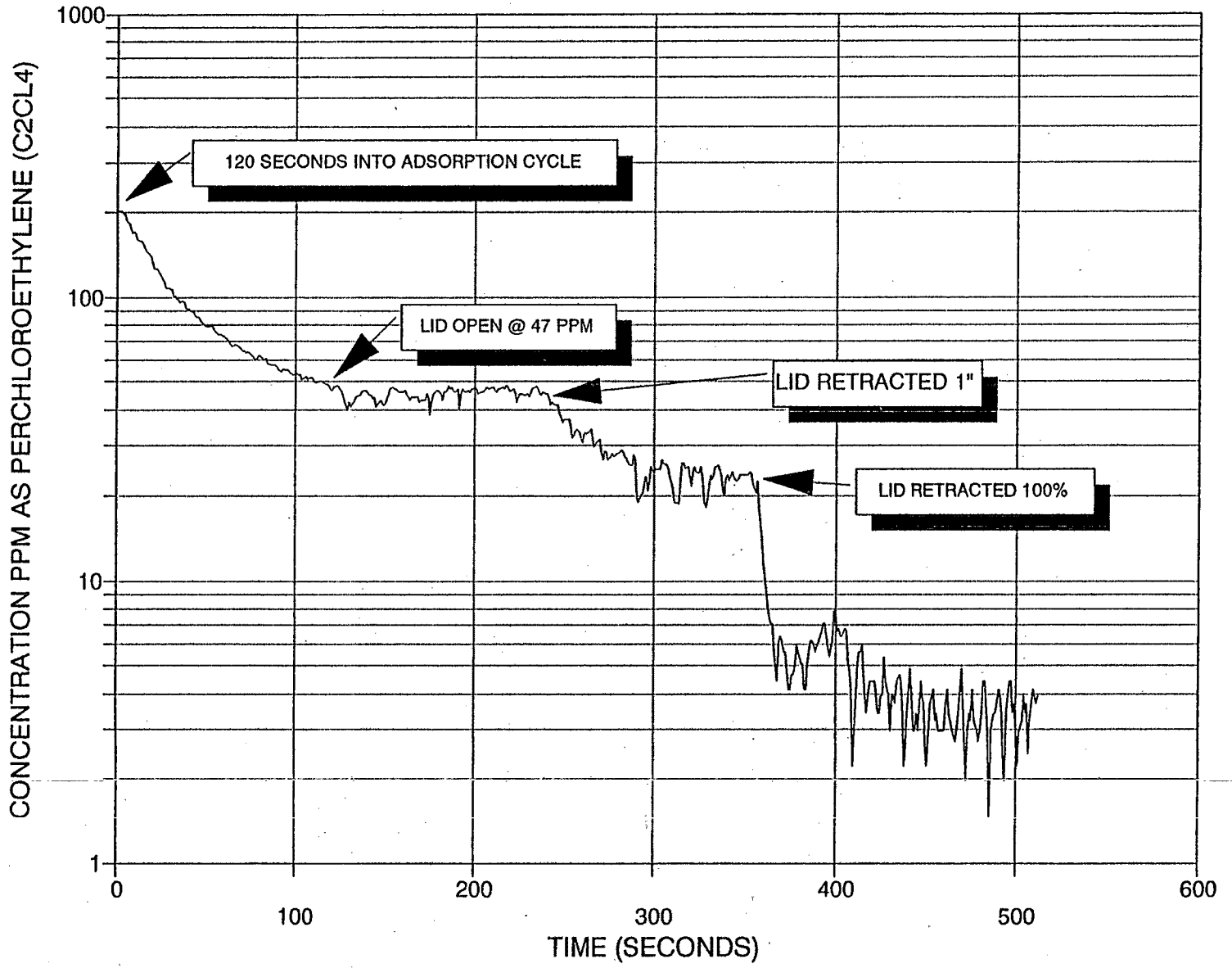

Figure D-4. Durr Ecoclean 83S, Battelle Run #6: Cleaning Chamber Solvent Concentration.

