P2 TECHNOLOGY REVIEW: AQUEOUS CLEANING IN MANUFACTURING OPERATIONS

A survey of what is currently known about water-based cleaning and degreasing

As part of an overall project to provide industry representatives, researchers, technical assistance providers, funders of research, and others with better access to information on pollution prevention research, the Pacific Northwest Pollution Prevention Research Center (PPRC) is undertaking literature reviews on alternative cleaning technologies that replace ozone-depleting and toxic-solvent approaches. The reviews, which focus on cleaning as part of manufacturing, will include aqueous cleaning, carbon dioxide cleaning, and no-clean approaches. The full-scale reviews will be available on the PPRC’s World Wide Web site at http://pprc.pnl.gov/pprc/p2tech/p2tech.html. The reviews will provide automatic connections to projects in the PPRC’s research projects database, links to other relevant Internet sites, and extensive bibliographies.

This is the first in a series of articles on the technology reviews that will appear in Pollution Prevention Review. This article summarizes the PPRC’s review of aqueous cleaning. Subsequent articles will examine carbon dioxide cleaning and no-clean approaches. The final article in the series will address the methods used to measure cleaning effectiveness.

Background

Efforts to replace the ozone-depleting solvents (such as Freon) often used in vapor degreasing systems primarily have occurred since the late 1980s. These efforts have resulted largely from the effects of the Montreal Protocol, which dictated a worldwide phase-out of many ozone-depleting chemicals. In the past decade, there have also been significant efforts to replace cleaning solvents that, regardless of their ozone-depleting potential, are known or suspected carcinogens. The desire to convert from ozone-depleting or carcinogenic solvents to alternative, less-polluting systems that do

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not require these solvents has led to a significant volume of research and a wealth of published literature.

In general, there are two types of published materials available that report on the technical and economic feasibility of converting to alternative systems: reports on research results from laboratory or pilot-scale experiments, and case studies from manufacturers that have successfully made the conversion. The PPRC has reviewed both types of references to answer the following questions:

- Have the alternatives been proven to be technically viable replacements for solvent-based systems? If so, what are key factors in their success? What limitations have been found?
- What do economic analyses of converting to the alternatives show?
- What gaps are there in the research that has been done to date?

Of the cleaning alternatives that have received attention in the literature, three are prominent: aqueous cleaning, carbon dioxide cleaning, and no-clean approaches. As noted above, the PPRC is undertaking a separate literature review on the technical and economic feasibility of each of these alternatives, as well as a final review to examine the methods used by researchers to determine the cleaning effectiveness of the three alternatives. These reviews are intended to serve as a valuable reference for individuals working on cleaning process design and implementation.

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**“Aqueous Cleaning” Defined**

In this article, “aqueous cleaners” are defined as those that typically contain at least 95-percent water. Cleaners that include larger percentages of other compounds, including solvents such as terpenes, typically are called “semi-aqueous.” While these are successfully used in a wide variety of industrial applications, they are not the focus of this review.

Aqueous cleaning solutions can include surfactants and other additives, but they are sometimes plain tap water or deionized water. Processes used as part of an aqueous cleaning system include high-pressure sprays, agitation, ultrasonic, and other physical processes that enhance cleaning effectiveness. Many aqueous cleaning systems used in the manufacturing environment are multistaged and include several of these processes.

For the most part, as the required cleaning becomes more difficult, aqueous cleaning systems contain more additives and/or become more complex. The primary pollution prevention benefit of aqueous cleaners is that they are non-ozone-depleting and carry few or no volatile organic compounds (VOCs). A primary disadvantage is that they generate wastewater streams, which must be properly disposed of or treated prior to discharge. More background information on aqueous cleaning can be found in a number of sources.

