Evaluation of Alternatives to Chlorinated Solvents for Metal Cleaning

by

Karen B. Thomas
Michael Ellenbecker
Toxics Use Reduction Institute
University of Massachusetts Lowell
Lowell, Massachusetts 01854

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Project Officer

Paul Randall
Sustainable Technology Division
National Risk Management Research Laboratory
Cincinnati, Ohio 45268

NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

Notice

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Foreword

The U.S. Environmental Protection Agency 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. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risk from threats to human health and the environment. The focus of the Laboratory's research program is on methods for prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This project report details results of investigations into alternatives to chlorinated solvents used for metal degreasing. Three companies participated in this project. The results reported for one company document a situation where the conversion to an aqueous cleaning system had already been implemented. Those for a second company provide real-time information about the conversion from an intermediate solvent to an aqueous system. Finally, results for the third company contribute information about alternatives that must be applicable to a variety of substrates and configurations. Testing of the alternatives was conducted both at the companies and at the Toxics Use Reduction Institute's Surface Cleaning Laboratory located at the University of Massachusetts at Lowell. In addition to the technical evaluations, the project report provides financial analyses and environmental impact assessments on the cleaning alternatives. For the financial analyses, the Total Cost Assessment methodology was used which includes many important environmental costs not typically included in a financial analysis. A substitution analysis methodology that provides qualitative results was developed and used to evaluate the environmental, occupational and public health effects of the alternative cleaning processes.

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Acronyms and Abbreviations

1,1,1-TCA	1,1,1-Trichloroethane
BOD	Biochemical Oxygen Demand
CAAA	Clean Air Act Amendments
DOT	Department of Transportation
DI	De-ionized Water
EPA	Environmental Protection Agency
FT-IR	Fourier transform-infrared spectrometry
HAP	Hazardous Air Pollutant
HEPA	High Efficiency Particulate Air
IARC	International Agency for Research on Cancer
IDLH	Immediately Dangerous To Life or Health
LCA	Life Cycle Analysis
LFL	Lower Flammability Limit
MACT	Maximum Available Control Technology
METH	Methylene Chloride
MSDS	Material Safety Data Sheet
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NESHAP	National Emission Standard For Hazardous Air Pollutants
NOAEL	No Observed Adverse Effect Level
NRMRL	National Risk Management Research Laboratory
OSEE	Optically stimulated electron emission
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PERC	Perchloroethylene
PNEC	Predicted No-Effect Concentration
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
SARA	Superfund Amendments and Reauthorization Act
SCF	Supercritical fluid
TCA	Total Cost Assessment
TCE	Trichloroethylene
TLV	Threshold Limit Values
TRI	Toxics Release Inventory
TURA	Toxics Use Reduction Act
TURI	Toxics Use Reduction Institute
TWA	Time Weighted Average
UFL	Upper Flammability Limit
US	United States
VOC	Volatile Organic Compound

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Executive Summary

The Clean Alternatives Project consisted of technical, financial and substitution (environmental, health and safety) analyses of alternatives to chlorinated solvents used for metal degreasing. The project focused on three 33/50 chemicals: dichloromethane, 1,1,1-trichloroethane and trichloroethylene. Three Massachusetts companies participated in this project. All three were at different stages of the conversion away from chlorinated solvent cleaning. The three situations offered different lessons about the success and applicability of alternative cleaning processes.

The project was organized into five phases, with the following objectives:

Phase 1:	to identify uses and users of the 33/50 metal degreasing solvents in Massachusetts,
Phase 2:	to evaluate the technical feasibility of alternative cleaning technologies and chemistries to 33/50 solvents in metal degreasing applications,
Phase 3:	to perform a total cost assessment on the cleaning alternatives for each case,
Phase 4:	to perform an environmental impact assessment for each case, and
Phase 5:	to perform technology transfer of project results.

In phase 1, uses and users of the 33/50 metal degreasing solvents in Massachusetts were identified using data generated by companies for the Massachusetts Toxics Use Reduction Act and by data from the federal Community Right-To-Know Act. From these data, the three participating companies were chosen based on current uses and potential transferability of results.

During the phase 2 technical analysis, alternatives to the chlorinated solvents were identified, demonstrated and evaluated. The three companies that participated in this project were Parker Hannifin Corporation, Market Forge and Company A. At its Waltham, Massachusetts facility, Parker Hannifin manufactures pumps for aircraft engines under primary SIC code 3724. In 1992, the company began to investigate the replacement of their two vapor degreasers with an aqueous cleaning system. The original idea was to replace both vapor degreasers with one immersion cleaning system that could satisfy their highest cleanliness needs. After careful consideration of cleaning needs and logistics, the company decided to replace the vapor degreasers with three pressure spray washers for frequent remote cleaning following machining, one ultrasonic unit for the highest cleanliness needs and one immersion tank for cleaning following heat treatment. Parker Hannifin was chosen to document a situation where the conversion to aqueous cleaning had already been made and to evaluate the new system for its health and safety, environmental and financial performance. A technical evaluation was performed for Parker Hannifin in order to make improvements to their current aqueous cleaning process.

Located in Everett, MA, Market Forge manufactures cooking steamers. Prior to August, 1993, Market Forge used a 1,1,1-TCA vapor degreasing system to degrease carbon steel and aluminum boiler parts prior to welding. The performance of TCA was satisfactory, but its use was discontinued because of the labeling requirements of the Montreal Protocol. On the advice of their supplier, a switch was made from TCA to an aliphatic petroleum distillate solvent (CAS 64742-88-7). As soon as the switch was made, the welders of both the carbon steel and aluminum parts began to experience problems. Market Forge was chosen as a company in the difficult transition stage. A technical evaluation was performed to find a suitable cleaning process and chemistry to replace the petroleum distillate. Based on the information obtained from this project, Market Forge purchased an American Metal Wash pressure spray washer. The unit was recently installed and has been operating effectively for four months.

Company A is a job-shop electroplating company located in Massachusetts. By the nature of the job-shop business, Company A cannot always predict what types of metals it will have to clean and thus requires a flexible cleaning system, capable of cleaning many different substrates. Currently the company cleans all their parts in a vapor degreaser using TCE. Company A was chosen because their situation is one shared by many job-shop platers in the northeast, namely, a wide variety of substrates and contaminants. A technical assessment identified the following alternatives for further study: media blasting using sodium bicarbonate, plastic or carbon dioxide, ultrasonic aqueous, "closed" vapor degreasing, upgrading the existing vapor degreaser, Advanced Vapor Degreasing (AVD^{TM}) system, and supercritical carbon dioxide.

Some general conclusions were drawn from the technical evaluation phase in regard to chemical compatibility/process specification and "drop-in" replacements. For chemical compatibility/ process specification, it was concluded that rinsing of a non-silicated cleaner is not always necessary even when a painting operation follows and aqueous immersion cleaning can be a viable option for steel and aluminum substrates either prior to nitriding or following heat treat operations. With regard to "drop-in" replacements, it was concluded that a thorough technical evaluation of so-called "drop-in" replacements is necessary to avoid unforeseen costs and that job shops present an (as yet) unmet challenge to the vendors of "drop-in" replacements.

For the financial analysis in phase 3, a total cost assessment methodology was used to perform financial analyses of the alternative cleaning processes. Some general conclusions were made:

- 1) if the aqueous systems are replacing older solvent-based equipment, a savings in electricity costs may be realized, especially if hot air drying is not required;
- 2) depending on the cooling capacity of the vapor degreaser, the aqueous systems may actually use less water;
- 3) the profitability of an investment in aqueous cleaning equipment can be improved by purchasing based on cleaning needs at different stages in the production process;
- 4) the aggressive taxes on CFC's and TCA have made aqueous alternatives feasible economically; and
- 5) the Total Cost Assessment methodology (P2/Finance Software) can be used in an iterative process to determine "costs" for unknowns by requiring a certain net present value. These "costs" can then be assessed to determine if, for example, a regulatory requirement could be met for a certain "cost" rather than actually attempting to place a value on meeting the regulatory requirement.

A substitution analysis methodology was developed during phase 4 and was used to evaluate the environmental, occupational, and public health effects of the alternative cleaning processes. The substitution analysis described is qualitative in nature. It allows the comparison of alternatives using many criteria, but a final decision as to the best alternative must be made by the investigator. Described in worksheet format, this approach highlights both the areas of concern for alternative substitute processes and areas where those substitutes clearly are superior to the current process. The worksheet will aid the decision maker in making informed decisions without overlooking important issues.

Finally phase 5, the information dissemination phase of the project, resulted in technical fact sheets, conference presentations, workshops, and the final EPA report. This work is part of a larger program at the Toxics Use Reduction Institute that includes laboratory assistance to companies through TURI's Surface Cleaning Laboratory, Research Fellows projects on "closed-loop" aqueous cleaning systems and further development of the substitution analysis, and the preparation of a manual "Cleaning is Greener in Massachusetts" in conjunction with the Office of Technical Assistance for Toxics Use Reduction.

This project studied three principle evaluation steps that inform the decision-making process for chemical or process substitution: technical evaluation, economic evaluation, and environmental, health and safety evaluation. Each evaluation step is important in determining the viability of a substitute technology in comparison to the existing technology as well as other competing substitute technologies. The steps can be performed in any order and their relative importance can vary from project to project. The technical evaluation of a potential replacement process for an existing technically successful process is often the most important evaluative step. The success or failure of the technical evaluation determines whether or not the process will be evaluated further. Complete technical evaluation at the lab and pilot scale levels can lead to a smooth transition into the new process. An incomplete technical evaluation can lead to unforeseen problems with the incorporation of the new process and necessitate further evaluation following installation. An economic evaluation of a technically-proven chemical or process provides valuable information affecting the decision to implement or not. Traditional financial analysis, however, often includes only the costs directly associated with production, such as labor and capital and does not include the costs (and savings) that make pollution prevention projects profitable. The Total Cost Assessment methodology used in this project is an innovative evaluative tool that examines many other important costs associated with an investment including such things as staff time for environmental reporting, waste management costs, and permitting fees. The results of the financial assessment further inform the decision to adopt or not. However, technical and financial information combined is not the final word in decision making. Further evaluation is required to assess the environmental, health and safety issues involved with the chemicals and processes. While the technical and cost assessments are not simple, the environmental, health & safety assessment, called substitution analysis, is perhaps the most difficult because there is no generally agreed on and reliable method for evaluating the environmental and worker health and safety risk of alternatives.

In using the three evaluative steps described above, it is important to remember that each project and facility may have different priorities for making decisions about whether to implement a particular technology. This was clearly demonstrated in this project as the participating companies had different motives for seeking substitute technologies. This in turn, dictated which evaluative step was most important to them and indicates that the results of any one of the three can be the driving factor in a decision. Despite the emphasis being placed on one evaluative step on a given project, all three aspects must be evaluated so that valuable pieces of information are not ignored.

Chapter 1
Introduction

Introduction

Cleaning and degreasing of metal parts in the metal finishing and metal working industries has traditionally been accomplished by the use of chlorinated solvents in vapor degreasers or immersion systems. In this context, cleaning and degreasing is, simply, the removal of contamination from the metal surface. This function is either necessary for successful part performance in subsequent operations (e.g., plating or welding) or is desirable aesthetically. The chlorinated solvents most commonly used for metal cleaning include: 1,1,1-trichloroethane (1,1,1-TCA), trichloroethylene (TCE), perchloroethylene (PERC), dichloromethane (methylene chloride or METH) and chlorofluorocarbons. Chlorinated solvents are effective cleaners and, in the past, have been considered "safe" to workers because they are nonflammable.

Due to concern over the ozone layer, photochemical smog and worker health, increasingly strict environmental regulations have been promulgated on the use of chlorinated solvents. The result has been higher costs associated with the purchase and disposal of chlorinated solvents. Traditional chlorinated solvent cleaning is becoming a process of the past. For many companies, however, changing from a proven process to a new technology is a difficult task. Many alternatives presented as "perfect" solutions are found to be ineffective cleaners, too expensive, or present safety hazards. A careful evaluation of the options can help in selecting the most cost effective and technically feasible solution without compromising worker health and safety or environmental protection.

EPA's 33/50 Program

As a part of EPA's pollution prevention[1] strategy, the Agency initiated the 33/50 Program. This was a voluntary pollution prevention program to reduce national releases and off-site transfers of 17 toxic chemicals. The Toxics Release Inventory (TRI), established by the Emergency Planning and Community Right-to-Know Act of 1986, was used to track these reductions using 1988 data as a baseline.

The 33/50 Program had three basic goals. First, the EPA aimed to reduce national aggregate environmental releases of the 17 target chemicals from 1988 levels by 33% by the end of 1992 and by 50% by the end of 1995. Second, the EPA encouraged companies to use pollution prevention practices rather than end-of-pipe treatment to achieve these reductions. Third, the EPA hoped that this program would help foster pollution prevention practices and principles in American businesses whereby companies would routinely analyze all their operations to reduce or eliminate pollution before it was created.[2]

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[1] Pollution prevention is defined by EPA as "the use of materials, processes, or practices that reduce or eliminate the creation of pollutants or wastes."

[2] EPA, Office of Research and Development, "Opportunities for Pollution Prevention Research to Support the 33/50 Program", EPA/600/R-92/175, October 1992.

EPA's National Risk Management Research Laboratory (NRMRL, formerly Risk Reduction Engineering Laboratory) funded research in support of the 33/50 Program. The broad goal of the research was to evaluate pollution prevention options for the 17 target chemicals and to disseminate the results of the evaluations. The Clean Alternatives Project was funded by a grant from NRMRL to the Toxics Use Reduction Institute[3] (TURI) at the University of Massachusetts Lowell.

Overview of the Clean Alternatives Project

The Clean Alternatives Project consisted of technical, financial, and substitution (environmental, health and safety) analyses of alternatives to chlorinated solvents used for metal degreasing. Three of the 33/50 chemicals commonly used for surface cleaning are dichloromethane, 1,1,1-trichloroethane and trichloroethylene. These three chemicals were the focus of this project.

Three Massachusetts companies participated in this project. During the technical analysis, alternatives to the chlorinated solvents were identified, demonstrated and evaluated. For the financial analysis, a total cost assessment methodology was used to perform financial analyses of the alternative cleaning processes. A substitution analysis methodology was developed and used to evaluate the environmental, occupational, and public health effects of the alternative cleaning processes.

This report of the Clean Alternatives Project supplements four other recent reports on the subject: *Guide to Cleaner Technologies: Alternatives to Chlorinated Solvents for Cleaning and Degreasing*, *Guide to Cleaner Technologies: Cleaning and Degreasing Process Changes*, and *Federal Facility Pollution Prevention Project Analysis: A Primer for Applying Life Cycle and Total Cost Assessment Concepts*, all by the US EPA and *Demonstration of Alternative Cleaning Systems* by The Center for Clean Products and Clean Technologies at the University of Tennessee.

The Clean Alternatives Project adds the following information to the body of literature:

- alternative demonstrations to chlorinated solvents for metal degreasing
- the role of total cost assessment in the decision making process
- the inclusion of worker health and safety concerns in a substitution analysis and
- the documentation of a substitution analysis methodology.

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[3] The Toxics Use Reduction Institute is a multi-disciplinary research, education, and policy center established by the Massachusetts Toxics Use Reduction Act of 1989. The Institute sponsors and conducts research, organizes education and training programs, and provides technical support to promote reduction in the use of toxic chemicals or in the generation of toxic chemical byproducts in industry and commerce.

Chapter 2
Methods and Materials for Surface Cleaning

Cleaning is a surface preparation process that removes contaminants and prepares parts for subsequent operations. The purpose of this chapter is not to give a detailed overview of all cleaning methods available but to address the cleaning methods used and considered by companies in this project. For a more complete description of current alternative cleaning processes as well as emerging technologies, consult EPA's *Guide to Cleaner Technologies: Alternatives to Chlorinated Solvents for Cleaning and Degreasing*.

Vapor Degreasing

Degreasing is an integral part of almost all metalworking and maintenance operations. It is used to remove oils, greases, waxes, tars, and moisture, preparatory to further surface treatment such as electroplating, painting, galvanizing, anodizing, and applying conversion coatings. Surface cleaning is also carried out in plastics fabrication and in the electrical, electronics and printing industries.