APPENDIX E

FEATURES OF THE CONVENTIONAL DEGREASER USED AS A COMPARISON

The baseline for comparing the pollution prevention and economic benefits of the LEVD was a conventional open-top vapor degreaser. The conventional unit selected was the size yields approximately the same production rate as the LEVD. The LEVD can process up to 560 lb/hr of steel parts (see Section 4 of this report). Based on information obtained from several vendors, such a conventional unit typically would have an opening of 4.5 ft^2. A standard unit comes with primary cooling coils and a freeboard ratio of 0.75. The heating requirement is 6 kW and water flow though the primary condenser is 2 gal/min. It should be noted that the physical dimensions of the vapor chamber of the selected conventional unit are much smaller than the LEVD. The same processing rate (560 lb/hr) is maintained by running smaller, more frequent batches.

Emissions from conventional vapor degreasers have been estimated in previous EPA-sponsored studies. In a previous 1992 study (Battelle, 1992a)*, a conventional open-top degreaser was found to be losing 6,145 lb/yr from a total feed of 6,190 lb/yr (over 99% of feed) due to air emissions. Another study by the Dow Chemical Co. (Suprenant, 1992) found that open-top vapor degreasers with 0.5 and 0.75 freeboard ratios were emitting 0.373 and 0.273 $lb/ft^2/hr$ of solvent.

A more detailed EPA-sponsored study (EPA, 1989)* had been conducted previously to estimate emission rates from conventional degreasers with varying control options. Losses due to air emissions were estimated for three categories — workload losses, idling losses, and downtime losses. Emissions, especially workload losses, varied depending on equipment- and operation-related factors. Workload and idling losses, measured in terms of lb of solvent per ft^2 of opening per hr ($lb/ft^2/hr$), generally were independent of the type of solvent used. Downtime losses were dependent on the type of solvent (vapor pressure). Therefore, during a 24-hr period, air emissions depended on the time distribution between working (workload processing), idling, and downtime for the degreaser.

For this study, the comparison was based on a degreaser that is operated (working) continuously for 16 hr (no idling period) and shutdown (downtime) for 8 hr. In the EPA (1989) study, 25 tests were conducted on various degreasers to estimate workload losses. Workload-

*References are listed in Section 7 of this report.

related losses include losses due to disturbance of the air-vapor boundary during entry-exit of the workload, processing of the workload, and liquid dragout on the workload. All the tests were performed using electric hoists to move the workload. None of the degreasers had a lip exhaust system. The tests included a wide range of room ventilation conditions. For the 25 tests, the average emission was 0.171 lb/ft^2/hr with a standard deviation of 0.141 lb/ft^2/hr. These tests were conducted on various sizes of degreasers. Of the 25 tests, 12 tests were conducted on degreasers with 4.5-ft^2 openings. For these tests, the average and standard deviation were 0.133 and 0.046 lb/ft^2/hr, respectively. Of these 12 tests, 6 were conducted on degreasers with a freeboard ratio of 0.75. For these six tests, the average emission and standard deviation were 0.147 and 0.051 lb/ft^2/hr, respectively. This workload-related average emission of 0.147 lb/ft^2/hr was used as the baseline in this study for comparison with the LEVD.

[Downtime losses, which were expected to be an order of magnitude below workload losses, were assumed to be minimal; these losses can be minimized by covering the vapor degreaser during standby. Idling losses in the EPA (1989) study were found to average 0.105, which is the same order of magnitude as the working losses. Therefore, idling losses were not quantified separately from working losses.]

The conventional open-top vapor degreaser selected for comparison with the LEVD, therefore, has the following characteristics:

- 4.5-ft^2 opening
- Approximately 560 lb/hr production rate for steel parts
- 0.75 freeboard ratio
- primary cooling coils
- 6-kW heater
- 2 gal/min tap water flow through primary cooling coils
- Working emissions of 0.147 lb/ft^2/hr.

Based on information supplied by various vendors, such a degreaser can be expected to cost approximately $8,500 (purchase price).

APPENDIX F

ECONOMICS OF ATMOSPHERIC UNIT

The costs utilized in the economic spreadsheets for the atmospheric unit (Tables F-1 to F-4) are described below:

- The cost of equipment of $14,300 includes the listed price of $12,995 plus 10% to cover freight, taxes, insurance, and spare parts.
- Materials, installation, plant engineering, and contingency costs are estimates based on experience.
- Working capital is based on a 1-month supply of materials (still bags and drums). Startup costs are estimated.
- Information on debt, depreciation, taxes, inflation, and cost of capital are general assumptions.
- Differences in operating costs are based on costs listed in Table 9 of the main report. Supervision and overhead costs are general assumptions.