**Technical Issues**

Aqueous cleaners have been used for decades to meet cleaning needs in the manufacturing environment. More recently, the published literature has shown aqueous cleaning processes to be technically feasible alternatives to solvents that are ozone-depleting or that have other undesirable characteristics. These studies have reported comparable or even superior cleaning results, and many have documented significant pollution prevented by using aqueous systems. Examples include the following:

- In a DuPont case study, the company cited a 98-percent waste reduction while meeting all cleaning requirements. DuPont converted from a solvent-based to a high-pressure, water-jet...
cleaning system for cleaning a polymer mixing tank used in a polymer production process. In a pilot test directly comparing automated aqueous rotary washing to perchloroethylene vapor degreasing of steel caplets at a metal finishing shop, both systems were found to meet cleaning requirements on the basis of visual inspection. But the aqueous system avoided solid hazardous waste and perchloroethylene air emissions; it generated only wastewater and oily liquid waste streams, which are less hazardous and less expensive to handle.

An automotive radiator manufacturer realized a 76.8-percent decrease in part reject rates and an 80-percent increase in production rates as a result of converting from a set of five 1,1,1-trichloroethane (TCA) vapor degreasers to a three-stage, conveyorized aqueous-cleaning system. The three stages were a tap-water wash, heated-detergent bath, and hot-water rinse. Decreases in reject rates were also seen by an automotive parts manufacturer that converted from trichloroethylene (TCE) vapor degreasers to several different aqueous-cleaning systems for the different parts made at the plant.

The Massachusetts Toxics Use Reduction Institute's Surface Cleaning Laboratory performed laboratory tests that showed pressure-spray aqueous cleaning worked successfully to clean the aluminum and carbon steel parts used to make cooking steamers. The aqueous solution was investigated as a replacement for a petroleum distillate solvent and a naphthalene-based solvent that had been used to replace the original TCA vapor degreaser. The petroleum and naphtha-based products had been unsatisfactory to the manufacturer for two reasons: because the parts were visibly less clean than parts cleaned with TCA, and because the parts produced fumes when they were welded subsequent to cleaning. The manufacturer successfully implemented the aqueous spray-wash system.

These examples support the conclusion that aqueous systems can in many cases replace solvent-based systems without sacrificing cleaning performance. In fact, they often have been shown to improve performance. Successful implementation of aqueous-cleaning systems generally has required a careful design effort. In addition, it often has increased the complexity of the cleaning process.

The increase in complexity can be partially attributed to the need for process steps to evaporate or otherwise remove water (e.g., the installation of blowers) after cleaning. These steps typically are not required when using a highly volatile solvent. In addition, in many cases, the equipment that applies the aqueous cleaning solution to the part may be more sophisticated (e.g., ultrasonic or high-pressure spray systems), and several stages may be needed to accomplish the required cleaning.

Key Factors in Successful Aqueous Cleaning

Published material describing successful tests or operations using aqueous cleaning systems identify a variety of factors that are important for aqueous systems to operate effectively. These factors, when examined as a group, show that successful aqueous cleaning systems for manufacturing are carefully designed, multistaged processes that exceed their solvent counterparts in complexity.

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Correct Cleaning Solution Composition

For the purposes of this review, cleaning solution composition was assumed to include all the constituents that make up the final cleaning solution used, such as acid or alkaline chemistries, surfactants (detergents), water conditioners, corrosion inhibitors, and foam stabilizers.

The correct choice of cleaner solution was essential in the cases reviewed, and correct composition of the solution was very case-specific. For example, strong alkaline solutions are avoided when the part is made of aluminum because undesired chemical reactions take place when the parts come in contact with each other. Some research has examined the effect that solution composition has on cleaning. In one laboratory experiment, it was found that cleaning efficiency could be maximized at the highest chemistry concentrations tested (the concentrations tested were 0.005, 0.05, and 0.5 percent by volume). The study also found that cleaning efficiency increased when the solution was either acidic or alkaline, as opposed to neutral. A small improvement was also observed when deionized water, rather than tap water, was used as the base liquid for the cleaning solution. A separate but similarly designed experiment found that surfactant type and concentration had a significant effect on cleaning efficiency. The surfactant type identified as most efficient had the highest hydrophilic-lipophilic balance, the longest chain length, and the highest ethoxylation level of those tested.