A vapor degreaser is a tank with heating coils in the bottom and a condensing zone near the top. The temperature of the solvent in the tank is raised to near boiling and the hot solvent vapor fills the tank up to the condensing zone. The vapor condenses on the dirty workpiece, dissolves the contaminants and drains back into the solvent reservoir. Solvent losses occur mainly when the vapor zone is disturbed by air drafts, when the workload is lowered into or raised out of the machine, or when the parts drag out condensed solvent. The chlorinated cleaning solvents used for the vapor degreasing situations analyzed for this project were TCE, 1,1,1-TCA, METH and CFC-113 (or Freon TF). (Note: CFC-113 is not part of EPA's 33/50 Program but was included in this report because one company previously used it.)

Prior to the 1970s, the vapor degreasing market was dominated almost completely by TCE. In the mid-1960s it was discovered that TCE was photochemically reactive and that its emissions contributed to smog formation. This led to limitations on its use. In some cases, these restrictions resulted in the replacement of TCE by less photochemically reactive solvents, although other companies continued to use TCE by reducing emissions. In 1975, TCE was identified as a carcinogen to mice and concern was expressed regarding worker exposure to its vapors.

TCE was often replaced by CFC-113, 1,1,1-TCA, and METH as more environmentally acceptable and less toxic replacements in vapor degreasing. Since the physical properties of 1,1,1-TCA are similar to those of TCE, it could be used as a drop-in replacement for TCE with only minor modifications. The use of CFC-113 and METH required additional equipment or procedural modifications. Table 1 shows how the properties of these four chemicals compare.

In the mid-seventies, CFCs and 1,1,1-TCA were found to contribute to the depletion of the earth's protective stratospheric ozone layer. As a result, these two cleaning agents are being phased out under the Clean Air Act as amended in 1990 and The Montreal Protocol on Substances that Deplete the Ozone Layer (a 1992 international agreement on the phasing-out of ozone depleting chemicals). The original protocol included only the phasing out of CFCs because of their higher ozone-depleting potential. Later, 1,1,1-

TCA was included in the amendment of the protocol because of the quantities used. In January 1992, NASA testing revealed the highest level of ozone-depleting substances ever. These findings have prompted an acceleration of the phase-out schedule from the original goal of the year 2000 to a phase-out by January 1, 1996.

METH and TCE are considered hazardous air pollutants under the 1991 Clean Air Act Amendments. Within ten years, the EPA will require major users to install maximum available control technology (MACT) to limit emissions. CFC-113 is mildly acutely toxic by ingestion and inhalation. TCE, 1,1,1-TCA and METH are suspected carcinogens as shown in Table 1.

Table 1. Summary of Chlorinated Solvent Properties

Property	TCE	1,1,1-TCA	METH	CFC-113
photo-chemically reactive	yes	no	no	no
ozone depletor	no	yes	no	yes
HAP	yes	no	yes	no
vapor density (air = 1)	4.53	4.63	2.93	6.5
boiling point	86-88 C	72-88 C	39.4-40.4 C	47.6 C
carcino-genicity[4]	suspected	suspected	suspected	no

Solvents Used in Vapor Degreasing

Trichloroethylene

The main advantages of TCE, chemical formula $ClCH{=}CCl_2$, are high vapor density and excellent stability, particularly when compared to 1,1,1-TCA. TCE is aggressive on dirt and oils and does not leave a film or other residue; furthermore it is easy to recycle. TCE has a big advantage over METH in that it is a drop-in replacement for 1,1,1-TCA.

In the US, consumption of TCE for degreasing has declined over the years, from about 337 million pounds in 1974 to approximately 92 million pounds in 1993[5]. Over 90% of the total consumption of TCE is for vapor degreasing. The consumption of TCE in 1995 is projected to be higher than in recent years, as it may be used to replace 1,1,1-TCA. However, toxicity concerns may curb its widespread use as a substitute for 111-TCA. According to the 1991 Massachusetts TURA data, SIC codes 33, 34, 36, and 38 account for over 96% of all TCE used for metal cleaning. These industries include primary and fabricated metal industries, electronic and other electric equipment manufacturing, and instruments and related products.

TCE is a suspected carcinogen. Human systemic effects and mutation data have been reported. A form of addiction has been observed in exposed workers. Prolonged inhalation of moderate concentra

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[4] Lewis, Richard J., Sr., "Sax's Dangerous Properties of Industrial Materials", 1992.

[5] SRI International, "Chemical Economics Handbook", 1995.

tions causes headache and drowsiness. There is damage to the liver and other organs from chronic exposure.[6]

1,1,1-Trichloroethane

1,1,1-Trichloroethane or 1,1,1-TCA, chemical formula CCl_3CH_3, is a good solvent for oils, greases, waxes, tars, fats, gums, and resins. It is the preferred solvent for cleaning electronic components, electrical parts and printed circuit boards where other solvents might damage insulation or cause heat warpage. Cleaning with 1,1,1-TCA in vapor degreasers does not require as high a temperature as cleaning with TCE.

The main technical shortcomings in the use of 1,1,1-TCA is its chemical stability. Relatively large amounts of stabilizers, as compared to other vapor degreasing solvents, must be added to avoid degradation of the solvent. If the stabilizer levels are below a certain minimum, 1,1,1-TCA may undergo hydrolysis in the presence of water and a potentially dangerous acid-forming reaction with aluminum.

The estimated U.S. consumption of 1,1,1-TCA for metal cleaning was 175 million pounds in 1993. Of this amount, 70% was for vapor degreasing and 30% for cold cleaning applications.[7]

1,1,1-TCA is classified as a suspected carcinogen and an experimental teratogen. Human systemic effects have been reported. The chemical is narcotic at high concentrations.[8]

Methylene Chloride

Methylene chloride or METH, chemical formula CH_2Cl_2, is effective on a wide variety of substrates and is relatively inexpensive. It has the ability to penetrate rapidly into a coating, causing the coating to swell and lift off the substrate. This makes the coating very easy to remove. METH is also an aggressive solvent to many fats, oils, greases, polymers, waxes, tars, lacquers, and natural and synthetic rubbers. METH has the lowest boiling point of the solvents used in vapor degreasing. It can be used when the temperatures required for higher-boiling solvents might damage the part.

As a vapor degreasing solvent, METH has a relatively low vapor density (three times heavier than air, while other solvents are 4.5-6.5 times heavier) and high evaporation rates. Therefore degreasers using methylene chloride require more cooling capability than those using other solvents. If adequate cooling is not supplied, the low vapor density and high evaporation rate of METH result in greater solvent loss and higher consumption than the competing solvents.

In several animal toxicological studies, inhalation of METH was found to cause liver cancer. As a result, the EPA has classified METH as a "probable" cause of cancer in humans. It is known that the chemical is irritating to skin, eyes and the respiratory tract. It is a central nervous system depressant and causes narcosis at high levels.

METH has an estimated 5-10% of the U.S. market for metal cleaning. In 1993, the U.S. consumption of methylene chloride for metal cleaning was 15 million pounds out of a total consumption of 237 million

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[6] Lewis, Richard J., Sr., "Sax's Dangerous Properties of Industrial Materials", 1992.

[7] SRI International, "Chemical Economics Handbook", 1995.

[8] Lewis, Richard J., Sr., "Sax's Dangerous Properties of Industrial Materials", 1992.

pounds.[9] According to the 1991 Massachusetts TURA data, SIC code 36, electronics and electrical equipment manufacturing, accounts for over 50% of all METH used for metal cleaning.

CFC-113

CFC-113, chemical formula $C_2F_3Cl_3$, is also known as Freon TF and trichlorotrifluoroethan. CFC-113 is not part of the EPA's 33/50 Program but is used as a vapor degreasing solvent. Before it was found to be ozone depleting, CFC-113 was widely used in cleaning applications because it was available and inexpensive. CFC-113 easily removes many different contaminants from many different substrates. In addition, it is less toxic to humans than 1,1,1-TCA, METH or TCE. Prices for CFCs and the cost of waste management have increased dramatically since the Montreal Protocol.

Alternative Cleaning Methods

Because of the worker and environmental health concerns with solvent-based metal cleaning methods, a number of alternative cleaning methods are being developed. These include aqueous cleaning, media blasting, carbon dioxide blasting, and supercritical carbon dioxide.

Aqueous Cleaning

Water-based and semi-aqueous cleaners will, most likely, be favored over the many possible replacements for chlorinated solvents. In some applications, hot water alone may be sufficient to clean parts. When a detergent is required, synthetic detergents and surfactants use water as the primary solvent. Synthetic detergents and surfactants are combined with special additives such as builders, pH buffers, inhibitors, saponifiers, emulsifiers, deflocculants, complexing agents, and anti-foaming agents. These agents provide multiple degrees of freedom in formulating, blending, and concentrating, and also provide useful synergistic effects.

Semi-aqueous cleaners are made of natural or synthetic organic solvents, surfactants, corrosion inhibitors, and other additives. Water is used in some part of the cleaning process (washing and/or rinsing), hence the name, semi-aqueous. Some common semi-aqueous cleaners are the water-immiscible types such as terpenes, high-molecular-weight esters, petroleum hydrocarbons, and glycol ethers and the water-miscible types such as low-molecular-weight alcohols, ketones, esters, and organic amines. These cleaners are non-ozone-depleting but they may contain volatile organic compounds. Therefore, their use raises more concerns about aquatic toxicity and human exposure than does the use of aqueous cleaners.[10]

Large-scale metal cleaning operations and captive shops may find it relatively easy to make the switch to these cleaners since, generally, water-based or semi-aqueous cleaners can be formulated to remove specific types of contaminants from given metal surfaces. For job shop operations or those with continually changing cleaning needs, the switch is much more difficult. These users may continue using chlorinated solvents because of their greater versatility. Also, some companies may not have adequate or existing wastewater discharge permits, which could be required for the disposal of aqueous cleaning solutions.

The aqueous based cleaning systems addressed in this report can be divided into three cleaning methods: immersion, spray, and ultrasonic. The *immersion* method cleans the parts by immersing them in a solution

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[9] SRI International, "Chemical Economics Handbook", 1995.

[10] USEPA, Office of Research and Development, "Guide to Cleaner Technologies: Alternatives to Chlorinated Solvents for Cleaning and Degreasing," February 1994.

and using some form of agitation to add the energy needed to displace and float away contaminants. Soil is removed from the metal surface by convection currents created by heating coils or by some mechanical action.

The *spray washing* method cleans parts with a solution sprayed at pressures from as low as 2 pounds per square inch (psi) to more than 400 psi. The higher spray pressure delivers more mechanical action to help remove soils from metal surfaces. Spray cleaners are prepared with low foaming detergents that are not as chemically effective as those used in immersion cleaners, but are still effective because of the increased mechanical action. Although spray cleaning is effective on most parts, certain part configurations, such as the interior of an automobile tail pipe, have soiled areas that are inaccessible to the spray cleaning solution. In these instances, immersion cleaners are more effective.

The *ultrasonics* method combines water, a detergent, and high frequency sound waves to provide the agitation. Ultrasonic cleaning uses sound waves in the 20 to 50 KHz range to produce cavitation bubbles in water. As the cavitation bubbles collapse and implode, it has been calculated that temperatures in excess of 10,000F and pressures in excess of 10,000 psi are generated.[11] The mechanical effect of the ultrasonic energy helps to dissolve and displace particles from the surface of the work piece.

Media Blasting

The media blasting process, in general, combines a certain abrasive media, a pressurized delivery system and one of a variety of cleaning chambers. Typically called impact or abrasive cleaning, this method of cleaning leaves no residue. Abrasive cleaning is not appropriate for grossly contaminated parts because the contaminants cause the media to stick together. However, media cleaning is appropriate for "normal" machining oils and contaminants. Glass beads and sand have been used as media in this process for years with the more recent introductions of plastic and sodium bicarbonate. These new media allow the technology to be used on a wider variety of substrates. Glass beads are compatible with 90% of substrates. Glass beads range in size from 840 microns to 88 microns. For stainless steel and other steels, glass beads in the 250-145 micron range are most effective. Glass beads may leave a matted finish on some softer metals unless the air pressure is correctly adjusted. Plastic media may be more appropriate for aluminum, but do not work as well on steel and stainless steel. Sodium bicarbonate is a relatively new media and has shown promise in many applications.

Carbon Dioxide Blasting

Carbon dioxide (CO_2) technology begins with the conversion of liquid CO_2 into solid CO_2. There are at least three carbon dioxide technologies in use: CO_2 snow, CO_2 pellet, and fragmented CO_2. In all forms, the cleaning action of the CO_2 is the same. As the material impacts the surface to be cleaned, it sublimes, returning to the gaseous state. The cleaning occurs as the sublimation causes turbulence on the surface and lifts the contaminants away. The contaminants and the CO_2 gas are passed through a high efficiency particulate air filter (HEPA) where the particulates are collected and the gas is released.

Carbon dioxide snow is formed when liquid CO_2, which is allowed to expand to atmospheric pressure through a nozzle, forms soft flakes. CO_2 snow technology can remove particles and debris without damage to the surface. CO_2 snow cleaning is effective for dust and dirt but not necessarily grease unless the pressure is between 400-800 psi. *CO_2 pellet* technology compresses CO_2 snow into hard pellets that are blasted toward a surface with a high pressure carrier gas, typically compressed air. The pellet process can

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[11] Fuchs, John F., "Ultrasonic Cleaning Fundamental Theory and Application", Blaskstone Ultrasonics, Jamestown, NY.

remove paint and rust but there is a greater risk of harming the surface than with CO_2 snow. Pellets are effective at removing oil and grease at relatively low pressures. These CO_2 techniques have been used for precision cleaning applications in the aerospace and electronics industries for about 12 years.[12] *Fragmented CO_2* is a relatively new technology where the CO_2 solid particles are randomly shaped, unlike pelletized CO_2, which has uniform shape. Fragmented CO_2 requires less equipment resulting in lower capital cost. It is also effective at removing oils and greases at relatively low pressures.

Supercritical Carbon Dioxide

Supercritical fluids (SCFs), which result from subjecting substances to temperatures and pressures above their critical points, possess properties intermediate between liquids and gases. Precision surface cleaning with SCFs takes advantage of these unique properties, such as liquid-like density and solvency combined with gas-like viscosity and diffusivity. SCFs can rapidly penetrate substrates and small interstitial spaces, dissolve the contaminants, and then be easily and completely removed since the SCF lacks surface tension.

SCF cleaning is typically a batch process performed using a system consisting of two primary pressure vessels (a cleaning chamber and a separator), high pressure pumps, pressure regulators, pressure reduction valves, and interconnecting piping. Initially, a liquid (in this case, CO_2) is pumped into the cleaning vessel, which is then pressurized to the operating conditions. At this point, the cleaning chamber, which contains parts totally immersed in supercritical CO_2, is isolated from the rest of the system. The cleaning process itself may involve simple immersion of the parts in the SCF for a given time period, or may incorporate SCF agitation and recirculation, and/or displacement of the contaminated SCF with fresh SCF. At the end of a cleaning cycle, additional fresh CO_2 is pumped into the cleaning chamber to displace the contaminated CO_2. The contaminated CO_2 is sent through a pressure reduction valve and vaporizes in the separator. CO_2 vapor exits from the top of the separator, while the non-volatile contaminants are collected in the bottom. Recovery and reuse of the CO_2 may be economically justified depending on the process scale.

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[12] Pollution Prevention Advisor, "<u>CO_2 Does Snow Job on Contaminated Surfaces</u>", Volume 5, Number 5, May 1995.

Chapter 3
Technical Evaluations

Introduction

The technical evaluation of a potential replacement process for an existing technically successful process is perhaps the most important evaluative tool. The success or failure of the technical evaluation determines whether or not the process will be evaluated further. Complete technical evaluations at the lab and pilot scale levels can lead to a smooth transition into the new process. An incomplete technical evaluation can lead to unforeseen problems with the incorporation of the new process and necessitate further evaluation following installation. Using data generated by companies for the Massachusetts Toxics Use Reduction Act and by data from the Federal Community Right-To-Know Act, three companies were chosen to participate based on current uses and potential transferability of results. All three were at different stages of the conversion away from chlorinated solvent cleaning. The three situations offered different lessons about the success and applicability of alternative cleaning processes.