The payback period can be determined from Table F-4 as the year in which the return on investment (ROI) exceeds 15% because 15% is the cost of capital (Table F-1).

TABLE F-1. CAPITAL COST OF THE ATMOSPHERIC UNIT

INPUT CAPITAL COST	
Capital Cost	
Equipment	$14,300
Materials	$ 100
Installation	$ 500
Plant Engineering	$ 100
Contractor/Engineering	$ 0
Permitting Costs	$ 0
Contingency	$ 800
Working Capital	$ 27
Startup Costs	$ 500
% Equity	100%
% Debt	0%
Interest Rate on Debt, %	10.00%
Debt Repayment, years	0
Depreciation Period	7
Income Tax Rate, %	34.00%
Escalation Rates, %	5.0%
Cost of Capital	15.00%

OUTPUT CAPITAL COST	
Construction Year	1
Capital Expenditures	
Equipment	$14,300
Materials	$ 100
Installation	$ 500
Plant Engineering	$ 100
Contractor/Engineering	$ 0
Permitting Costs	$ 0
Contingency	$ 800
Startup Costs	$ 500
Depreciable Capital	$16,300
Working Capital	$ 27
Subtotal	$16,327
Interest on Debt	$ 0
Total Capital Requirement	$16,327
Equity Investment	$16,327
Debt Principal	$ 0
Interest on Debt	$ 0
Total Financing	$16,327

TABLE F-2. NET OPERATING COSTS/SAVINGS FOR THE ATMOSPHERIC UNIT

DIFFERENCE IN OPERATING COSTS (parentheses indicate negative values)			
Marketable By-products		Operating Labor Cost	
	$ 0	Operator hrs	17
Total $/yr	$ 0	Wage Rate, $/hr	$ 8
		Total $/yr	$ 136
Utility Cost			
Electric	$ 51	Operating Supplies	
Water	$ 18	Still bags	$ 120
Total $/yr	$ 69		
		Maintenance Costs	
Raw Material Savings		Labor	$ 96
Solvent	$ 6,670	Materials	$ 86
Water	$ 0		
Total	$ 6,670		
		Supervision Costs	
Decreased Waste Disposal		(% of O&M Labor)	10.0%
Spent Solvent	$ 6,550		
Residue	($3,220)	Overhead Costs	
Labor	$ 40	(% of O&M Labor + Supervision)	
Transportation	$ 0	Plant Overhead	25.0%
Storage Drums $	$ 480	Home Office	20.0%
Total Disposal $	$ 3,850	Labor Burden	28.0%

TABLE F-3. ANNUAL OPERATING SAVINGS FOR THE ATMOSPHERIC UNIT

REVENUE AND COST FACTORS				
Operating Year Number		1	2	3
Escalation Factor	1.000	1.050	1.103	1.158
INCREASED REVENUES				
Increased Production		$ 0	$ 0	$ 0
Marketable By-products		$ 0	$ 0	$ 0
Annual Revenue		$ 0	$ 0	$ 0
OPERATING SAVINGS (Numbers in parentheses indicate net expense)				
Raw Materials		$ 7,004	$ 7,354	$ 7,721
Disposal Costs		$4,043	$4,425	$4,457
Maintenance Labor		($ 101)	($ 106)	($ 111)
Maintenance Supplies		($ 90)	($ 95)	($ 100)
Operating Labor		($ 143)	($ 150)	($ 157)
Operating Supplies		($ 126)	($ 132)	($ 139)
Utilities		($ 72)	($ 76)	($ 80)
Supervision		($ 24)	($ 26)	($ 27)
Labor Burden		($ 75)	($ 79)	($ 83)
Plant Overhead		($ 67)	($ 70)	($ 74)
Home Office Overhead		($ 54)	($ 56)	($ 59)
Total Operating Savings		$10,294	$10,808	$11,349