In a majority of the research and case studies reviewed, a tap-water or deionized-water wash was not adequate to meet the cleaning needs of the process. Typically, tap water was used in a multi-staged cleaning operation as a pre- and/or post-clean stage, with the central cleaning step containing the surfactants and other additives mentioned above.

Aqueous cleaner composition has changed (for the most part positively) over the last decade. One article discusses a number of the changes that have happened in aqueous cleaning solutions, including the shift to using liquid cleaners, rather than powders, as the basis for a cleaning solution. The author notes that this change has occurred because of the "reduced safety hazards associated with" the use of liquid cleaners. She also discusses a trend toward the use of deionized water instead of tap water in order to minimize salt buildup on the surface of parts. Water salts can cause spotting or accelerate corrosion. Finally, the author notes that aqueous cleaners are becoming even more environmentally benign now that constituents such as phosphates are being eliminated, and biodegradable surfactants are becoming available.

Obtaining Adequate Surface Impingement (Mechanical Force)

Solvent-based cleaning applications primarily rely on the chemical properties of the solvent, as opposed to mechanical action. By contrast, the available literature indicates that aqueous cleaning installations depend heavily on the mechanical properties of the system, which one article refers to as "impingement." The author defines impingement as "the surface impact caused by directing a solution, under pressure, at the part to be cleaned." The mechanical action is actually used to force the contaminants off the part in conjunction with any solvating power of the cleaning solution. Research reports and industry case studies have found adequate impingement to be a key factor in successful aqueous cleaning. This appears to be especially true for cleaning parts with difficult-access surfaces or otherwise complex geometries.

One case study discusses an automotive radiator manufacturer that made a conversion from a TCA vapor degreaser to an open-air spray,
aqueous cleaning system. The system was required to remove residual oil and aluminum fines. The complex geometry of the radiators being cleaned meant that the system had to provide aggressive impingement to ensure that all the tubes and fins were adequately cleaned. The radiators were processed on a special conveyorized belt that held them at an angle to promote solution flow-through and drainage. The process was actually found to improve parts cleanliness when compared to the old system.

Impingement can be obtained through methods such as open-air sprays, submerged pressure sprays, bath or part agitation, and ultrasonics.

Spray-based aqueous cleaning has been used in a number of the tests and case studies found in the literature. Spray-type systems appear to be the most popular selection for manufacturing operations. Sprayers come in a variety of configurations and at both low- and high-pressure, depending on the system requirements. Conveyorized, automated sprayer systems are more typical for large volumes of small parts. Chamber-type, batch power-washers are typical for larger parts. To obtain increased impingement on the part's surface, the cleaner is forced through the spray nozzle at a higher pressure.

Several case studies involve ultrasonic aqueous cleaning systems. Ultrasonic cleaning systems use high-frequency sound waves to force the formation and collapse of low-pressure bubbles. The bubble formation is called "cavitation." The bubbles provide additional mechanical cleaning action and increase the ability of cleaning agents to reach all surfaces of a workpiece.

A typical ultrasonic system comprises four stages: an ultrasonic cleaning tank containing a water-based detergent; two rinse tanks; and a drying stage. Usually, a tap-water rinse removes any residual contamination and drag-out from the first tank. The second rinse tank, containing deionized water, is designed to provide a high-quality, spot-free finish. Next, the product is dried, to prevent any corrosion that might occur. Ultrasonic cleaning often is not economically viable for very large parts because of the amount of electrical power required to run the transducers that generate sound waves in an ultrasonic system. One article provides a report on the laboratory and pilot testing that went into the installation of a full-scale ultrasonic cleaning facility at Corpus Christi Army Depot.

Other articles discuss aqueous cleaning systems that use agitation from sources other than ultrasonics. Agitation can be accomplished by a number of means, including tumbling and mixing with an impeller. Moving the part or mixing the cleaner both result in added impingement and, therefore, improve cleaning effectiveness.

**Temperature**

The literature on aqueous cleaning repeatedly cites temperature as having a significant effect on the effectiveness of cleaning. Generally, increasing the temperature above ambient levels increases the cleaning efficiency, as long as the temperature is not so hot that the part being cleaned could be damaged or the properties of the cleaning solution altered in a negative fashion. Temperature, along with surface impingement, is cited as the most common way to improve the aqueous cleaning process without changing the makeup of the cleaning solution.