Parker Hannifin was chosen to document a situation where the conversion to aqueous cleaning had already been made and to evaluate the new system for its health and safety, environmental and financial performance. A technical evaluation was performed for Parker Hannifin in order to make improvements to their current aqueous cleaning process.

Market Forge was chosen as a company in the difficult transition stage. The elimination of their chlorinated degreasing solvent, trichloroethane, was a management mandate at their facility. They had tried some vendor recommended "drop in" replacement solvents that had failed for their application. A technical evaluation was performed to find a suitable cleaning process and chemistry.

Company A was chosen because their situation is one shared by many job shop platers in the Northeast, namely, a wide variety of substrates and contaminants. A technical evaluation was performed to identify alternatives for further study.

Quality Assurance Plan

A document titled *Quality Assurance Project Plan for Evaluation of Alternative Surface Cleaning Methods* was prepared for this project. As required by the National Risk Management Research Laboratory, this document outlines the quality assurance (QA) objectives, defines sampling, analytical, and calibration procedures, plans for checks on quality control and details corrective action should it be necessary.

The QA objectives associated with performing the technical feasibility assessments of this research project were three-fold:

- to establish the level of cleanliness for each case using current cleaning methods as a baseline reference,

- to demonstrate the technical feasibility of alternate cleaning chemistries on actual company parts or test materials, or, in the case of Parker Hannifin, to determine the cause of cleaning problems in the current aqueous process,

- to identify technically feasible alternatives to the chlorinated hydrocarbon solvents currently used in metal degreasing operations at Market Forge and Company A.

Establish Baseline "Clean"

- *Substrate Identification*: metal test coupons or company supplied parts
- *Standardized Cleaning Procedure*: must be performed prior to contamination step in order to establish a baseline clean
  example: 15 minute ultrasonics wash @ 140°F, 10 % solution Daraclean 232 cleaner, 5 minute immersion rinse @ 140°F in tap water, 5 minute immersion rinse @ 140°F in DI water, 10 minute dry @ ambient temperature Laminaire Flow Station, 30 minute dry @ 158°F oven, cool to ambient conditions
- *Gravimetric Analysis of "Cleaned" Substrates*: determine weight of cleaned coupons before contamination
- *Supplemental Analytical Characterization*: establish baseline readings for the "clean" substrate (FT-IR/Grazing Angle Reflectance, OSEE).

Contamination Protocol

- *Designate Contaminant*: cutting oils, lubricants, greases, coolants, particulates, chips and fines, oxidation products, fingerprints, waxes, aqueous-based, synthetic, petroleum-based, natural products
- *Contaminant Application*: loading is dependent on the method used. Range: 0 mg/sq cm to customer specified level
- *Application Method*: spray on soil/solvent solution; roll/wipe-on using brush; dip/soak in soil/solvent solution; other: "as received" from customer
- *Drying Process*: dry/age in air for 24 hrs. or dry/process at elevated temperature
- *Gravimetric Analysis of Contaminated Coupons*: determine contaminated loading (mg/sq cm)
- *Supplemental Characterization*: OSEE, FT-IR to establish readings for the "dirty" substrates

Cleaning, Rinsing, and Drying Protocol

- *Select Substrate Material for Contamination*: ferrous, non-ferrous, plated alloys
- *Select Cleaning Chemistry* from technical literature, product bulletin, MSDS, manufacturer, distributor
- *Select Appropriate Number of Test Materials* for statistical validation and design of experimental trials based on the number of experimental variables chosen
- *Select Process Cleaning Equipment*: ultrasonics, soak immersion, agitated immersion, pressure/spray wash
- *Selected Variables to Investigate*: wash time (1 to 15 minutes), wash temperature (70-190°F), concentration of cleaning solution (start with manufacturer's recommendations)

Figure 1. Laboratory Evaluation Protocol

Figure 1 outlines the Laboratory Evaluation Protocol developed by TURI's Surface Cleaning Laboratory for evaluation of alternative cleaning chemistries. First, a baseline "clean" must be established on company supplied parts if possible or on laboratory metal test pieces called coupons. Next, the contaminants are identified and the part or coupon is contaminated. Then a cleaning, rinsing and drying protocol was followed for each situation tested. All cleaner performance evaluations were performed in strict adherence to established protocol (preclean, clean, rinse, dry schedules) in order that the results would be comparable between trial runs.

Aqueous cleaner performance was evaluated using the critical measurement of contaminant loading. For this evaluation, three weight measurements are necessary: after baseline clean, following contamination, and following cleaning. The differences between these weights represent the amount of contamination on the part and the amount of contamination remaining after cleaning. From these results, the average removal efficiency is determined. In addition, the noncritical measurement of microscopic analysis at elevated magnification was used to assess particulates on the part or coupon prior to and after contamination and following cleaning. The QAPP presented optically stimulated electron emission (OSEE) and Fourier transform-infrared spectrometry (FT-IR) as possible critical measurements for the evaluation of cleaner performance. Neither of these analytical techniques was appropriate or necessary for the situations studied for this project. In some situations, it was necessary to analyze the effectiveness of a cleaning chemistry or process using methods commonly accepted by the companies for whom the testing was being conducted. These situations are described in the text.

Information on the procedures used for QA, calibration and sampling can be found in Appendix A.

Parker Hannifin Corporation

Parker Hannifin Corporation manufactures motion control products for industrial and aerospace applications. The company is headquartered in Cleveland, OH and is part of EPA's 33/50 Program. At the Waltham, Massachusetts facility, pumps for aircraft engines are manufactured under primary SIC code 3724.

Name: Parker Hannifin, Nichols Aircraft Division
Location: Waltham, MA
Primary SIC Code: 3724
Products: pumps for aircraft engines

In 1992, the company began to investigate the replacement of their two vapor degreasers with an aqueous cleaning system. The company was using CFC-113 in one degreaser and in the process of switching from METH to 1,1,1-TCA in the other degreaser. The original idea was to replace both vapor degreasers with one immersion cleaning system that could satisfy their highest cleanliness needs. After careful consideration of cleaning needs and logistics, the company decided that it would be more effective to replace the two vapor degreasers with three different cleaning methods because of the different cleaning needs. First, three pressure spray washers were installed for frequent remote cleaning following machining. Second, one ultrasonic unit was installed for the highest cleanliness needs. Third, one immersion tank was installed for cleaning following heat treatment.

Figures 2 and 3 show schematics of the vapor and aqueous degreasing systems. For the vapor degreaser systems shown in Figure 2, mass balance calculations were performed. The difference between the amount of CFC-113 purchased and the amount of CFC-113 disposed of in the waste oil for 1992 was 20,285 pounds which was lost to the atmosphere. The losses calculated for the 1,1,1-TCA/METH vapor degreaser were less dramatic, 496 pounds and 126 pounds respectively. The calculations for water use revealed large quantities of water required for both degreasing processes, over 300,000 cubic feet each. As a result of Parker Hannifin's aggressive cleaning project, they eliminated the use of chlorinated cleaning solvents over a four year period as shown in Table 2.

Table 2. Parker's Toxics Use Reduction Act Data Pounds of Solvents Otherwise Used, 1990-1994

Chemical	1990	1991	1992	1993	1994
CFC-113	28290	29000	21000	6517	0
1,1,1-trichloroethane	0	0	600	1200	0
Methylene chloride	11848	10400	1047	0	0
Total	41138	39400	22647	7717	0

Pressure Spray Washers

The three ADF Systems Ltd. pressure spray washers, which operate at 750-800 psi, clean aluminum and 8620[13] steel parts with a 10-20 minute wash cycle followed by a hot air dry. One washer cleans aluminum parts using WR Grace's Daraclean 282 GF. Steel parts, heavily soiled with a hydraulic oil containing silicone from a lapping operation, are pre-washed in a mineral spirits bath for 10-15 minutes and then cleaned in the second spray washer also using WR Grace's Daraclean 282 GF. These aqueous cleaners are described in more detail in the Technical Evaluation Supplement section which begins on page 18. (Note: The company plans to evaluate an aqueous-based lapping compound that could eliminate the mineral spirits pre-wash.) The third washer, using Brulin 63-G at 8-10% concentration, cleans steel parts which do not have the silicone contaminant. The two different detergents used in the three spray washers were the result of a trial-and-error process that the company performed with the assistance of detergent vendors. The parts were previously cleaned in a vapor degreaser using CFC-113.

Ultrasonic System

Both 8620 steel and aluminum parts are cleaned in the Talley ultrasonic system. These parts, contaminated with a rust inhibitor oil, require the highest level of cleanliness in the process. The system consists of a 2 minute wash, two tap water rinses at 140F and 170F, one DI rinse at 115F, and a one minute drying cycle at 150F. The detergent is Brulin 815 GD at 3% concentration. Before conversion to the ultrasonic system, these parts were cleaned in the vapor degreaser using CFC-113.

Immersion Tank

In the Kleer Flo immersion tank, 8620 steel parts are cleaned on the way from a quench oil heat treat to a nitriding[14] process. The detergent in the immersion system is Oakite Inpro-Clean 2500 at an 8% concentration. The air agitated immersion tank operates at 160F and parts are immersed for 20 minutes.

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[13] 8620 is a number designation of the American Iron and Steel Institute and the Society of Automotive Engineers for carbon and alloy steels. The 86xx series defines a minimum nickel-chromium-molybdenum content and the xx20 indicates the carbon content.

[14] Nitriding is a process to introduce nitrogen into the surface layer of a solid ferrous alloy by holding it at a suitable temperature in contact with a nitrogenous material, usually ammonia or molten cyanide.

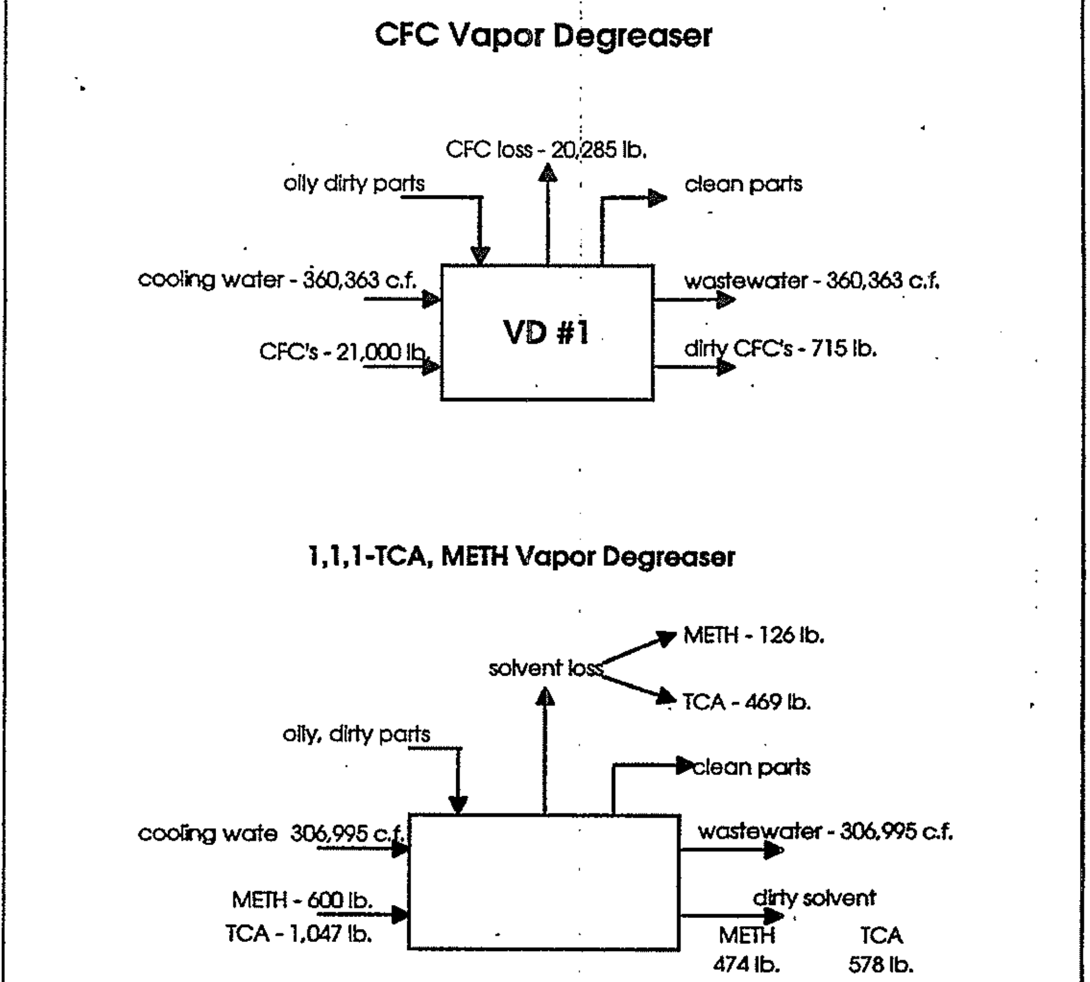

Figure 2. Schematic of Parker Hannifin Vapor Degreasing Systems

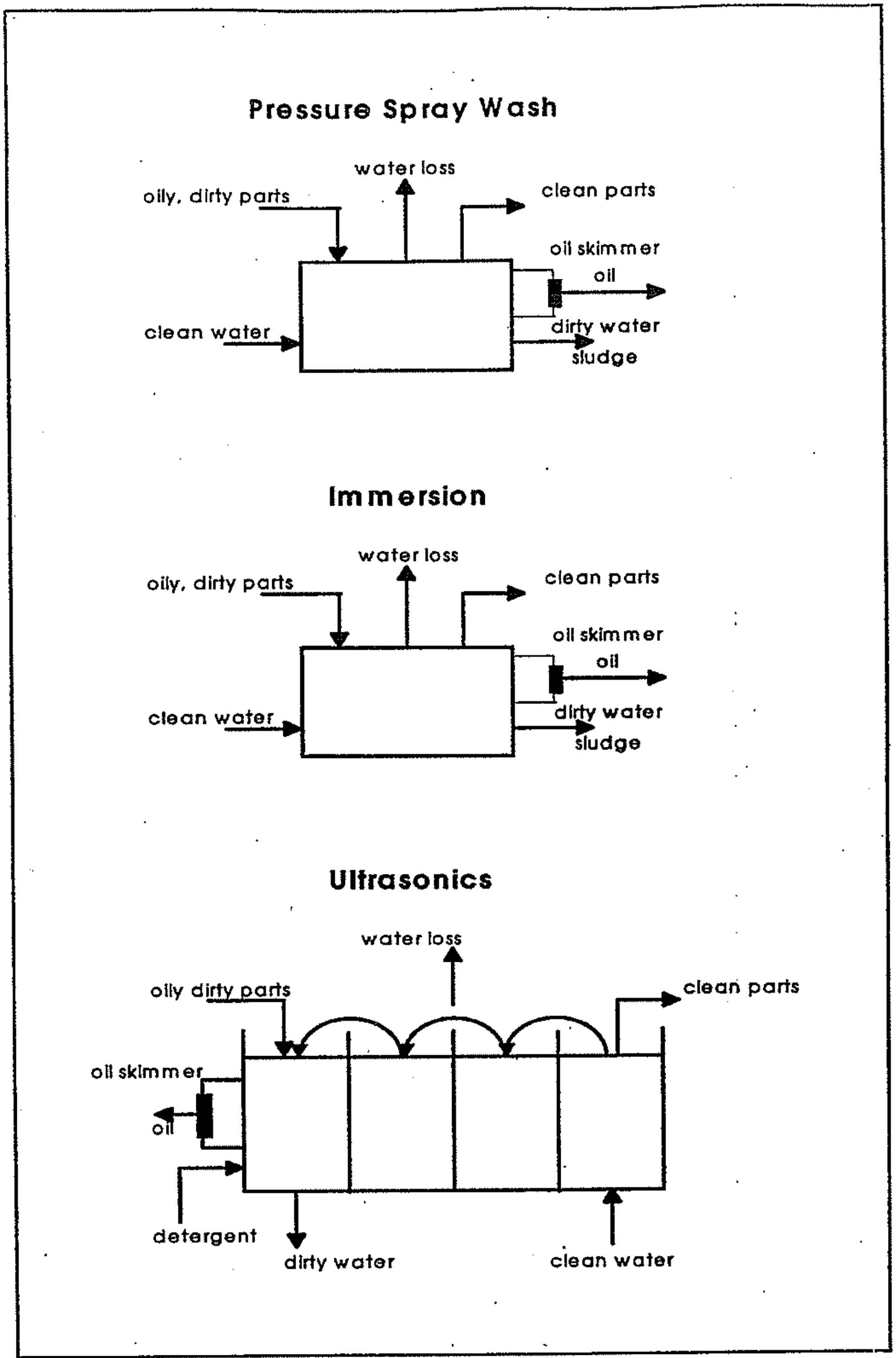

Figure 3. Schematic of Parker Hannifin Aqueous Degreasing System

Prior to conversion to this aqueous system, the parts were cleaned in a vapor degreaser with methylene chloride and for a short time with 1,1,1-trichloroethane.