TABLE F-4. RETURN ON INVESTMENT FOR THE ATMOSPHERIC UNIT

RETURN ON INVESTMENT– –ATMOSPHERIC UNIT				
Construction Year	1			
Operating Year		1	2	3
Book Value	$16,300	$11,643	$ 8,316	$ 5,940
Depreciation (by straight-line)		$ 2,329	$ 2,329	$ 2,329
Depreciation (by double DB)		$ 4,657	$ 3,327	$ 2,376
Depreciation		$ 4,657	$ 3,327	$ 2,376
Cash Flows				
Construction Year	1			
Operating Year		1	2	3
Revenues		$ 0	$ 0	$ 0
+ Operating Savings		$10,294	$10,808	$11,349
Net Revenues		$10,294	$10,808	$11,349
– Depreciation		$ 4,657	$ 3,327	$ 2,376
Taxable Income		$ 5,637	$ 7,482	$ 8,973
– Income Tax		$ 1,916	$ 2,544	$ 3,051
Profit after Tax		$ 3,720	$ 4,938	$ 5,922
+ Depreciation		$ 4,657	$ 3,327	$ 2,376
After-Tax Cash Flow		$ 8,377	$ 8,265	$ 8,298
Cash Flow for ROI	($16,327)	$ 8,377	$ 8,265	$ 8,298
Net Present Value	(16,327)	($9,042)	($2,793)	($2,663)
Return on Investment		–48.69%	1.29%	24.64%

APPENDIX G

MAINTENANCE COSTS OF THE VACUUM UNIT

Based on information from the vendor, the following annual routine maintenance costs were estimated. The unit is expected to be operated for approximately 660 hr/yr at this site, based on plant information and this testing, which showed 55 batches/yr and 12 hr/batch.

- Pump oil change once every 3 months, i.e., 4 times/yr and 0.5 hr/change.
- Ceramic filter cleaning once in 3 months (4 times/yr and 0.5 hr/change). Ceramic filter changed once in 2 yr at $129.55/filter.
- Pump overhaul once in 2 yr (4 hr/overhaul). Spare parts (gaskets, O-rings, etc.) are $216/overhaul (maximum).
- Cleaning inside of evaporator once a year (2 hr/yr). Spare parts are $307/cleaning (maximum).

APPENDIX H

ECONOMICS OF VACUUM UNIT

The costs utilized in the economic spreadsheets for the vacuum unit (Tables H-1 to H-4) are described below:

- The cost of equipment of $25,900 includes the listed price of $23,500 plus 10% to cover freight, taxes, insurance, and spare parts.
- Materials, installation, and plant engineering costs are estimates based on experience. Contingency costs are based on an assumption of 5% of fixed capital costs.
- Working capital is based on a 1-month supply of materials (drums). Startup costs are estimated.
- Information on debt, depreciation, taxes, inflation, and cost of capital are general assumptions.
- Differences in operating costs are based on costs listed in Table 10 of the main report. Supervision and overhead costs are general assumptions.

The payback period can be determined from Table H-4 as the year in which the return on investment (ROI) exceeds 15% because 15% is the cost of capital (see Table H-1).

TABLE H-1. CAPITAL COST OF THE VACUUM UNIT

INPUT CAPITAL COST	
Capital Cost	
Equipment	$25,900
Materials	$100
Installation	$500
Plant Engineering	$100
Contractor/Engineering	$0
Permitting Costs	$0
Contingency	$1,330
Working Capital	$10
Start–up Costs	$500
% Equity	100%
% Debt	0%
Interest Rate on Debt, %	10.00%
Debt Repayment, years	0
Depreciation period	7
Income Tax Rate, %	34.00%
Escalation Rates, %	5.0%
Cost of Capital	15.00%

OUTPUT CAPITAL REQUIREMENT	
Construction Year	1
Capital Expenditures	
Equipment	$25,900
Materials	$100
Installation	$500
Plant Engineering	$100
Contractor/Engineering	$0
Permitting Costs	$0
Contingency	$1,330
Start–up Costs	$500
Depreciable Capital	$28,430
Working Capital	$10
Subtotal	$28,440
Interest on Debt	$0
Total Capital Requirement	$28,440
Equity Investment	$28,440
Debt Principal	$0
Interest on Debt	$0
Total Financing	$28,440

TABLE H-2. NET OPERATING COSTS/SAVINGS FOR THE VACUUM UNIT

DIFFERENCE IN OPERATING COSTS (parentheses indicate negative values)				
Marketable By–products			Operating Labor Costs	
	$0		Operator hrs	55
Total $/yr.	$0		Wage rate, $/hr.	$8.00
			Total $/yr.	$440
Utility Costs				
Electric	$39		Operating Supplies	
Water	$0			$0
Total $/yr.	$39			
			Maintenance Costs	
Raw Material Savings			Labor	$128
Solvent	$9,830		Materials	$494
Water	$0			
Total	$9,830			
			Supervision Costs	
Decreased Waste Disposal			(% of O&M Labor)	10.0%
Spent Solvent	$7,500			
Residue	($340)		Overhead Costs	
Labor	$104		(% of O&M Labor + Supervision)	
Oil from recycling unit	($12)		Plant Overhead	25.0%
Storage Drums $	$2,080		Home Office	20.0%
Total Disposal $	$9,332		Labor Burden	28.0%