One article reports that Ford Motor Company pilot tested aqueous cleaning of aluminum heat exchangers and demonstrated that the effectiveness of the cleaners is influenced by temperature, concentration, and time of contact. In laboratory experiments conducted at the Toxics Use Reduction Institute's Surface Cleaning Laboratory to assist an adhesive products manufacturer to implement aqueous cleaning, it was found that the...
temperature had to be increased to 141°F to obtain the desired cleanliness level in an agitated soak bath.\textsuperscript{20}

In a controlled experiment that examined the effect of pH variations, temperature, chemistry concentration, and water quality on aqueous-based ultrasonic cleaning efficiency, it was found that temperature was by far the largest contributor to changes in efficiency; temperature contributed to "over 70 percent of the variation in the experiment."\textsuperscript{21} Interestingly, the effect was found to be non-linear, with 77°F and 194°F having a higher efficiency than 122°F.

Related experiments found that maintaining the cleaning solution temperature just above the cloud point resulted in the highest cleaning efficiency.\textsuperscript{22} (The cloud point for a particular surfactant is the temperature above which the surfactant becomes insoluble in the solution.) This is interesting because conventional wisdom says that optimum efficiency is achieved at a temperature just below the solution's cloud point. The reason for this discrepancy has not been explained to date.

**Adequate Rinsing and Drying**

Rinsing after the cleaning stage is almost a standard in aqueous cleaning processes that use cleaning solutions other than tap water in a manufacturing environment. Rinse baths or sprays prevent chemical residues left by the cleaning step from contaminating downstream processes. Some aqueous processes use multistaged, countercurrent rinsing similar to that utilized in other primary manufacturing processes, such as metal plating and anodizing.

Most full-scale systems discussed in the literature also include a drying stage. Two articles specifically discuss the importance of the drying stage in aqueous cleaning systems.\textsuperscript{23} In traditional solvent-based cleaning applications, volatile cleaners such as Freon evaporate very rapidly after cleaning. Water, with its higher boiling point, can take hours to evaporate completely at ambient temperature and pressure.

Inadequate removal of water can lead to a number of problems, including corrosion or spotting of metal parts, contamination of downstream process baths, or incomplete processing of a part in downstream manufacturing steps. Aqueous cleaning solutions and/or water rinses need to be removed, but manufacturing processes cannot allow parts to sit for hours while they dry at ambient conditions. This has led to the use of a number of different drying processes, including ovens, air blowers (often used in conjunction with air knives), and centrifuges.

**Limitations and Disadvantages of Aqueous Cleaning**

The available literature identifies several limitations and disadvantages of aqueous cleaning:

- Aqueous cleaning generates a wastewater stream that requires treatment and discharge. Efforts to extend the life of aqueous cleaning solutions are ongoing and will continue to reduce the severity of this limitation.
- Aqueous cleaning solutions are much more limited in their ability to remove contaminants by chemical action alone than their solvent counterparts. This necessitates the use of mechanical action and increased temperatures. In cases where the contaminants to be removed are especially thick or insoluble, large amounts of mechanical action can be required. For delicate parts contaminated with thick grease or other similar compounds, the usefulness of aqueous cleaning systems can be significantly limited.
- Spotting or corrosion of parts can be a problem with aqueous cleaning if adequate rinsing and drying are not included as part of the system.
These additional processes can be a disadvantage when compared with highly volatile cleaners.

- While aqueous cleaning systems have been shown to equal or even exceed the performance of solvent systems, the initial effort required to correctly design, test, and install an aqueous cleaning system is much greater due to the increased complexity of the aqueous cleaning process and the increased reliance on cleaning equipment, as opposed to the cleaning solution itself. This limitation can be very significant for manufacturers that are short on time or capital, and it can lead to a preference for "drop-in" replacements. Such replacements require little time and effort, but they may offer fewer opportunities for operational savings. Manufacturers may opt for petroleum distillate or semi-aqueous cleaners in these cases.