Technical Evaluation

Parker Hannifin's conversion to aqueous cleaning was not without challenges. The majority of the problems were experienced in the immersion process. It is very important that the parts be free of residue prior to the nitriding process. If a residue remains on the part and causes failure in the nitrider, production is delayed 48 hours. Parker originally used W. R. Grace's Daraclean 282 GF in the immersion system but experienced failures in the nitrider. Daraclean 282 GF contains silicates which were the suspected, but not proven, cause of the failures. Parker made the switch to Oakite's Inpro-Clean 2500, a non-silicated cleaner and at the same time added the following four steps to the cleaning process: rinsing with a hose, blowing drying with air, glass peening,[15] and drying in the oven. This made the immersion cleaning process very labor-intensive but there were no part failures with the additional four steps. Although this procedure worked, it was expensive due to the four labor-intensive steps added to the process as well as the use of of Oakite Inpro-Clean 2500 at a higher concentration than recommended by the manufacturer. (Oakite recommends 2.38% by weight. Parker Hannifin was using an 8% by weight solution.)

As both the four additional labor steps and the higher concentration of cleaner were introduced into the process at the same time, it was unclear whether they were all necessary. Elimination of any or all of them would reduce the process cost and increase its viability as a cleaning alternative. Testing was done in TURI's Surface Cleaning Laboratory to evaluate the necessity of each of the additional steps as well as to determine the minimum amount of cleaner needed.

Testing in TURI's Surface Cleaning Laboratory

In order to determine which steps in the cleaning process were unnecessary, TURI's Surface Cleaning Laboratory Staff attempted to determine the cause of part failure in the nitrider. For the first test, an actual dirty part was obtained from Parker . Parker's cleaning process was then simulated in TURI's lab. The dirty part was immersed in a 160F bath of 8% Oakite Inpro-Clean 2500 for 20 minutes. The part was not rinsed and it was air dried. The dried part was examined under the microscope in order to identify any residue. This part was compared to parts from the second test.

For the second test, samples of actual parts were collected from the Parker facility following each step in the cleaning process. These samples were taken to TURI's Lab where they were examined under the microscope. Microscopic examination of all the parts determined that the process parts did not contain soap residue. The rinsing and drying steps did not contribute to part cleanliness. Residual surface contamination and oil were found on the process parts indicating inefficient cleaning.

The next test was to study the effect of soap concentration on part cleanliness. This test followed TURI's basic protocol for lab testing. Seven parts were acquired from Parker. All seven parts were precleaned in the ultrasonics tank in a 10% by volume concentration of WR Grace's Daraclean 283, a non-silicated cleaner. All parts were immersed in a quench oil sample obtained from Parker.

Two parts were immersion cleaned in a 2.36% by weight solution of Oakite Inpro-Clean 2500; two parts were immersion cleaned in an 8% by weight solution of Oakite Inpro-Clean 2500; two parts were immersion cleaned in a 20% by weight solution of Oakite Inpro-Clean 2500; and one part was not cleaned.

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[15] Peening refers to the mechanical working of metal by hammer blows or shot impingement (e.g., glass beads).

The parts were not rinsed. The parts were taken to Parker Hannifin for further processing in the nitrider. The results indicated that only the part that was not cleaned failed in the nitrider. This test suggested that the cleaner concentration could be decreased to the manufacturer's recommendation without jeopardizing the nitriding process while saving money on raw material costs.

During the first months of the aqueous system, Parker was changing the bath on a monthly basis. Operators added soap randomly to the bath as they felt necessary. This often resulted in a higher soap concentration than needed. Parker has since instituted a policy, recommended by the manufacturer, to perform weekly titrations on a small sample of the bath to determine alkaline content. The titration results allow the operators to add the correct amount of detergent to make up for drag-out losses without increasing the concentration unnecessarily.

Lessons Learned

- Aqueous immersion cleaning of steel and aluminum substrates following oil heat treat is a viable option for the replacement of chlorinated solvents.
- Aqueous immersion cleaning of steel and aluminum substrates prior to nitriding is a viable option for the replacement of chlorinated solvents. However, the cleaning process conditions must be controlled to ensure efficient cleaning.
- Replacing a silicated aqueous cleaner with a non-silcated cleaner in a no rinse system solved a residue problem.

Technical Evaluation Supplement

Parker Hannifin has done much trial-and-error work regarding the use of various aqueous cleaners on their particular substrates and contaminants. Table 3 summarizes the substrates, contaminants, aqueous processes, and aqueous chemistries that are effective on the four cleaning situations at Parker Hannifin.

Table 3. Summary of Aqueous Chemistries

Substrate	Contaminant	Aqueous Process	Aqueous Product	Aqueous Chemistry*			
				P	S	GE	Si
aluminum	hydraulic oil with silicone	pressure spray	Daraclean 282 GF	No	No	No	Yes
steel	non-silicone machining oils	pressure spray	Brulin 63-G	Yes	Yes	No	Yes
steel & aluminum	rust inhibiting oil	ultrasonics	Brulin 815 GD	Yes	No	No	No
steel & aluminum	heat treat quench oil	immersion	Oakite Inpro-Clean 2500	Yes	Yes	Yes	No

WR Grace Daraclean 282 GF is a low-foam, multi-metal cleaner. The product is specially formulated to be non-aggressive toward aluminum and zinc alloys. Product literature claims biodegradability and the absence of chlorine, sulfur, phosphorous, nitrites and glycol ethers. The literature also indicates that the product has excellent hard water tolerance. The excellent hard water tolerance and the lack of phosphorous indicate the presence of orthosilicates as sequestering agents in this formulation. The presence of silicates also allows for the non-aggressive behavior toward aluminum.

The product literature for Brulin 63-G states that it is a biodegradable, alkaline detergent containing phosphates and silicates and developed for use in spray wash equipment. Brulin 63-G is stated to effectively remove coolant residues and other oil-based soils and to contain a rust inhibitor package that protects both steel and aluminum. It is designed to be low foaming at temperatures between 140-180F with a recommended dilution of 3-5% in water.

The product literature for Brulin 815-GD states that it is an aqueous-based, biodegradable, alkaline detergent developed for the aerospace industry for hot tank immersion cleaning and degreasing. It exhibits superior cleaning ability on ferrous and non-ferrous metals including aluminum, titanium, and brass, as well as plastics and composites. The recommended temperature and dilution in water are 140-180F and 5-20%. This product is reported to rinse freely, leaving no residue. The product contains phophates, alkaline builders, detergents and inhibitors.

According to the MSDS and product literature for Oakite Inpro-clean 2500 contains tetrasodium pyrophosphate, sodium carbonate, sodium sulfate, and sodium tetraborate as builders, diethylene glycol butyl ether as solvent and nonylphenoxy as a polyethoxy ethanol nonionic surfactant. It also contains naphthalenesulfonic acid and sodium salt condensed. This product is non-silicated and non-caustic.

Parker found that one product, Oakite Inpro-Clean 1300, was too aggressive on the aluminum parts in the ultrasonic system. They switched to Brulin 815 GD for their ultrasonics cleaning. Oakite Inpro-Clean 1300 is a non-caustic cleaner containing tetrapotassium pyrophosphate and ethoxylated secondary alcohol. It does not contain silicates, sulfur or glycol ethers. Product literature warns that slight etching of aluminum and zinc alloys may occur at higher temperatures or concentrations. This is due to the lack of silicates or other inhibitors.

Market Forge

Located in Everett, MA, Market Forge manufactures cooking steamers. Prior to August, 1993, Market Forge used a 1,1,1-TCA vapor degreasing system to degrease carbon steel and aluminum boiler parts prior to welding. The performance of TCA was satisfactory, but its use was discontinued because of the labeling requirements of the Montreal Protocol. On the advice of their supplier, Market Forge switched to an aliphatic petroleum distillate solvent (CAS 64742-88-7). To accommodate the switch, the vapor degreaser was modified to remove the heating capabilities and add filter capacity. Besides the modifications to the equipment, it was assumed that the petroleum distillate solvent would be a drop-in replacement. However, as soon as the switch was made, the welders of both the carbon steel and aluminum parts began to experience problems.

Name: Market Forge
Location: Everett, MA
Primary SIC Code: 3499
Product: cooking steamers

Problems with Cleaning Carbon Steel

The carbon steel parts are received from the supplier coated with East Falls Hydraulic Oil 8-32. The oil is a heavy paraffinic petroleum distillate used as a pickling oil to prevent rusting during storage and shipping. Market Forge adds two petroleum oils to the carbon steel parts during processing. One oil is TRIM SOL, an aliphatic petroleum naphtha (CAS 8002-05-9) containing sulfonates and chlorinated alkenes and reported on the Material Safety Data Sheet to be 100% soluble in water. The second oil is C-EBLIS Cutting Oil, a naphthenic petroleum distillate (CAS 64742-53-6, 64742-52-5) which is not soluble in water. After cleaning the parts in the replacement petroleum distillate solvent, the welders report that the parts are visibly less clean than parts cleaned with the TCA system and that the parts produce fumes when welded. The welders have noticed an "eggshell" film on the parts and describe the parts as appearing "wet" following cleaning with the petroleum distillate and drying.

Problems with Cleaning Aluminum

Unlike carbon steel, the aluminum parts are received "clean" with a protective coating of plastic shrink wrap. However, during processing at Market Forge, the parts are contaminated by C-EBLIS Cutting oil used in the stamping operation and aliphatic hydrocarbon oil used for drilling and tapping operations. Cleaning of these contaminants using the replacement petroleum distillate solvent proved unsuccessful and resulted in a visible oily film which prevented proper welding. Consequently, the welders were spraying and hand wiping with Magnuflux, a light aliphatic naphtha solvent (CAS 64742-89-8).

Technical Evaluation

The goal of the technical evaluation was to find a cleaning system that would effectively clean both the carbon steel and aluminum. From their analysis of the soils, the project team (TURI staff and Market Forge personnel) decided that aqueous degreasing would be tested. Two fundamental sets of tests were run, one to determine the most appropriate cleaning system and one to determine an effective cleaner.

Cleaner Systems Testing

In order to reduce the number and types of contaminants a potential cleaning system would have to clean, the first course of action was to determine if it was possible to use no oil, less oil, water soluble oils, or the same types of oils in Market Forge's processing of both metals. Unfortunately, no methods were found to achieve these goals.

The supplier of the carbon steel indicated that the East Falls Hydraulic Oil could be cleaned with "soap and water." Of the three remaining oils involved, the non-water-soluble C-EBLIS Cutting Oil and the aliphatic hydrocarbon drilling and tapping oil were potentially the most difficult to clean. An attempt was made to substitute the water-soluble TRIM SOL oil for the oil currently used in aluminum drilling and tapping operations. When this proved unsuccessful, the aliphatic hydrocarbon oil was retained.

The next step was to establish a baseline clean for samples of carbon steel and aluminum using TURI's Surface Cleaning Laboratory. For testing purposes, an ultrasonics system was used to establish an acceptable level of cleanliness for both materials. Samples of both metals were cleaned with an aqueous cleaner, at 130F, using ultrasonic agitation for 10 minutes. A shop weld trial proved that the cleaning was sufficient. The parts were not rinsed during this lab test for two reasons. First, the rust inhibitors in the detergent were needed to protect the parts from rusting during storage prior to welding. Second, current processes at the company do not require a wastewater discharge permit, so it was desirable to minimize the use of water in the aqueous system. (Note: The company plans to explore options for extending cleaner bath life by filtration.)

Having established baseline clean and decided on aqueous degreasing, testing was begun to determine the most effective alternative cleaning method. First, samples of both metals were cleaned at 130 degrees F for 10 minutes with an alkaline low-foam cleaner containing rust inhibitors. No agitation was used and the parts were not rinsed. A shop weld trial proved that the welding was unsuccessful because fumes, beyond normal welding fumes, were emitted. The results of this test, combined with the weld tests on baseline clean metal, established what acceptable and unacceptable levels of cleanliness were and also established the effects of poorly cleaned metal on the welding process. These combined results led to the development of a lab test used to determine the acceptability of various immersion and pressure spray cleaning tests. The lab test simulated the welding process by subjecting sample plates of metal to a flame from an oxy-propane torch while two observers watched for fumes. A visible difference between the acceptable and unacceptable samples was seen.

The results of the testing, by company personnel visual inspection and company-approved weld test, indicated that both immersion with agitation and pressure spray systems cleaned the metal effectively. As Market Forge did not have a wastewater discharge permit, the project team decided on a pressure spray aqueous system because less water was required compared to the immersion system.

Testing Efficiency of Different Cleaners

Having decided on a pressure spray system, the next objective was to determine the cleaning efficiencies of various aqueous chemistries. Tests were performed on Market Forge carbon steel parts, cut to 2" x 1" pieces. Initially, a high pressure spray washer (1000 psi) was used for this evaluation. Overall results showed that the high pressure spray system could not be used when testing the differences in efficiencies of cleaners because the cleaning ability of the high pressures masked the small differences between the cleaners.

Three different cleaners were tested in TURI's low pressure (~20 psi) spray washer. The cleaners were chosen based on compatibility with metals and contaminants, ability to be used in a pressure spray system, and previous success in similar applications. The three cleaners were WR Grace Daraclean 283 (5% by volume), Brulin Corporation 815-GD (5% by volume) and Oakite Products Inpro-Clean 2500 (54.49 g/gallon - company recommends 2.38% by volume). There were nine samples for two trials (two controls). and eight samples for the third trial (one control).

Part samples were precleaned in the ultrasonics tank and weights were taken. The samples were then contaminated by wiping them with East Falls Hydraulic Oil 8-32 and allowed to age for two hours. All testing was done in accordance with the Quality Assurance Project Plan. The Plan was modified to more closely represent the actual situation at Market Forge by changing the sample aging time following contamination from 24 hours to 2 hour. The weight of contaminant removed was then determined by weighing the samples before and after cleaning. A removal efficiency was then calculated. The raw data for the testing results are in Appendix B. Table 4 provides a summary of the data.