TABLE H-3. ANNUAL OPERATING SAVINGS FOR THE VACUUM UNIT

REVENUE AND COST FACTORS					
Operating Year Number		1	2	3	4
Escalation Factor	1.000	1.050	1.103	1.158	1.216
INCREASED REVENUES					
Increased Production		$0	$0	$0	$0
Marketable By–products		$0	$0	$0	$0
Annual Revenue		$0	$0	$0	$0
OPERATING SAVINGS (Numbers in parentheses indicate net expense)					
Raw Materials		$10,322	$10,838	$11,379	$11,948
Disposal Costs		$9,799	$10,289	$10,803	$11,343
Maintenance Labor		($134)	($141)	($148)	($156)
Maintenance Supplies		($519)	($545)	($572)	($600)
Operating Labor		($462)	($485)	($509)	($535)
Operating Supplies		$0	$0	$0	$0
Utilities		($41)	($43)	($45)	($47)
Supervision		($60)	($63)	($66)	($69)
Labor Burden		($184)	($193)	($203)	($213)
Plant Overhead		($164)	($172)	($181)	($190)
Home Office Overhead		($131)	($138)	($145)	($152)
Total Operating Savings		$18,426	$19,347	$20,314	$21,330

TABLE H-4. RETURN ON INVESTMENT FOR THE VACUUM UNIT

RETURN ON INVESTMENT--VACUUM UNIT					
Construction Year	1				
Operating Year		1	2	3	4
Book Value	$28,430	$20,307	$14,505	$10,361	$6,299
Depreciation (by straight-line)		$4,061	$4,061	$4,061	$4,061
Depreciation (by double DB)		$8,123	$5,802	$4,144	$2,960
Depreciation		$8,123	$5,802	$4,144	$4,061
Cash Flows					
Construction Year	1				
Operating Year		1	2	3	4
Revenues		$0	$0	$0	$0
+ Operating Savings		$18,426	$19,347	$20,314	$21,330
Net Revenues		$18,426	$19,347	$20,314	$21,330
– Depreciation		$8,123	$5,802	$4,144	$4,061
Taxable Income		$10,303	$13,545	$16,170	$17,268
– Income Tax		$3,503	$4,605	$5,498	$5,871
Profit after Tax		$6,800	$8,940	$10,672	$11,397
+ Depreciation		$8,123	$5,802	$4,144	$4,061
After-Tax Cash Flow		$14,923	$14,742	$14,816	$15,459
Cash Flow for ROI	($28,440)	$14,923	$14,742	$14,816	$15,459
Net Present Value	($28,440)	($15,464)	($4,317)	$5,425	$14,263
Return on Investment		-47.53%	2.86%	26.23%	38.03%

APPENDIX I

ENERGY REQUIREMENT OF LEVD

The energy requirement for a 1-hour cycle is calculated in the Table I-1, based on the ratings of the heaters and pumps in the LEVD and their period of operation during each stage.

TABLE I-1. ELECTRICITY CONSUMPTION OF LEVD

Stage	1	2	3	4	5	6	7	Total Cycle
Stage time (min) for 560 lbs/hr	27.5	1	2	2	22.5	1	4	60
								Total Cycle kwhr
Heater (kw)	27	27	9	9	9	9	9	17.6
Fill/drain prep (kw)	0.75	0.75	0.75	0.75				0.4
Compressor (kw)	4.35	4.35	4.35	4.35 *	4.35 *	4.35 *	4.35 *	2.9
Fan (chiller) (kw)	0.9	0.9	0.9	0.9 *	0.9 *	0.9 *	0.9 *	0.6
Compressed air (kw)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total								21.8 kwhr

* operates 30% of the time

Stage 1 = Vapor fill
Stage 2 = Degreasing
Stage 3 = Condensation
Stage 4 = Air recirculation
Stage 5 = Carbon heat up
Stage 6 = Desorption
Stage 7 = Adsorption