The Economics of Aqueous Cleaning

Even if a company finds it technically feasible to change to an aqueous cleaning system, the change will not be adopted without a strong understanding of costs and benefits. Unfortunately, it is impossible to generalize about the overall economics of converting to aqueous cleaning because the values and methods that go into making such an analysis are very company-specific. Factors such as choice of discount rate, tax rate, depreciation method, and vendor selection can all affect the results of an economic assessment.

Nonetheless, it is possible to identify which factors save money and which ones generate new costs. In addition, a review of the literature reveals a number of specific cases where the economics associated with aqueous cleaning technology were compared with solvent cleaning. In many cases, aqueous cleaning faired quite favorably.

Some reports also examined how using traditional cost estimating versus total cost assessment or another more comprehensive approach affected the results of the economic analysis. The more comprehensive estimation methods try to take into account a wider range of costs than those traditionally used to make an assessment, and sometimes even include intangibles such as future liability. Generally, the investment in aqueous cleaning appears more economically beneficial as the cost assessment methodology becomes more comprehensive. This indicates that converting to aqueous cleaning may be more beneficial than many companies realize. And the benefits will become even greater if the cost of purchasing solvents and disposing of their associated wastes continues to increase.

Several of the studies that evaluated economics were especially extensive and made use of financial data from manufacturers that had recently converted from solvent to aqueous cleaning. One author used the total cost assessment method to evaluate the economics of conversion for eight projects and found that operational costs were reduced by 75 percent in three cases and by more than 95 percent in five cases. All the cases resulted in a positive net present value. The author identified reduced chemical costs as the single largest cost savings. (The high cost of purchasing chlorinated solvents and chlorofluorocarbons was largely attributed to the taxes assessed on them.) The author also found that the labor required for maintenance generally increased with an aqueous system. However, this contradicts the findings of some industry case studies in which it was reported that less labor time was spent maintaining an aqueous cleaning system than a vapor degreaser.

One article analyzed the economics of converting to an aqueous cleaning system from a TCA vapor degreaser within an automotive radiator manufacturing line. Using a "hybrid" cost analysis similar to total cost assessment, the payback was found to be 2.4 years. In this analysis, labor costs...
for daily maintenance were $87,500 annually for the vapor degreaser, versus $5,400 for the aqueous system. The payback period increased to 11.6 years when the same process change was evaluated using a "traditional" cost analysis approach that ignored many of the less obvious costs related to both the old and new processes. This example highlights the large difference that can be seen when using different cost accounting methods and reinforces the concept that aqueous cleaner investments will often appear more favorable as the economic analysis becomes more detailed.

One economic evaluation compared automated aqueous rotary washing of steel caplets to perchloroethylene (PCE) vapor degreasing. This analysis showed a payback of seven years, much too long to be considered a favorable investment for most manufacturers. However, the analysis assumed an annual chemical cost of $1,795 for vapor degreasing versus $2,711 for aqueous cleaning. The vapor degreasing chemical cost figure may be based on an outdated price for PCE, which probably would now be much more expensive.

Because costs can vary greatly both over time and among geographical areas, the transferability of the economic analyses reviewed is very limited. In addition, as noted above, differences in methodology and in the choice of key cost parameters can also limit the applicability of economic analyses. However, the economic analyses are of value since they appear to verify that there are a number of cases where aqueous cleaning has been economically viable. In addition, the analyses can be useful as examples.

Gaps in Existing Aqueous Cleaning Research

Efforts to better understand and document the successes of aqueous cleaning are ongoing. Several areas that merit future study are:

- **Extending the life of aqueous cleaning solutions using closed-loop approaches.** The use of oil skimmers or similar equipment to remove large quantities of oil from aqueous cleaners is widespread and well known. But more sophisticated approaches, such as membrane filtration, still are not fully understood by many manufacturers. To date, the majority of work on extending cleaner life has been done within private companies and has not been made publicly available.