Table 4. Average Removal Efficiency for Three Chemistries on Steel Parts: Market Forge Application

Cleaner	Average Removal Efficiency (%)	Standard Deviation (%)
Daraclean 283	96.231	1.493
Brulin 815-GD	92.382	2.727
Inpro-Clean 2500	91.566	2.343

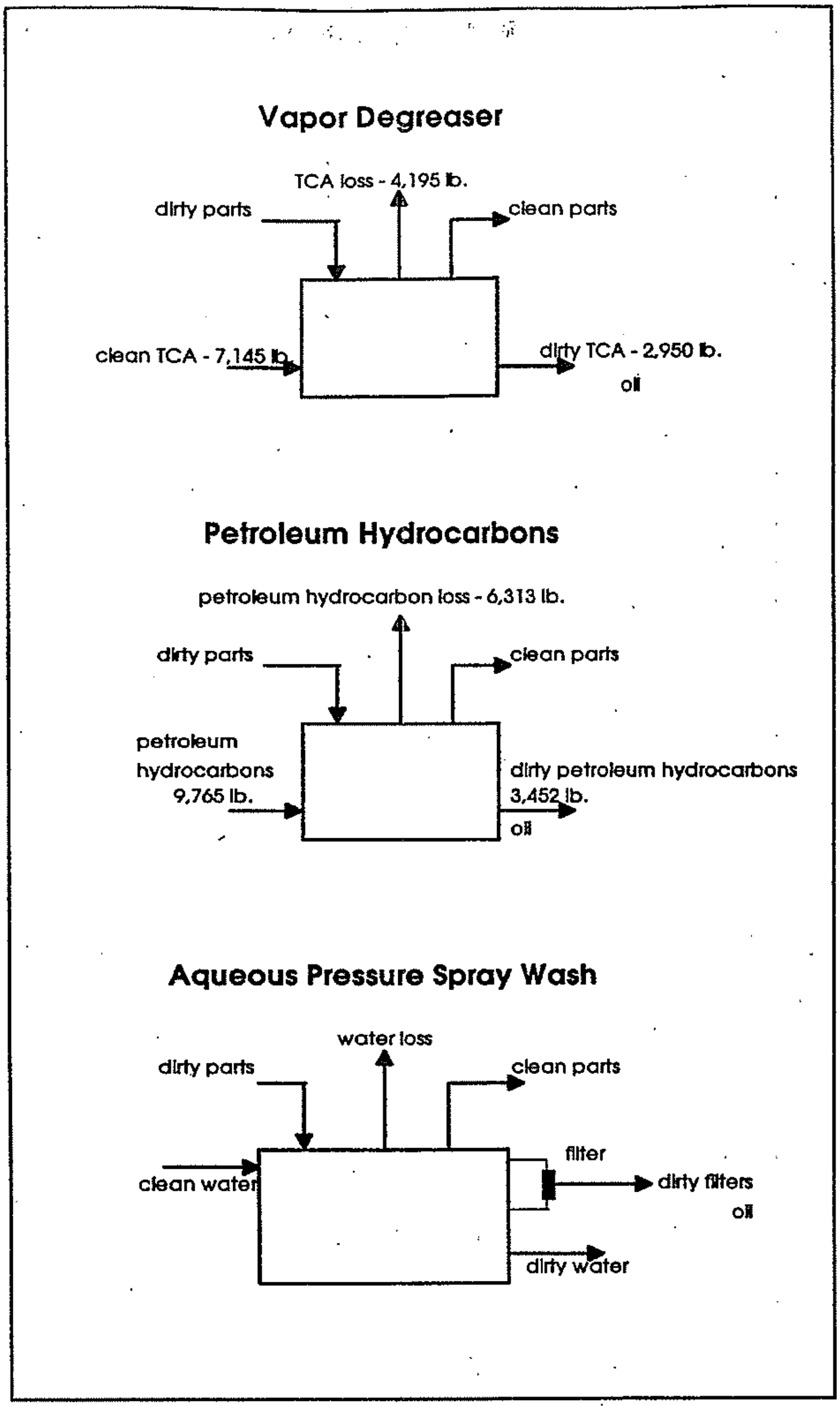

Figure 4. Market Forge Metal Cleaning System

Since the cleanliness of the carbon steel parts was the most immediate need, the testing was first performed on those parts. As is shown in Table 4, the Daraclean 283 gave the best results and was chosen by the project team. The carbon steel cleaned with Daraclean 283 passed visual inspection and shop weld tests. Because Market Forge does not test for adequate paint adherence using any of the common tests, the paint adherence test performed here was simply a visual inspection of paint adherence immediately following paint application and again four weeks following application. Subsequent cleaning trials performed on the aluminum parts indicated that the Daraclean 283 was acceptable for aluminum as well. The aluminum parts were visually inspected, shop weld tested, and also tested for paint adherence. The aluminum passed all these tests and, although stained by the process, it was not etched. Staining is not a problem for this application.

During initial site visits, the project team also discussed standard operating procedures. Included in this discussion were the issues of parts configuration during cleaning and parts inventory control. The current parts configuration procedure for the degreaser requires that parts do not cover one another thus preventing cleaning; however this procedure is not always followed. Market Forge is implementing a more aggressive education program to address this issue. In addition, the company is exploring methods of more efficient materials movement. Currently, cleaned parts may be stored for months before use. Storage conditions of the dirty and clean parts were also discussed. Current storage conditions add contaminants to the dirty parts and do not adequately protect the cleaned parts from leaking roofs and other shop dirt. Improvements in these areas will be necessary for the success of any alternate cleaning system.

Based on the information obtained from this project, Market Forge purchased an American Metal Wash pressure spray washer. (See Figure 4 for a schematic representation of the vapor degreaser, the naphtha solvent system and the pressure spray washer.) The unit was recently installed and has been operating effectively for three months. The viability of close looping the aqueous cleaning system with an ultrafiltration unit was researched. Two successful closed loop aqueous cleaning projects are described in Appendix C.

QA Results

QA tests determined that the analytical balance used here had a precision of 0.1 mg and an accuracy of 0.3 mg. In the performance tests, the contaminant loading ranged from 16.8 to 74.2 mg. Using the smallest loading, the maximum error in precision was 0.6% and the maximum error in accuracy was 1.8%. (See the equations in the box.) These numbers can be compared to the experimental results summarized in Table 5. Since the standard deviations of the removal efficiencies ranged from 1.5-2.3%, it can be concluded that most of this variability was due to the actual differences in removal efficiency from test to test, rather than imprecision in the measurement. Again comparing this number to Table 5, average experimental removal efficiencies for the three cleaners were 91.6%, 92.4%, and 96.2%. The difference in average cleaning efficiency between the best cleaner (Daraclean 283) and the second best cleaner (Brulin 815-GD) was 3.8%; since this is more than twice the maximum accuracy error of 1.8%, it can be stated with confidence that Daraclean 283 had the best removal efficiency under the conditions tested.

$$\frac{0.1}{16.8}\ x\ 100 = 0.6\%$$

$$\frac{0.3}{16.8}\ x\ 100 = 1.8\%$$

Lessons Learned

- "Drop-in" petroleum solvents are not always effective alternatives to chlorinated solvents for cleaning prior to welding operations as evidenced at this test facility..
- Pressure spray aqueous cleaning can effectively remove pickling oil from carbon steel and aluminum parts.
- A no-rinse aqueous degreasing process is a viable alternative prior to painting for aluminum parts.

Company A

Name: Company A
Location: Massachusetts
Primary SIC Code: 3471
Products: electroplated parts

Company A is a job-shop electroplating company located in Massachusetts. By the nature of the job-shop business, Company A cannot always predict what types of metals it will have to clean and thus requires a flexible cleaning system, capable of cleaning many different substrates. Currently the company cleans all their parts in a vapor degreaser using TCE. In 1993, Company A used 8,600 pounds of TCE; in 1994 they used 11,152 pounds. Figure 5 shows a mass balance of the TCE vapor degreaser using 1994 data. Calculations to obtain the mass balance revealed that almost 94% (or 10,466 pounds) of the TCE in the system is lost to the atmosphere. There is no cooling on the degreaser. As experienced by other companies, Company A has seen an increase in the need for cleaning because their customers, who used to supply parts that had been cleaned with CFC's, are cleaning less due to regulations on ozone depleting chemicals. As a result, Company A is very interested in evaluating cleaning alternatives to decrease their use of TCE .

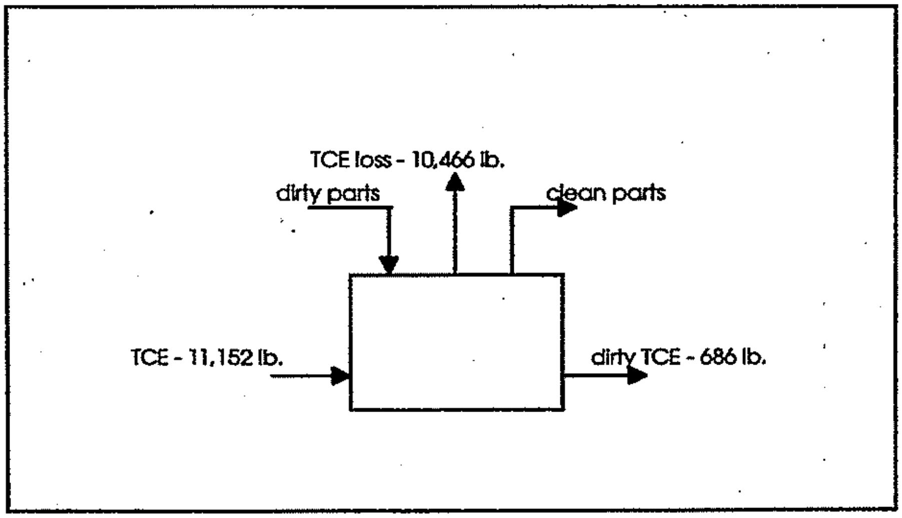

Figure 5. Company A TCE Vapor Degreaser

Ninety percent of the base metals cleaned at Company A are: carbon steel, stainless steel (303, 316 L, 400, 416, 410, 174PH, 155PH), aluminum (6061, 2024, 356, 7075) and copper (brass and bronze). The remaining 10% of the base metals cleaned are: titanium, zinc diecast, aluminum diecast, plastics and other metals depending on the customer.

Currently, all parts are cleaned in the TCE degreaser. Subsequent processing steps, considered to be surface preparation steps by the company, may include electrocleaning, acid cleaning or caustic cleaning depending on the surface required. A diagram of this process is shown in Figure 6. These subsequent processing steps provide opportunities for performing some of the cleaning function currently performed by the degreaser. The electroclean bath contains a silicated cleaner, Rokleen 123 from McGean-Rohco at a 6 oz/gallon concentration and a temperature of 150F. The solution is changed every three or four months. The acid clean bath contains hot sulfuric acid. All aluminum parts are soak-cleaned in a borax (caustic) solution.

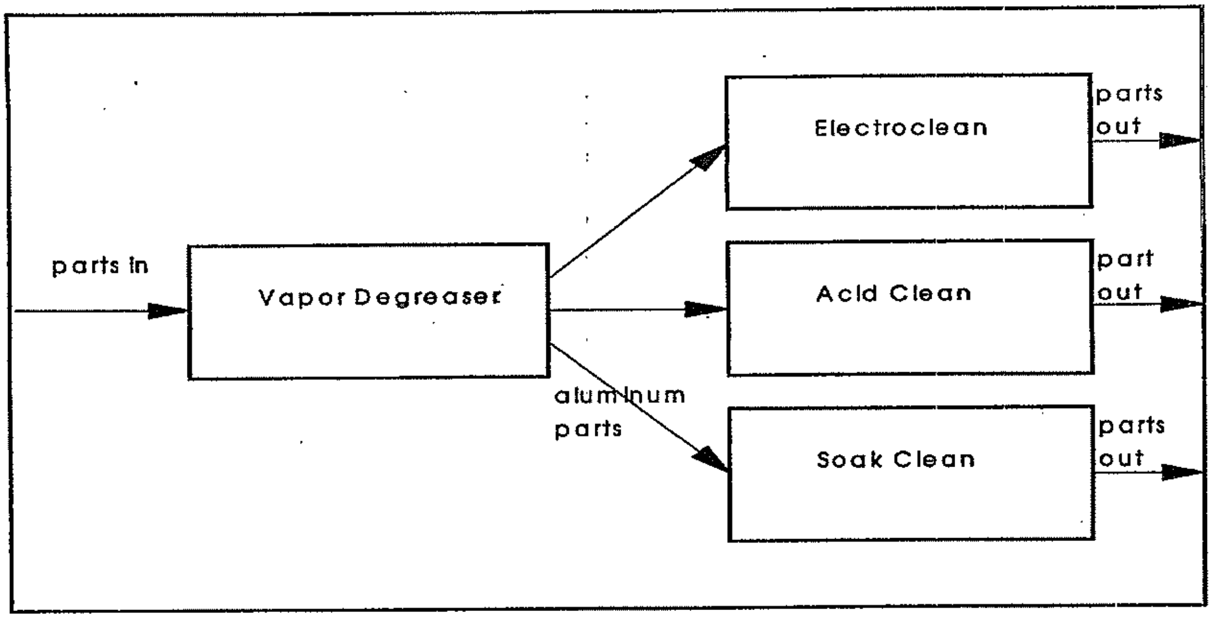

Figure 6. Company A Cleaning and Surface Preparation Process

Due to the relative low cost and effectiveness of TCE for all of their cleaning needs, Company A is apprehensive about investing in an unproven technology that may not be effective on all substrates. Faced with similar decisions, other plating companies have phased in aqueous cleaning alternatives for specific substrate groups. Once they developed confidence in aqueous cleaning, they were able to expand its use and eliminate the use of chlorinated solvents. Presently, Massachusetts plating companies are at various stages of converting to new cleaning technologies. The preferred cleaning alternative in the plating industry has been aqueous cleaning.

Identification of Options

Due to the variety of substrates and contaminants that require cleaning at Company A, it would be difficult to define an aqueous cleaning chemistry and process that would work for all the possible variations. Due to the sensitivities of their wastewater treatment system, Company A is not able to consider petroleum-based solvents, long chain organics or aqueous chemistries with silicates. Their wastewater treatment system is able to handle the once-every-three-or-four-months dump of the Rokleen 123 bath. However, this bath dump is not easy for the wastewater sytem to process and the company does not want to add more of this type of wastewater to its treatment system.

Depending on the aqueous chemistry, heated rinse tanks with agitation may be available for use. The company also has drying capabilities. The company currently has a small sand blasting unit which is used for surface preparation on specific materials. In addition, the operators are skilled and familiar with different processes required for different metals.

The goal of this project was to identify a cost effective cleaning system that will clean all possible substrates and contaminants, or selected substrates and contaminants, with the minimum use of listed substances. The cleaning system must also be compatible with the waste water treatment system. In a brainstorming session with company representatives, the following options were identified for further evaluation.

- media blasting - sodium bicarbonate, plastic, carbon dioxide
- ultrasonic aqueous
- "closed" vapor degreasing
- upgrading existing vapor degreaser
- Advanced Vapor Degreasing (AVD™) system
- supercritical carbon dioxide

Evaluation of Options

The six options identified were screened for potential applicability. A description and outline of the technical evaluation is provided for each option. A summary table (Table 5) of results follows the descriptions. Options with promise were further evaluated in the financial and substitution analysis sections.

Media Blasting

Sodium Bicarbonate--Abrasive blasting with sodium bicarbonate was evaluated as a cleaning step for aluminum parts. Sodium bicarbonate is a relatively new media for the blasting process. It has been used effectively to strip paint in a number of applications. The waste resulting from this process is dirty (oily) sodium bicarbonate which would most likely be nonhazardous waste based on the experience of the equipment salesman. The waste from this trial was not tested to determine whether it was hazardous.

The trial was performed at the Dawson-McDonald company located in Wilmington, MA. Dawson-McDonald distributes blasting equipment manufactured by Empire Abrasive Equipment Corporation in Langhorne, PA. The sodium bicarbonate was delivered by suction feed at 50 psi in a media blast cabinet. Following blasting the aluminum part looked very clean, but had a dull finish. The part was returned to the company for inspection and further processing. The company representative was satisfied with the level of cleanliness of the part but was not satisfied with the dull finish. While a shiny appearance of the finish prior to plating is not an actual requirement, the company did not want to risk possible unacceptable plating. Therefore the part was buffed and cleaned in the TCE degreaser prior to plating.

Empire Abrasive Equipment Corporation sells tumble blast, pass through automation and rotary table equipment. The availability of space may be a problem for the pass through automation equipment. For the rotary table equipment, an operator stands outside the cabinet and replaces dirty parts for clean parts as appropriate.

Plastic--Media blasting using plastic media was evaluated as a cleaning step for aluminum parts. Plastic media was chosen for this evaluation because it will not harm the soft aluminum surface. The medium evaluated was Polyplus from U.S. Technology Corporation in Putnum, CT. The plastic particles are irregularly shaped with sharp edges for effective cutting action. The hardness of the particles on the Moh scale is 3.5. The medium has a density of 1.5 g/cm^3. The mesh size of the media tested was 30-40 mesh (0.023-0.015 in.).