APPENDIX J

ECONOMICS OF LEVD

The costs utilized in the economic spreadsheets for the LEVD unit (Tables J-1 to J-5) are described below:

- The cost of equipment of $231,000 includes the listed price of $210,000 plus 10% to cover freight, taxes, insurance, and spare parts.
- Materials, installation, and plant engineering costs are estimates based on experience. Contingency costs are assumed at 5% of fixed capital costs.
- Working capital is based on a 1-month supply of materials (PCE). Startup costs are estimated.
- Information on debt, depreciation, taxes, inflation, and cost of capital are general assumptions.
- Differences in operating costs are based on costs listed in Table 12 of the main report. Supervision and overhead costs are general assumptions.

Because of the high capital cost of the LEVD, a loan of 60% of the cost was assumed. Because the calculation for return on investment (Table J-4) does not take into account the costs of a loan, a second spreadsheet Table J-5, which includes these costs, is provided. This second spreadsheet includes both a return on equity (return on the 40% capital put up by the purchaser) and a return on assets (return on the total capital).

If no loan is taken (that is, if the purchaser puts up the entire capital himself), then the payback period (year in which return on investment exceeds 15%) is 9 years (Table J-4). If 60% of the capital is raised through a loan, then the payback period (year in which return on assets exceeds 15%) is more than 10 years (Table J-5).

TABLE J-1. CAPITAL COST OF THE LEVD

INPUT CAPITAL COST	
Capital Cost	
Equipment	$231,000
Materials	$500
Installation	$1,000
Plant Engineering	$1,000
Contractor/Engineering	$0
Permitting Costs	$0
Contingency	$11,700
Working Capital	$1,060
Start–up Costs	$2,100
% Equity	40%
% Debt	60%
Interest Rate on Debt, %	10.00%
Debt Repayment, years	7
Depreciation period	7
Income Tax Rate, %	34.00%
Escalation Rates, %	5.0%
Cost of Capital	15.00%

OUTPUT CAPITAL REQUIREMENT	
Construction Year	1
Capital Expenditures	
Equipment	$231,000
Materials	$500
Installation	$1,000
Plant Engineering	$1,000
Contractor/Engineering	$0
Permitting Costs	$0
Contingency	$11,700
Start–up Costs	$2,100
Depreciable Capital	$247,300
Working Capital	$1,060
Subtotal	$248,360
Interest on Debt	$14,328
Total Capital Requirement	$262,688
Equity Investment	$105,075
Debt Principal	$143,285
Interest on Debt	$14,328
Total Financing	$262,688

TABLE J-2. NET OPERATING COSTS/SAVINGS FOR THE LEVD

DIFFERENCE IN OPERATING COSTS (parentheses indicate negative values)				
Marketable By–products	$0		Operating Labor Costs	
			Operator hrs	(3,667)
			Wage rate, $/hr.	$8.00
Utility Costs			Total $/yr.	($29,336)
Electricity	$3,749			
Water	($480)		Operating Supplies	
Electric heat	($1,020)		Chemicals	$0
Total $/yr.	$2,249			
			Maintenance Costs	
Raw Materials Savings			Labor	$1,920
Solvent	$1,876		Materials	$2,012
Total	$1,876			
			Supervision Costs	
Decreased Waste Disposal			(% of O&M Labor)	10.0%
Spent Solvent	$0			
Residue	$0		Overhead Costs	
Labor	$0		(% of O&M Labor + Supervision)	
Transportation	$0		Plant Overhead	25.0%
Storage Drums $	$0		Home Office	20.0%
Total Disposal $	$0		Labor Burden	28.0%