  One article reviewed the concepts and techniques for closed-loop aqueous cleaning and presented three short industry case studies where filtration was used to extend the life of aqueous cleaners. In one of the examples, a metal parts manufacturer reduced daily wastewater discharges from 2,000 to 75 gallons by installing a cleaner recycling system that uses hollow fiber ultrafiltration.

  Additional applied research and documentation of industry experiences are necessary to provide an available knowledge base to help manufacturers reduce the wastewater streams they generate as a result of aqueous cleaning. Extending the life of the cleaning solution will reduce the cost of both purchasing cleaners and treating wastewater.

- **Obtaining a better understanding of temperature’s effect on the aqueous cleaning process.** The significance of temperature in aqueous cleaning was discussed earlier, but several important questions remain unanswered. Why did some experimentation show that operation at temperatures above the cloud point resulted in higher cleaning efficiencies? Is this finding, which contradicts the conventional wisdom, true for cleaning solutions other than those already tested? Gaining a better understanding of the effects of temperature will allow manufacturers to operate their cleaning processes more efficiently.
Additional case studies of manufacturers’ efforts to implement and improve aqueous cleaning systems. Continued documentation of industry’s experiences in this area is essential to promote the transfer of information among companies as continued improvements are made by individual manufacturers in their aqueous-cleaning processes. Ultimately, what does and does not work in the manufacturing environment will be defined by manufacturers themselves. And continued transfer of this knowledge will reduce the number of companies that waste time when trying to implement or improve their own aqueous-cleaning process.

Summary
The following summarizes the major findings of this review:

- Aqueous cleaning has been found to be a technically viable cleaning alternative for manufacturers in a number of cases. Many laboratory experiments and industry case studies even document improved cleaning with aqueous systems. Changing to aqueous cleaning from a solvent-based system also greatly reduces or even eliminates two waste streams from cleaning: solid hazardous waste and air emissions. Unfortunately, aqueous cleaning creates a new waste stream in the form of wastewater, and this must be properly treated or disposed.

- The results of economic analyses of changing to aqueous cleaning from solvent-based vapor degreasing have varied significantly, with payback periods as low as one year and as high as 12 years. One of the largest contributors to this variation was the analytic method used to calculate payback. Typically, more detailed analyses that include a greater range of costs yield the most favorable results. This indicates that many manufacturers may be underestimating the economic benefit of converting to aqueous cleaning. Aqueous cleaning has also become more economically favorable as the taxes and other charges associated with ozone-depleting and chlorinated solvents continue to rise.

- The most important factors in successful aqueous cleaning have been found to be proper choice of cleaner solution, obtaining adequate mechanical force on the part to be cleaned, and increasing the temperature to improve cleaning efficiency.

  Cleaning solutions must be chemically compatible with the part being cleaned, they must provide appropriate surfactants to enhance removal of the specific contaminants on the parts, and they must contain any needed additives to prevent problems such as excessive solution foaming or part corrosion.

  Mechanical force (which can be obtained with equipment such as mixers, pressure sprayers, and ultrasonic transducers) is critical in aqueous cleaning since chemical action is not as strong as with traditional cleaning solvents. Increased temperature was used in the majority of industrial applications reported in case studies, and it was found to improve the removal of contaminants. However, to avoid damaging parts or significantly exceeding the cloud point temperature of the surfactants used in many aqueous cleaning applications, care must be taken not to raise temperatures too much.

- Aqueous cleaning systems in the manufacturing environment are typically multi-staged processes and have historically required careful design and testing to operate effectively. The need for design and testing has been a barrier to implementing these systems because many manufacturers are not able to allocate the...
necessary time. The requirements related to design and testing have decreased over the last decade and should continue to lessen as aqueous cleaning systems become more standardized and the collective level of knowledge about them within industry increases.

- Areas that merit future study include options for extending aqueous cleaning solution life and the effect of temperature. In addition, more case studies of industry experiences are needed. Continued study in these and other areas can help improve the effectiveness and economics of aqueous cleaning.

Notes

8. Surface Cleaning Laboratory Case Study #1: Market Forge (Toxics Use Reduction Institute, Lowell, Massachusetts, 1995).
P2 and the Clean Air Act Amendments of 1990