The medium was expelled via a 25 psi pressurized air stream. Pressurized air was used as a final step to blow off the media. The media was filtered through a cartridge filter. The waste that is produced in this process is dirty (oily) plastic media most likely be nonhazardous waste depending on actual test result from a sample of the waste.

The trial was performed at the Dawson-McDonald company located in Wilmington, MA. The media blast cabinet used was manufactured by Empire Abrasive Equipment Corporation in Langhorne, PA. Following blasting, the aluminum part looked very clean and had a shiny finish. The part was returned to the company for inspection and further processing. The company representative was satisfied with the level of cleanliness of the part and the part was satisfactorily plated with no further cleaning or buffing.

Carbon dioxide--Fragmented carbon dioxide blasting was examined for the cleaning of all parts at Company A. A trial was performed on three aluminum pieces at Environmental Alternatives, Inc. in Westmoreland, NH. Environmental Alternatives, Inc. offers design, sales, and training expertise. The parts tested were adequately cleaned. However, the parts were deformed as a result of the cleaning process to levels that were unacceptable to the company.

Ultrasonics

For this application, an ultrasonic cleaning process was evaluated as a cleaning step prior to surface preparation for the aluminum pieces that comprise 25% of the total cleaning needs.

A technical evaluation was performed at TURI's Surface Cleaning Laboratory. The aluminum part, contaminated with various oils and machining fluids, was obtained from the company. A neutral cleaner, WR Grace's Daraclean 235 (pH 7.1) was chosen to give a wide range of substrate compatibility and to ensure that no etching would take place on the aluminum part. This product also contains no silicates. A 7% by volume solution of the Daraclean 235 was used. The part was immersed in a 140F ultrasonics bath (6 transducers, 40 kHz, 500 watt) for 10 min. It was rinsed in 148F tap water for 2 min and in 116F deionized water for 2 min. The part was dried using air knives at room temperature. The part was returned to the company for inspection and plating. By visual inspection the part was clean. It was then plated successfully with no additional cleaning.

Supercritical Carbon Dioxide

This technology was considered for its theoretical technical feasibility, noting its current state of development. Discussions were conducted with a vendor of the equipment and with an academic researcher in the field. According to these experts, supercritical carbon dioxide has been proven to clean precision parts and works well on all metal parts that can be subjected to high pressures and temperatures.

For the cleaning needs at Company A, it is very likely that supercritical CO2 technology could effectively clean all parts prior to surface preparation. However, based on the capital cost requirement and the fact that Company A was not interested in this technology, no technical evaluation was performed. This technology may eventually become cost effective. More information on this technology can be found in EPA's Guide to Cleaner Technology: Alternatives to Chlorinated Solvents for Cleaning and Degreasing.

New Vapor Degreaser

The degreaser currently used by the company is an older model degreaser that allowed large evaporative losses to the atmosphere. The company representatives wanted to explore the purchase of a new degreaser. Newer model vapor degreasers, still using TCE or other solvents, incorporate features such as additional freeboard area, improved chillers, and cover panels that are designed to prevent excessive solvent losses to the atmosphere. If the new degreaser was supplemented with operator training the use of TCE would decrease significantly from current use. No technical evaluation was necessary due to the fact that this is a proven technology for this application.

Retrofit Existing Vapor Degreaser

The company representatives also wanted to evaluate the option of retrofitting their existing vapor degreaser by improving the cooling capacity to decrease evaporative loss of solvent. This option involves increasing the freeboard area within the current degreaser and adding an associated freeboard chiller. In this manner, more of the TCE vapor will condense on the degreaser walls and flow back into the sump rather than escaping to the atmosphere. No technical evaluation was necessary due to the fact that this is a proven technology for this application.

Implement AVD™ System

The company had read about the AVD™ system in a trade journal and was interested in pursuing its applicability to their needs. The AVD™ system, developed by Petroferm, Inc. uses a cosolvent system: one for cleaning, which leaves an oily residue on the part, and one for rinsing and drying, a perfluorinated compound. The process uses a retrofitted two sump vapor degreaser or new equipment. The AVD™ unit contains two compartments to hold each of the solvents, and otherwise functions in a manner similar to other vapor degreasers. This type of unit is most beneficial when cleaning small, intricate parts such as electrical connectors and jewelry.

The two, non-miscible, materials are a solvating agent and a rinsing agent. The solvating agent, manufactured by Petroferm, Inc., is an ester based material with a flash point of over 200F. The rinsing agent is a perfluorocarbon material manufactured by 3M. It has no flash point. In the wash sump, the two materials are combined in equal proportions by weight and the bath is highly agitated. The parts are immersed in the mixture, which is heated to 133F, for 2-5 minutes. In the rinse sump, the parts are immersed in 100% perfluorocarbon which is not heated. Parts emerge residue free and dry.

EPA's current position on perfluorocarbons is that without more complete knowledge of their global warming impacts, they may only be used as a substitute for ozone depleting solvent cleaners where no other substitutes exist.[16] Based on this position, cleaning of basic metal parts is unacceptable because alternative cleaning processes are available. Although a direct technical evaluation was not performed, all

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[16] EPA Memorandum from Nina Bonnelycke, Stratospheric Protection Division, "Uses of Perfluorocarbons in Industrial Cleaning", 1/6/93.

reports and available data about the technology suggest that it would be appropriate for the materials and contaminants at Company A.

Lessons Learned

- Plating companies experienced an increased demand for cleaning as regulations on ozone depleting chemicals discouraged their customers from cleaning parts.
- There are no simple, drop-in cleaning alternatives for job shops making the gradual phasing out of chlorinated solvents a preferred option.
- Because TCE is not heavily regulated, the motivation for replacing TCE as a degreasing solvent is not as great as the motivation for replacing the ozone depletors.

Table 5. Options Analysis Summary: Company A

Option	Cost	Advantages	Disadvantages	Conclusions
Sodium Bicarbonate Media Blasting	Approx. $4000, cabinet system for aluminum pieces	Uses no hazardous substances; creates no aqueous waste	Performance not acceptable; more labor-intensive than the current process	Not recommended based on technical evaluation
Plastic Media Blasting	Approx $4000, cabinet system for aluminum pieces	Uses no hazardous substances; creates no aqueous waste	More labor-intensive than the current process	Recommended based on tech evaluation; labor requirements must be considered
Carbon Dioxide Blasting	Cost estimate for a 6' x 8' enclosure including HEPA filter ventilation system, fragmented CO_2 cleaning unit, nozzles, installation, training, is $90,000; A smaller enclosure would cost approx $5,000 less	CO_2 is nontoxic, nonflammable and is not an ozone depletor; waste is the removed dirt and oil; CO_2 tech are appropriate for a wide range of substrates; CO_2 tech has been shown to reduce cleaning time up to 50% when compared to solvent cleaning	More labor-intensive than vapor degreasing	Preliminary cleaning results with fragmented CO2 technology were positive; however, parts were deformed; additional testing at different pressures is recommended.
Ultrasonics	A 250-gallon ultrasonic wash tank is approx. $60,000 (per Talley of N. Attleboro, MA) This is approx. one-half the size of the current degreaser and would be sufficient for even the largest aluminum piece	Does not use any listed substances; no increase in the manual labor or time requirements as compared to the current system	One study reported that the OSHA action level for noise was exceeded during operation of a 300 gallon tank with 10 ultrasonic transducers (1000 watt, 20kHz)[17]; produces aqueous waste stream	Keeping the disadvantages of the noise level and the aqueous waste stream in mind, this option is technically viable for this application.
Supercritical Carbon Dioxide	Estimated capital cost for SCF equipment for this application is $400,000 (per Phasex Corporation); operating costs were not determined	Uses a non-ozone-depleting, non-toxic substance[18]; contaminants are easily contained for disposal; CO_2 may be recovered and recycled, resulting in a zero emission cleaning process	High capital cost requirement; worker safety concerns for high pressure system	Based solely on economics, this technology is not appropriate for this application.

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[17] US Air Force Aeronautical Systems Center, Wright-Patterson AFB, "Industrial Modernization Incentives Program: Phase II, Final Report for Solvents Substitution Project", United Technologies Pratt & Whitney, May 1993.

[18] Carbon dioxide contributes to global warming; however, it is available as a byproduct of industrial processes such as petroleum refining so there would be no net contribution to global warming by the use of this technology.

Option	Cost	Advantages	Disadvantages	Conclusions
New Vapor Degreaser	Capital cost is approx. $60,000, including two 4'x3' units with primary refrigeration and freeboard chiller; operating costs comparable to present system; maintenance to change filter ($3 each, 12 times/yr) and remove sludge same as for the current system	Less solvent losses; less exposure to workers; less TCE used may result in less environmental regulation of the system	Use of a listed hazardous substance, TCE; produces hazardous waste; exposure of workers to TCE	Option not desirable due to the dependance on the listed material, TCE
Retrofit Existing Vapor Degreaser	Capital cost is approx. $19,000, including an additional 8" of freeboard and chiller; operating cost is comparable to the present system; less TCE will be used so the raw material cost will be lower	Reduced amount of TCE lost to the atmosphere, less exposure to workers, less TCE used may result in less environmental regulation of the system	Use of a listed hazardous substance, TCE; produces hazardous waste; exposure of workers to TCE	Option not recommended as a final solution, but may be desirable as an interim step on the way to the goal of less dependance on TCE
Implement AVD™ System	Due to the high chemical costs for the ester-based material ($45/gallon) and the perfluorocarbon ($130/gallon), the AVD™ process is not attractive for processes requiring large part cleaning; it would not be possible to retrofit the existing degreaser, a dual sump degreaser would cost approx. $200,000. Initial chemical purchase would be $130,000. Based on these rough cost figures, no further cost analysis was performed.	Non-ozone-depleting and nonflammable solvents Solvent losses to the atmosphere are reduced by the incorporation of various design features into the new equipment; low cycle time; no aqueous waste	High capital cost; perfluorocarbon solvent has high global warming potential; perfluorocarbons have hazardous thermal decomposition products (hydrogen fluoride and perfluoroisobutylene)	The AVD™ process for this application is not an option given EPA's position for cleaning metal parts.

Table 5. Options Ananlysis Summary: Company A (continued)

Chapter 4
Investment Analysis

Introduction

In addition to the outcome of technical evaluations, major deciding factor when considering alternatives to current processes is the result of an investment analysis. Typically companies attempt to predict the profitability of their investments by performing calculations using initial investment costs and annual savings generated by new equipment. Traditional financial analysis, however, often includes only the costs directly associated with production, such as labor and capital and does not include the costs (and savings) that make pollution prevention projects profitable. The Total Cost Assessment (TCA) methodology used in this project is an innovative evaluative tool that examines many other important costs associated with an investment including such things as staff time for environmental reporting, waste management costs, and permitting fees.

The Total Cost Assessment tool was used in three different ways in the four analyses in this section. The first two analyses were performed on the cleaning situations at Parker Hannifin. The company had already implemented aqueous cleaning to replace chlorinated solvent vapor degreasing. In the first analysis, TCA was used to take a retrospective look at the investment. In the second analysis, a TCA was compared to the companies' own financial analysis of the project. In the third analysis, TCA was applied to the Market Forge case to support the degreasing project as it competed with other projects for capital. An analysis was also performed on the intermediate, naphtha solvent system to see how this system compared to the aqueous alternative. For the fourth and final analysis, TCA was used as a decision making tool to help decide among technically feasible alternatives at Company A.

Each company was in a different state of implementing the cleaning alternatives and the data for each subsequent analysis became less precise the further the project was from implementation. The use of TCA as a piece of the decision making process for each situation is discussed in the conclusion of this section. (The use of pay-back period and net present value as financial indicators is presented in Appendix D.)

Total Cost Assessment

Total cost assessment is an innovative analytical approach for evaluating and comparing the full costs of production related investments. It is innovative because all the costs associated with a production investment are included in the assessment, rather than only including the costs directly associated with production, such as labor and capital. Costs often missing in simple production related investment evaluations include insurance, waste disposal, compliance with environmental regulations, utilities, and occupational safety and health training. Businesses typically group many of these costs in overhead accounts or non-production departments such as environmental and occupational safety and health.

Many business accounting systems often do not track environmental costs in a manner in which they can be allocated to the products and processes responsible for producing those costs. As a result of this, many businesses make investment decisions that are based on insufficient information and have a tendency to ignore the environmental impact of an investment.

The financial impact of environmental costs is increasing for several reasons. In recent years insurance companies have increased the premiums for businesses that use toxic chemicals because of the hazards posed to workers[19]. Additional regulations, fines for emissions, and fees for the use of toxic chemicals have resulted in increasing costs of compliance. As a result environmental costs are significant factors in investment analyses.

Total cost assessment is used in this report to assess and compare all costs associated with using toxic chemicals and alternative cleaning systems. Critical elements in a total cost assessment include

- expanded cost inventory
- direct allocation of costs to processes and products
- extended time horizon
- use of long-term financial indicators

These four elements help demonstrate the true costs of production to a firm, the net benefits, or costs, of pollution prevention programs, and how prevention-oriented investments compete for investment capital within company-defined standards of profitability.

It should be noted that the analyses here are limited to internal costs (i.e., those with measurable financial consequences to the company). No attempt was made to estimate the costs to the community surrounding the manufacturing facility or to society at large. By definition, full cost accounting would include these costs, such as health effects to the surrounding community from the use of hazardous substances and ozone depletion from the use of chlorinated solvents.

Data Collection

The data for this study were taken or derived from company purchase orders, waste manifests, chemical inventories, maintenance records, and catalog prices. Indirect costs were found through labor rates, fees and taxes, and time required for compliance with applicable environmental regulations. Helpful resources included environmental managers, operating engineers and accountants within the subject companies, vendors of alternative cleaning systems and cleaning agents, TURI's Technology Transfer Center, representatives of state agencies, representatives of reclaimers and waste haulers, and other case studies of total cost assessment.

The biggest challenge to providing an accurate assessment of all quantifiable costs associated with total cost assessment was data collection. Costs were not often available within companies and other data sources were used. Collection of these data is often very difficult and time-consuming. These costs may be significant and demonstrate the importance of accuracy in cost tracking. When assumptions on costs were made, plant personnel and specialists were consulted. Explanations for missing data are given in the text.

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[19] Dyer, J.A. and K. Mulholland, "Toxic Air Emissions: What is the Full Cost to Your Business?", Chemical Engineering, February 1994.

Parker Hannifin switched to aqueous cleaning prior to in 1993. The 1994 costs were used rather than 1993 costs for two reasons. First, because the data was collected in 1994, actual costs could be used rather than estimations of 1993 costs. Second, because of the ever increasing cost of chlorinated solvents, using 1994 data provided the most up-to-date analysis (and outcome) possible. It must be noted that the use of 1994 data results in a more positive outcome for the aqueous system than when Parker Hannifin actually made the decision to invest.

Parker Hannifin: Analysis One

Background

The first analysis was performed on Parker Hannifin's aqueous immersion cleaning process. The company uses a discount rate of 16% and a labor rate of $16.05 per hour. Parker Hannifin has assigned this project an economic lifetime of seven years.

Cleaning Operations

Prior to the use of aqueous cleaning systems, the company used two vapor degreasers for cleaning. The company made the switch to aqueous cleaning in 1993. This analysis addresses the replacement of one vapor degreaser by an immersion tank; the replacement of the second vapor degreaser is addressed in the second analysis. An immersion tank was selected to replace the vapor degreaser in which 1,1,1-trichloroethane and methylene chloride were used.

Capital Costs

Prior to the installation of the immersion tank, the vapor degreaser had to be cleaned and disposed. Disposal cost of the vapor degreaser was estimated at $1,000.[20] The clean out resulted in one drum of reclaimed 1,1,1-trichloroethane and one drum of reclaimed methylene chloride. Using 1994 prices for reclaimed solvents, this would result in a $50 benefit. Therefore the total cost for disposal of the vapor degreaser was $950.