TABLE J-3. ANNUAL OPERATING SAVINGS FOR THE LEVD

REVENUE AND COST FACTORS--LEVD									
Operating Year Number		1	2	3	4	5	6	7	8
Escalation Factor	1.000	1.050	1.103	1.158	1.216	1.276	1.340	1.407	1.477
INCREASED REVENUES									
Increased Production		$0	$0	$0	$0	$0	$0	$0	$0
Marketable By-products		$0	$0	$0	$0	$0	$0	$0	$0
Annual Revenue		$0	$0	$0	$0	$0	$0	$0	$0
OPERATING SAVINGS (Numbers in parentheses indicate net expense)									
Raw Materials		$1,970	$2,068	$2,172	$2,280	$2,394	$2,514	$2,640	$2,772
Disposal Costs		$0	$0	$0	$0	$0	$0	$0	$0
Maintenance Labor		($2,016)	($2,117)	($2,223)	($2,334)	($2,450)	($2,573)	($2,702)	($2,837)
Maintenance Supplies		($2,113)	($2,218)	($2,329)	($2,446)	($2,568)	($2,696)	($2,831)	($2,973)
Operating Labor		$30,803	$32,343	$33,960	$35,658	$37,441	$39,313	$41,279	$43,343
Operating Supplies		$0	$0	$0	$0	$0	$0	$0	$0
Utilities		($2,361)	($2,480)	($2,603)	($2,734)	($2,870)	($3,014)	($3,165)	($3,323)
Supervision		$2,879	$3,023	$3,174	$3,332	$3,499	$3,674	$3,858	$4,051
Labor Burden		$8,866	$9,310	$9,775	$10,264	$10,777	$11,316	$11,882	$12,476
Plant Overhead		$7,916	$8,312	$8,728	$9,164	$9,622	$10,104	$10,609	$11,139
Home Office Overhead		$6,333	$6,650	$6,982	$7,331	$7,698	$8,083	$8,487	$8,911
Total Operating Savings		$52,277	$54,891	$57,635	$60,517	$63,543	$66,720	$70,056	$73,559

TABLE J-4. RETURN ON INVESTMENT FOR THE LEVD

RETURN ON INVESTMENT--LEVD									
Construction Year	1								
Operating Year		1	2	3	4	5	6	7	8
Book Value	$247,300	$176,643	$126,173	$90,124	$54,795	$19,467	$0	$0	$0
Depreciation (by straight-line)		$35,329	$35,329	$35,329	$35,329	$35,329	$35,329	$0	$0
Depreciation (by double DB)		$70,657	$50,469	$36,050	$25,750	$15,656	$5,562	$0	$0
Depreciation		$70,657	$50,469	$36,050	$35,329	$35,329	$19,467	$0	$0
Cash Flows									
Construction Year	1								
Operating Year		1	2	3	4	5	6	7	8
Revenues		$0	$0	$0	$0	$0	$0	$0	$0
+ Operating Savings		$52,277	$54,891	$57,635	$60,517	$63,543	$66,720	$70,056	$73,559
Net Revenues		$52,277	$54,891	$57,635	$60,517	$63,543	$66,720	$70,056	$73,559
− Depreciation		$70,657	$50,469	$36,050	$35,329	$35,329	$19,467	$0	$0
Taxable Income		($18,380)	$4,421	$21,586	$25,189	$28,214	$47,253	$70,056	$73,559
− Income Tax		($6,249)	$1,503	$7,339	$8,564	$9,593	$16,066	$23,819	$25,010
Profit after Tax		($12,131)	$2,918	$14,247	$16,624	$18,622	$31,187	$46,237	$48,549
+ Depreciation		$70,657	$50,469	$36,050	$35,329	$35,329	$19,467	$0	$0
After-Tax Cash Flow		$58,526	$53,388	$50,296	$51,953	$53,950	$50,654	$46,237	$48,549
Cash Flow for ROI	($248,360)	$58,526	$53,388	$50,296	$51,953	$53,950	$50,654	$46,237	$48,549
Net Present Value	($248,360)	($197,468)	($157,099)	($124,028)	($94,324)	($67,501)	($45,602)	($28,220)	($12,349)
Return on Investment		−76.43%	−40.38%	−19.01%	−5.79%	2.64%	7.78%	11.01%	13.42%