Table 6. Parker Hannifin Analysis One - Capital Costs

Capital Costs	**Vapor Degreaser**	**Immersion Tank**
Equipment purchase	NA	$20,000
Disposal of old process	$950	NA
Initial permits	NA	0
Building/process changes	NA	included in purchase
Total Capital Costs		$20,950

The company purchased an immersion tank, model PW200, from Kleer-Flo Cleaning. The tank, with a loading capacity of 200 pounds, is used to clean steel parts. It contains an oil skimmer and an upgraded filter system. The costs for purchasing, modifying and installing the equipment were $20,000. The capital costs are summarized in Table 6.

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[20] Capital Appropriations Request by Parker Hannifin.

Operating Costs

The operating costs are summarized in Table 7.

Table 7. Parker Hannifin Analysis One - Operating Costs

OPERATING COSTS		Vapor Degreaser	Immersion Tank
Chemical Purchases	1,1,1-TCA*	$918	NA
	Methylene chloride	$691	NA
	Oakite Inpro Clean	NA	$696
Waste management		$15,938	$10
Safety training/equip		0	0
Insurance		0	0
Fees		0	0
Filing paperwork time		undefinable	undefinable
Annual permitting		undefinable	undefinable
Maintenance	labor	included in materials	$201
	materials	$1,010	$1,000
Production costs		0	0
Utilities	elect.	$2,652	$780
	water	$4,938	$5
	gas/steam	0	0
Total annual operating costs*		$26,147	$2,692
Incremental cash flow*		$23,455	

*These figures are for the first year of operation. The second year costs for 1,1,1-TCA, total annual operating costs and incremental cash flow are $978, $31,290, $26,377. In the remaining years these figures will go up as the excise tax on 1,1,1-TCA increases by $0.045/lb/yr.

Chemicals and Wastes

The solvents used in the vapor degreaser were methylene chloride and 1,1,1-trichloroethane. The total consumption of methylene chloride in 1992 was 1,047 pounds. At the 1994 price of $0.66 per pound, this would cost $691.02.[21] The 1992 consumption of 1,1,1 trichloroethane was 600 pounds. At the 1994 price of $1.53 per pound,[22] the cost for 1,1,1 trichloroethane was $918. The total cost of 1,1,1 trichloroethane and methylene chloride was $1,609 per year.

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[21] DOW Chemicals, market price quote, July 1994.

[22] Ashland Chemical Corporation, market price quote, July 1994. This price includes the excise tax on ozone depleting chemicals which is $0.435/lb for 1,1,1-trichloroethane. The tax will go up to $0.535/lb in 1995 and will increase by $0.045/lb each year thereafter. This tax increase is considered in the financial analysis.

The cleaning product currently used in the immersion tank is Oakite Inpro Clean 2500. The cleaner is replaced every month whether or not there is any indication that a bath change is needed. No detergent is added between bath changes. For each batch, 40 pounds of cleaner is used resulting in an annual consumption of 480 pounds. At a cost of $1.45 per pound, the annual cost of cleaner is $696.

The wastewater generated from the cooling water for the vapor degreaser was 306,995 cubic feet per year. The sewer cost for a cubic foot of water in the City of Waltham is $0.0283. The total sewer cost of cooling water is $8,688. The wastewater resulting from the monthly changeover of the immersion tank is evaporated therefore no sewer costs are associated with this cleaning process.

The disposal costs for two types of hazardous waste can be attributed to the vapor degreaser: contaminated solvent and contaminated oil. One drum of contaminated 1,1,1 trichloroethane and 1 drum of contaminated methylene chloride were generated in 1992. These drums were sent to a reclaimer. The yield of trichloroethane was 93%,which resulted in a credit of $55 for one drum.[23] The yield of methylene chloride was 77% which resulted in a credit of $15.[24] It was common practice for the machine operators to have containers of the chlorinated solvents at their work stations for periodic cleaning needs. As a result, the waste oil from these machines was contaminated with the solvent and required a higher price for disposal than if the oil had not been contaminated. In 1992, the company had to dispose of 54 drums of 1,1,1 trichloroethane-contaminated oil, at a cost of $230 per drum, or $12,420.[25] The cost per drum of non-contaminated oil is $95. The difference in disposal cost of the waste oil is $7,290. This cost can be attributed to the vapor degreasing system. Using the aqueous cleaning system, no solvent is available for use by the operators. As the practice was one of convenience more than necessity, no new cleaning practice was undertaken for periodic cleaning needs. The total annual waste management costs were $15,938 per year ($8,688 + $7,290 - $55 + $15). Costs for transportation of hazardous wastes are not included in this analysis.

The wastes created by the immersion process are oils that are skimmed off and filters that need to be replaced. The total disposal cost of oil skimmed from all of the company's cleaning systems was divided over the separate systems by using the number of parts each system cleans. The total cost for hazardous waste disposal for the immersion tank is $9.68. It was impossible to account for the individual cost of filters and residuals from the evaporator for this degreaser. The filters are disposed of along with other wastes from other processes at the facility. The wastewater from the immersion process is a negligible amount of the waste that is processed in the evaporator.

Regulatory Costs

The company did not have to pay fees under the Toxics Use Reduction Act (TURA) on methylene chloride or 1,1,1 trichloroethane because neither use exceeded 10,000 pounds. TURA fees must be paid when the consumption of a listed chemical that is 'otherwise used' exceeds 10,000 pounds. Likewise, the company did not have to report under the Superfund Amendments and Reauthorization Act (SARA) Title III because the amount used did not meet the threshold. Due to the large quantity of water used in the vapor degreasing system, there would be some cost associated with the permitting and sampling requirements.

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[23] General Chemical Corporation, Framingham, MA, market price quote, August 1994.

[24] General Chemical Corporation, Framingham, MA, market price quote, August 1994.

[25] Laidlaw Environmental Corporation, North Andover, MA, August, 1994. This price is an estimation; the exact price is determined after a sample is analyzed.

However, the company was unable to provide any estimation of the time associated with these duties. For the purposes of this analysis, then, it was assumed that there was no difference in regulatory/permitting costs between the two systems although one would assume that the immersion tank would have a lower cost associated with it than the vapor degreaser.

Production and Maintenance Costs

It is difficult to account for differences between the systems with regard to production costs. Neither the vapor degreaser nor the aqueous cleaning systems require an operator because the cleaning activities are integrated into the production process. The parts in the immersion tank have to be cleaned for a longer period of time, but this has not resulted in a loss of production because the workers perform other activities while the parts are being cleaned.

Based on information supplied by the company, the maintenance costs for the vapor degreaser were calculated at $1,010 per year (using the company's 50 week year). The two filters on the immersion tank cost $10 each and are replaced every week , or $1,000 per year. Maintenance on the immersion tank is estimated at a quarter of an hour per week; this is 12.5 hours per year times $16.05 per hour labor, totaling $201 per year.

Utility Costs

The annual cooling water consumption of the vapor degreaser was 306,695 cubic feet. The cost for a cubic foot of water in the City of Waltham is $0.0161. The total cost of cooling water is $4,938. The water consumption in the immersion tank is calculated as follows: 200 gallons/change of tank times 12 changes per year or 2400 gallons per year. The total cost of this water is $5.17. The cost of electricity for the vapor degreaser and the immersion tank are, respectively, $2,652 (20,400 KW * $0.13 $/KW)[26, 27] and $780. The hourly electricity consumption of both systems is the same but the vapor degreaser operated 68 hrs/week and the immersion tank operated 20 hrs/week. (Although the immersion process requires that the parts are cleaned for a longer time than was required by the degreaser, the immersion tank has a larger capacity.) Because the wastewater from the immersion process is a negligible amount of the waste that is processed in the evaporator, the energy costs of the evaporator that could be attributed to this process were assumed negligible and were not calculated.

Project Outcome

The net present value of the investment is $40,940. (See Table 8.) An investment is considered profitable if the NPV is positive; the higher the value, the more profitable the investment. The payback period for the investment is 10.8 months before taxes (i.e., the cost of the capital investment was recovered in 10.8 months of operation.) This is considerably less than the company's required payback period of 2 years.

Often times the operating period of equipment is longer than the depreciation period. This means the investment is more profitable because it continues to generate savings beyond the seventh year. For example, if the equipment operates for ten years, the after tax cash flow in each of the last three years would be approximately $16,000 (no depreciation tax shield). If this after tax cash flow is discounted over years 8, 9 and 10 of the investment, the net present value of the investment would be over $60,000.

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[26] Quotes from manufacturers of immersion and vapor degreasing systems, August 1994.

[27] City of Waltham representative quote, August 1994.

Table 8. Parker Hannifin Analysis One: Option Analysis Summary[23]

Financial Indicators	Value
Incremental cash flow*	$23,455
- Depreciation (7-year straight-line)*	$2,993
Taxable income*	$20,462
- Income tax (40%)*	$8,185
Net income*	$12,277
+ Depreciation	$2,993
After tax cash flow*	$15,270
Present value	$61,890
- Total capital cost	$20,950
Net present value	$40,940
Benefits / cost ratio	1.95
Payback period*	10.8 months

*These values are for the first year of the investment. Subsequent year's figures, except for payback, would be higher because the excise tax on 1,1,1-TCA is increasing.

Lessons Learned

- Aqueous degreasing used less water than vapor degreasing because of the large cooling requirements of the vapor degreaser.
- Costs for the disposal of waste oil decreased dramatically with the aqueous system because operators no longer had solvents available for cleaning equipment, hence no contaminated waste oil was generated.
- Electricity costs decreased with the aqueous system because of the larger load capacity.

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[23] Results obtained using *P2/Finance Software*, Tellus Institute, Boston MA, 1995.

Parker Hannifin: Analysis Two

Background

The second analysis was performed on Parker Hannifin's replacement of the CFC-113 vapor degreaser. The company uses a discount rate of 16% and a labor rate of $16.05 per hour. Parker Hannifin has assigned this project an economic lifetime of seven years.

Cleaning operations

Prior to installing the aqueous cleaning systems the company used a vapor degreaser with Freon TF (CFC-113). The production of this ozone depleting chemical was phased out by January 1995. Freon is currently no longer being produced but small quantities of recycled material remain available. Although the company switched to aqueous cleaning in 1992, it is assumed for this analysis that the investment was made in 1994. This is done so the financial impact of the investment can be analyzed using actual costs rather than using estimated costs.

The company decided to replace the vapor degreaser with one ultrasonic cleaning system and three spray washers. These two different aqueous cleaning systems were chosen because the demands for cleanliness of the parts differ in different stages of the production line. The spray washers do not clean as effectively as the ultrasonics system but they are less expensive. This system has two important advantages: (1) parts can be cleaned at different locations so there is little loss of time, and (2) the initial investment cost was lower than buying one large system to satisfy to highest need for cleanliness.

Capital Costs

Before the new cleaning system could be installed the vapor degreaser had to be cleaned and disposed. The cleaning resulted in 330 gallons (6 drums) of Freon-contaminated oil. The disposal cost of this oil was $230 per drum, $1,380 total.[29] The disposal cost of the vapor degreaser was estimated at $1,000[30]. The total cost for the clean out of the old cleaning system was $2,380.

The company purchased a Tally ultrasonic cleaning system with one wash tank, two tap water rinses, one deionized water rinse and a drying chamber. The system cleans both aluminum and steel parts whose main contaminant is rust inhibitor oil. The total cost for this investment was $33,964. Equipment installation and modification are included in the purchase price.

The company bought three ADF spray washers at a cost of $10,043.50 each. Two of the spray washers clean steel parts and the third cleans aluminum parts. The cleaning cycle includes a hot-air dry. Some parts are pre-washed in a mineral spirits bath; the costs of the pre-wash are not included in this analysis as they did not change by switching to the aqueous system. Adaptation and installation costs were included in the purchase price of the equipment. Total investment cost for the spray washers was $30,131. The capital costs are summarized in Table 9.

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[29] Laidlaw Environmental Corporation, North Andover, MA, August, 1994. This price is an estimation; the exact price is determined after a sample is analyzed.

[30] Capital Appropriations Request by Parker Hannifin.

Table 9. Parker Hannifin Analysis Two - Capital Costs

Capital Costs	Vapor Degreaser	Ultrasonic Tank	Spray Washers
Equipment purchase	NA	$33,964	$30,131
Disposal of old process	$2,380	NA	NA
Initial permits	NA	0	0
Building/process changes	NA	included in purchase	included in purchase
Total Capital Costs	$66,475		

Operating Costs

The operating costs are summarized in Table 10.

Chemicals and Wastes

The solvent used in the vapor degreaser was Freon TF (CFC-113). In 1992 the company used 18,200 pounds of Freon at a cost of $2.67 per pound. The total cost of Freon was $48,594. The 1994 price for Freon, including all taxes, is $11.23[31] per pound. Parker would have to pay $204,386 to clean the parts with Freon today.

Brulin Formula 815 GD, 3% by volume, is the detergent used in the ultrasonic tank. The detergent is replaced every three months, and the annual cost for this cleaner is $49 (4 gallons * $12.12/gallon).

Daraclean 282 GF at a 9% concentration is used in two of the spray washers that clean both aluminum and steel parts. The detergent is replaced every month. The annual consumption of Daraclean is 76 gallons per year, or $1,636[32]. Brulin 63 G at 9% concentration, is used in the third spray washer which cleans only aluminum parts. The detergent is replaced monthly which results in a detergent cost of $498 per year[33].

In 1992, 360,363 cubic feet of cooling water was used in the vapor degreaser. The sewer costs in the City of Waltham for 1994 are $0.0283 per cubic foot. The total cost of wastewater is $10,198. As stated previously, it was common practice for the machine operators to have containers of the chlorinated solvents at their work stations for periodic cleaning needs. As a result, the waste oil from these machines was contaminated with the solvent and required a higher price for disposal than if the oil had not been contaminated. In 1992, the company had to dispose of thirty three drums of Freon-contaminated oil, at a cost of $230 per drum, or $7,590.[34] The cost per drum of non-contaminated oil is $95. The difference in disposal cost of the waste oil is $4,455. This cost can be attributed to the Freon vapor degreasing system. There were two drums of spent Freon, 50% yield, sent to General Chemical Corporation. This resulted in

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[31] Van Waters and Rogers, Salem, MA, market price quote, August, 1994.

[32] Service Chemical, North Andover, MA, market price quote, July 1994.

[33] Brulin Corporation, Indianapolis, IN, market price quote, July 1994.

[34] Laidlaw Environmental Corporation, North Andover, August, 1994. This price is an estimation; the exact price is determined after a sample is analyzed.

no cost or gain for the company. Two filters on the vapor degreaser were replaced every week. The filters were disposed of along with other waste from the facility. It was impossible to estimate the cost of disposal of the filters from this single process. Therefore these costs were not included in this analysis. The total waste management cost for the vapor degreaser is $14,653 ($10,198 + 4,455).

Table 10. Parker Hannifin Analysis Two - Operating Costs

Operating Costs		Vapor Degreaser	Ultrasonic Tank	Spray Washers
Chemical Purchases	Freon (first year only)	$204,386	NA	NA
	Brulin	NA	$49	NA
	Brulin & Daraclean	NA	NA	$2,134
Waste management		$14,653	$19	$19
Safety training/equip		0	0	0
Insurance		0	0	0
Fees		$5,172	0	0
Filing paperwork time		$4,200	0	0
Annual permitting		0	0	0
Maintenance	labor	included in materials	$32	$64
	materials	$1,186	$24	$472
Production		$54,570	0	0
Utilities	elect.	$1,432	$702	$1,697
	water	$5,802	0	$4
	gas/steam	0	0	0
Total annual operating costs		$291,401	$826	$4,390
Incremental cash flow		$286,184		

There are no sewer costs for the wastewater of the aqueous cleaning systems because these small quantities of wastewater are evaporated. The aqueous cleaning systems are equipped with oil skimmers that skim oil from the cleaning bath water. Together the water-based cleaning systems produce 55 gallons per year of oil which costs $1.28 per gallon to dispose. This figure is divided over the cleaning systems (ultrasonics, spray washers and the immersion tank addressed in Analysis One) by using the number of parts each system cleans.

As in the first analysis, it was impossible to account for the individual cost of filters and residuals from the evaporator for this degreaser. The filters are disposed of along with other wastes from other processes at the facility. The wastewater from the immersion process is a negligible amount of the waste that is processed in the evaporator.