TABLE J-5. RETURN ON ASSETS FOR THE LEVD

RETURN ON EQUITY/RETURN ON ASSETS--LEVD									
Construction Year	1								
Operating Year		1	2	3	4	5	6	7	8
Book Value	$247,300	$176,643	$126,173	$90,124	$54,795	$19,467	$0	$0	$0
Depreciation (by straight-line)		$35,329	$35,329	$35,329	$35,329	$35,329	$35,329	$0	$0
Depreciation (by doubleDB)		$70,657	$50,469	$36,050	$25,750	$15,656	$5,562	$0	$0
Depreciation		$70,657	$50,469	$36,050	$35,329	$35,329	$19,467	$0	$0
Debt Balance	$157,613	$157,613	$135,097	$112,581	$90,065	$67,548	$45,032	$22,516	$0
Interest Payment		$15,761	$13,510	$11,258	$9,006	$6,755	$4,503	$2,252	$0
Principal Repayment		$22,516	$22,516	$22,516	$22,516	$22,516	$22,516	$22,516	$0
CASH FLOWS									
Construction Year	1								
Operating Year		1	2	3	4	5	6	7	8
Revenues		$0	$0	$0	$0	$0	$0	$0	$0
+ Operating Savings		$52,277	$54,891	$57,635	$60,517	$63,543	$66,720	$70,056	$73,559
Net Revenues		$52,277	$54,891	$57,635	$60,517	$63,543	$66,720	$70,056	$73,559
– Depreciation		$70,657	$50,469	$36,050	$35,329	$35,329	$19,467	$0	$0
– Interest on Debt		$15,761	$13,510	$11,258	$9,006	$6,755	$4,503	$2,252	$0
Taxable Income		($34,141)	($9,088)	$10,328	$16,182	$21,460	$42,750	$67,805	$73,559
– Income Tax		($11,608)	($3,090)	$3,511	$5,502	$7,296	$14,535	$23,054	$25,010
Profit after Tax		($22,533)	($5,998)	$6,816	$10,680	$14,163	$28,215	$44,751	$48,549
+ Depreciation		$70,657	$50,469	$36,050	$35,329	$35,329	$19,467	$0	$0
– Debt Repayment		$22,516	$22,516	$22,516	$22,516	$22,516	$22,516	$22,516	$0
After-Tax Cash Flow		$25,608	$21,955	$20,350	$23,493	$26,976	$25,166	$22,235	$48,549
Cash Flow for ROE	($105,075)	$25,608	$21,955	$20,350	$23,493	$26,976	$25,166	$22,235	$48,549
Net Present Value	($105,075)	($82,808)	($66,207)	($52,826)	($39,394)	($25,983)	($15,103)	($6,744)	$9,127
Return on Equity		-75.63%	-40.51%	-19.64%	-5.44%	4.06%	9.56%	12.84%	17.40%
Cash Flow for ROA	($262,688)	$25,608	$21,955	$20,350	$23,493	$26,976	$25,166	$22,235	$48,549
Net Present Value	($262,688)	($240,421)	($223,820)	($210,439)	($197,008)	($183,596)	($172,716)	($164,357)	($148,486)
Return on Assets		-90.25%	-65.81%	-46.96%	-32.26%	-21.50%	-14.72%	-10.30%	-3.96%

APPENDIX K

LEVD CYCLE TIME VARIATION FOR VARIOUS METALS

Table K-1 lists the thermal conductivity (k), density (d), and specific heat (Cp) values as given in *Chemical Engineers' Handbook* (Perry and Chilton, 1973) for steel, aluminum, brass, and copper. The thermal diffusivity (α) is calculated from these values by the relationship

$$\alpha = \frac{k}{d \cdot C_p}$$

Based on experimental total cycle times measured for 165 and 915 lb of steel (Table 11 in this report), the total cycle time for 1,100 lb of steel (maximum load) is calculated by linear extrapolation. From the total cycle times for steel, 40 min (the constant component) is subtracted to give the variable component of the vapor-fill stage time. The relationship αmetal • tmetal = αsteel • tsteel is then applied to the variable component of vapor-fill times for steel to obtain the corresponding times for the other metals.

TABLE K-1. VARIATION OF LEVD CYCLE TIMES FOR VARIOUS METALS

	k (Btu/ft/hr/F)	Density (lb/ft3)	Specific Heat (Btu/lb/F)	Thermal Diffusivity (ft2/hr)
Steel	26	490.8	0.107	0.495
Aluminum	118	169.3	0.23	3.030
Brass	58	520.1	0.09	1.239
Copper	220	556.4	0.092	4.298

	Variable Component of Vapor fill (min)	Total (min)	Mass (lbs)	Variable Component of Vapor fill (min)	Total (min)	Mass (lbs)	Variable Component of Vapor fill (min)	Total (min)	Mass (lbs)
Steel	11	51	165	29	69	915	34	74	1100
Aluminum	2	42	57	5	45	316	6	--	379
Brass	4	44	175	12	52	970	14	54	1166
Copper	1	41	187	3	43	1037	4	44	1247

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