Regulatory Costs
The number of pounds of Freon used in the vapor degreaser required a fee under the Toxics Use Reduction Act (TURA). The fee paid for 1992 was $5,172. The environmental manager estimated that 210 hours were spent filling out TURA and SARA reports for the vapor degreaser in this analysis. At a wage rate of $20/hour the cost for time spent on paperwork is $4,200. Once the company stopped using Freon, they no longer were required to report under SARA or TURA.

As in the first analysis, due to the large quantity of water used in the vapor degreasing system, there would be some cost associated with the permitting and sampling requirements. However, the company was unable to provide any estimation of the time associated with these duties. For the purposes of this analysis, then, it was assumed that there was no difference in costs between the two systems with regard to permitting and sampling.

Production and Maintenance Costs
Operation of the vapor degreaser required an operator for 68 hours per week. The cost for labor was $54,570 per year (68 hours/week * $16.05 * 50 weeks). Even though the parts have to be cleaned longer in the new cleaning systems, they do not require a full-time operator because the cleaning process is integrated into the production process (i.e., the parts are cleaned in between other activities.) This worker was reassigned within the facility.

Based on information supplied by the company, the maintenance costs for the vapor degreaser totaled $1,186 per year. The maintenance of the ultrasonic system involves replacing the detergent and the filter. The cost of labor associated with replacing the filter every three months is $24 per year. The cost of labor for replacing the detergent four times per year is $32, two hours per year at a cost of $16.05 per hour.

The labor costs for maintenance of the three spray washers are $64 (4 hours per year). Each of the spray washers has a cartridge filter, $129 each, and 2 micron filters, $43 each. The cartridge filter is replaced once a year and the micron filter is replaced four times per year at a total cost of $473.

Utility Costs
The vapor degreaser used 360,363 cubic feet of cooling water at a cost of $0.0161/ft^3 in the city of Waltham, or $5,802. The water in both the ultrasonics system and the spray washers is recycled and replaced only when the detergent is replaced. Because the water from the rinse tanks is used for make-up water in the wash tank, the cost associated of water consumption for the ultrasonic system is negligible. The detergent is replaced only 4 times per year for a total water consumption of 15 cubic feet. The water cost for the spray washers is $4 (3 spray washers * 73 cubic ft water * $0.0161/ft^3).

Based on vendor estimates, the electricity cost for the vapor degreaser is $1,432. The ultrasonic system consumes 18 KW and operates 6 hours per week for 50 weeks. The cost of electricity in the city of Waltham is $0.13 /KWH. The yearly electricity cost for the ultrasonic tank is $702. The spray washers use 8.7 KW, and they operate 30 hours per week for 50 weeks costing $1,697 per year. Because the wastewater from the immersion process is a negligible amount of the waste processed in the evaporator, the energy costs of the evaporator that could be attributed to this process were assumed negligible and were not calculated.

Comparison to Company Financial Assessment

The Parker Capital Appropriations Request Original Submission for the one large immersion system to satisfy all cleaning needs showed a pre-tax rate of return of 81.6%. The request considered capital costs (including freight, installation and engineering support) and the cost of removal of the old degreasers. Operating costs considered were the cleaning agent, water use, direct labor, gas and electric utilities and maintenance. The following costs were not included in the company analysis: waste management costs, filing paperwork time and fees associated with the use of a listed chemical. These costs were quantified in the TCA analyses. These three categories of costs amount to $39,963 ($48 for the aqueous system), or 27% of the total capital cost of the proposed project. Without considering these costs, the company's original analysis vastly underestimated the success of this project.

Project Outcome

The net present value of the investment is $700,125. (See Table 11.) This means that the projects returns $700,125 more than the company requires for their investments. The payback period for the investment is 2.4 months (i.e., the savings of the new equipment were higher than the initial investment of $66,475 in less than three months). For each dollar invested Parker will receive ten dollars during the economic lifetime of the equipment.

Table 11. Parker Hannifin Analysis Two: Option Analysis Summary[35]

Financial Indicators	Value
Incremental cash flow (first year only)	$286,184
- Depreciation	$9,496
Taxable income*	$276,688
- Income tax (40%)*	$110,675
Net income*	$166,013
+ Depreciation	$9,496
After tax cash flow*	$175,509
Present value	$766,600
- Total capital cost	$66,475
Net present value	$700,125
Benefits / cost ratio (NPV/capital costs)	10.5
Payback period*	2.4 months

*These figures are for the first year of the investment. Subsequent year figures will increase (except payback) with the increase in the CFC excise tax.

Often times the operating period of equipment is longer than the depreciation period. This means that the profitability of the investment would increase even more. For example, if the equipment operates for ten

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[35] Results obtained using *P2/Finance Software*, Tellus Institute, Boston MA, 1995.

years, the after tax cash flow for the last three years would be over $170,000 with no depreciation tax shield. If this after tax cash flow is discounted over years 8, 9 and 10 of the investment, the net present value of the investment would be greater than $1,000,000.

Lessons Learned

- The aggressive tax on Freon and the cost of disposing of wastes containing Freon made the switch to aqueous cleaning very economical.
- By assessing the cleaning needs at various stages in the production process, Parker was able to greatly improve the profitability of the investment by purchasing remote cleaning stations.
- As in Analysis One, aqueous degreasing used less water than vapor degreasing because of the large cooling requirements of the vapor degreaser.

Market Forge Financial Analysis

Background

This analysis was performed on the metal cleaning processes at Market Forge. Three situations were analyzed: the vapor degreasing process with 1,1,1-trichloroethane, the petroleum naphtha solvent agitated immersion system ,and the pressure spray aqueous system. The company uses a discount rate of 16% and a labor rate of $15.00 per hour. The project has an economic lifetime of seven years.

Cleaning Operations

Market Forge previously used a 1,1,1-trichloroethane vapor degreasing system. Because of the requirements of the Labeling Act of 1993, Market Forge management decided to consider the elimination of 1,1,1-trichloroethane. On the recommendation of their vendor, Market Forge changed the cleaning process to use a naphtha solvent as a replacement to 1,1,1-trichloroethane. As stated in Chapter 2, the welders have never been satisfied with the cleaning abilities of the naphtha solvent system. Based on the technical evaluation for this project, Market Forge purchased an aqueous pressure spray washer. Total Cost Assessment methodology was used to compare both alternatives to the vapor degreasing system.

Capital Costs

The vapor degreaser was modified for the use of a naphtha solvent by removing the heating capabilities. This involved 5 hours of an electrician's time at a cost of $75.

With the new aqueous system, the vapor degreaser will be disposed. Estimated disposal cost of the vapor degreaser is $2,000. Purchase price of the American Metal Wash Pressure Spray Washer was $36,000. Installation required a contractor for plumbing and ventilation system work. The total amount of the contract was $6,000. Electrical supplies for installation totaled $2,400. All capital costs were obtained from Market Forge documents or personnel and are summarized in Table 12.

Table 12. Market Forge - Capital Costs

Capital Costs	Vapor Degreaser	Naphtha Solvent	Pressure Spray Wash
Equipment purchase	NA	0	$36,000
Disposal of old process	$2,000*	NA	NA
Initial permits	NA	0	0
Building/process changes	NA	$500	$8,400
Total Capital Costs	NA	$500	$46,400

*The $2000 disposal of the vapor degreaser is only incurred for the pressure spray wash system and not for the naphtha solvent system.

Operating Costs

The operating costs are summarized in Table 13.

Chemicals and Wastes

Based on Market Forge records, the 1993 consumption of 1,1,1-TCA was 4,397 pounds. The switch to the naphtha solvent was made on August 15, 1993. Using the factor of 32/52 weeks, the projected use of 1,1,1-trichloroethane for 1993 is 7,145 pounds. At the 1994 price of $1.53 per pound[36], the cost for 1,1,1 trichloroethane was $10,932.

In 1994, the company used 1,485 gallons (specific gravity = 0.770) of the naphtha solvent (CAS 64742-88-7) at a total cost of $4,321.

Based on testing in TURI's Surface Cleaning Lab, the detergent used in the spray washer is W. R. Grace's Daraclean 283. Each time the water is changed, 15 gallons of the cleaner will be used. It is expected that this water will be changed four[37] times a year at a total cost of $1,140.

The waste management cost associated with the vapor degreasing system was the waste solvent reclaimed by the vendor. In 1993, their was no cost to the company to dispose of 5,899 pounds of low yielding waste solvent.

The waste management cost associated with the naphtha solvent is the disposal of spent solvent. In 1994, the company disposed of 1,050 gallons at a total cost of $390.

The waste management costs associated with the aqueous cleaning process, without ultrafiltration are the four times a year disposal of the spent bath. This amounts to 1,200 gallons of high pH, oily wastewater at

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[36] Ashland Chemical Corporation, market price quote, July 1994. This price includes the excise tax on ozone depleting chemicals which is $0.435/lb for 1,1,1-trichloroethane. The tax will go up to $0.535/lb in 1995 and will increase by $0.045/lb each year thereafter. This tax increase is considered in the financial analysis.

[37] Estimation from American Metal Wash personnel based on similar applications.

a cost of $764 ($35 per drum)[38] In addition, the spray system produces oil wastes that are skimmed off the bath and filters that need to be replaced. The total disposal cost of oil skimmed from the cleaning system will be negligible compared to the amount of oil disposed of by the company for other processes.

Regulatory Costs

There are no regulatory impacts with the switch to either new system. However, if the company had continued to use 1,1,1-trichloroethane, they would have had to comply with the requirements of the Labeling Act of 1993. This law requires the labeling of all products made with ozone depleting substances, including 1,1,1-trichloroethane. In addition, if the company had continued to use 1,1,1-trichloroethane, they would have been affected by the Clean Air Act Amendments (CAAA). By discontinuing use of this substance, the costs of compliance with these laws were avoided. Since this financial analysis was performed when the process was not regulated by the CAAA, these costs were not quantified.

Production and Maintenance Costs

The vapor degreaser required an operator for 15 hours per week at a rate of $15 per hour ($11,250 per year). The solvent immersion system requires the same operator time. However, there is an added cost associated with the current system, because the welders have become so frustrated with the inability of the current system to clean the parts adequately that they have begun cleaning by hand. It is difficult to estimate the time that is being spent on this additional cleaning as it depends greatly on the frustration level of the welder. It is estimated that an additional 60 hours per week are spent on this cleaning, at an annual cost of $45,000. Even with this additional cleaning, the welders are not satisfied with the cleanliness of the part. It is estimated that the aqueous system will require an operator for 15 hours per week at a cost of $11,250 per year.

Based on Market Forge maintenance logs, the maintenance requirements for the vapor degreaser were two operators for one day every four months to clean out the tank. This costs $720 per year. The naphtha system requires one operator for one day every six months to clean out the tank. This costs $240 per year. The naphtha system filter requires changing every three months. The filters cost $10 each and the cost of labor for changing the filters is $15. (Total cost of maintenance for the current system is $240 + $40 + $15, or $295.)

Maintenance on the aqueous spray washing system requires the monthly changing of the cartridge filter and changing the bath four times a year. Cost of the filters are $5.75 each at a total cost of $69. Labor to perform filter and bath changes totals $45[39].

Utility Costs

There was no water used in the vapor degreasing process. There was no water associated with the naphtha solvent system. The aqueous system will use an estimated 1,330 gallons (1,200 gallons for bath changes and 130 gallons[40] for water replacement) of water per year at a cost of $120.

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[38] Based on Market Forge records for similar waste stream.

[39] Estimation of American Metal Wash personnel based on similar applications.

[40] Estimation from American Metal Wash representative based on similar applications.

Table 13. Market Forge - Operating Costs

Operating Costs		Vapor Degreaser	Naphtha Solvent	Pressure Spray Wash
Chemical Purchases	1,1,1-TCA*	$10,932	NA	NA
	Naphtha solvent	NA	$4,321	NA
	Daraclean 283	NA	NA	$1,140
Waste management		0	$390	$764
Safety training/equip		0	0	0
Insurance		0	0	0
Fees		0	0	0
Filing paperwork time		0	0	0
Annual permitting		0	0	0
Maintenance	labor	$720	$255	$45
	materials	0	$40	$69
Production costs		$11,250	$56,250	$11,250
Utilities	elect.	$7,020	negligible	$513
	water	0	0	$120
	gas/steam	0	0	negligible
Total annual operating costs*		$29,922	$61,256	$13,901
Incremental cash flow*			($31,334)	$16,021

*These figures are for the first year of operation. In the remaining years these figures will go up as the excise tax on TCA increases by $0.045/lb/yr.

The vapor degreaser vendor estimates that the 1955 model degreaser consumes 54 KW.[41] Operating 1000 hours per year and using an electricity cost of $0.13/KWH, the total annual cost of electricity for the vapor degreaser is $7,020. It is difficult to estimate the electricity consumption of the naphtha system. Some small amount of electricity is being used to provide agitation; this was assumed negligible. The cost of electricity for the aqueous spray washer amounts to $513. (23 amps * 220 V = 5060 W operating 15 hours/week = 780 hours per year = 3946.8 KWH @ $0.13/KWH = $513)

Project Outcome

Using the figures presented, the net present value of switching from vapor degreasing with 1,1,1-TCA to the naphtha solvent is *negative* $73,680. This is due mainly to the extra costs incurred as the welders are cleaning by hand. However, the full cost of continuing to use the 1,1,1-TCA system in the future is not adequately represented because of the missing cost of compliance with the Labeling Law and the Clean Air Act Amendments.

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[41] Estimation from Detrex representative.

Because estimating compliance with these two laws is so difficult, an alternate strategy was employed. Using an iterative process with the P2/Finance software, it was determined that in order to have a net present value in year seven of $0, a cost of $30,400 must be incurred by the vapor degreasing system. This means that the cost of compliance with the Labeling Law and the CAAA must be less than $30,400 in order to make staying with the 1,1,1-TCA vapor degreasing system economical. This result was discussed with Market Forge representatives. Though the actual cost of compliance was not calculated, the representatives were certain that the strict requirements of the Labeling Law and the CAAA could not be met with such a small investment amount. In addition, compliance costs alone do not account for any negative customer image that could be incurred by the company for compliance with the Labeling Law. Based on this information, this investment could be considered financially viable for Market Forge.

Even if the cost of compliance mentioned above is ignored in the switch from the 1,1,1-TCA vapor degreasing system to the aqueous pressure spray wash system, a net present value of positive $5,761 results. The main reason for the positive outcome in this situation is the high cost of 1,1,1-TCA and of electricity for the old vapor degreaser. (See table 14 for the option analysis summary.)

Table 14. Market Forge - Option Analysis Summary[42]

Financial Indicator	**Switch from Naphtha Solvent to Aqueous**	**Switch from 1,1,1-TCA to Aqueous**
Incremental cash flow*	$47,315	$16,021
- Depreciation (7-year straight-line)*	$6,629	$6,629
Taxable income*	$40,686	$9,392
- Income tax (40%)*	$16,275	$3,757
Net income*	$24,412	$5,635
+ Depreciation	$6,629	$6,629
After tax cash flow*	$31,040	$12,264
Present value	$125,359	$52,161
- Total capital cost	$46,400	$46,400
Net present value	$78,959	$5,761
Benefits / cost ratio	3.77	0.27
Payback period*	1.0 months	2.9 months

*These values are for the first year of the investment. Subsequent year's figures, except for payback, would be higher because the excise tax on 1,1,1-TCA is increasing.

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[42] Results obtained using *P2/Finance Software*, Tellus Institute, Boston MA, 1995.

Analysis of the switch from the naphtha solvent to the aqueous pressure spray wash system results a net present value of positive $78,959. The reason for the positive outcome in this situation is the additional cost incurred as the welders perform cleaning duties to make up for the inability of the current system.

Lessons Learned

- The excise tax on 1,1,1-TCA made the switch away from its use more economical.
- Cost for electricity for the 1955 vapor degreaser was more than for the new aqueous pressure spray washer.
- Incomplete technical evaluation of the "drop in" replacement cost the company an additional $45,000 per year.
- P2/Finance software can be used in an iterative process to test various scenarios when estimations are difficult to make.

Company A Financial Analysis

Background

This analysis was performed on the potentially feasible options identified for Company A. The company uses only pay-back period as a financial indicator and a labor rate of $30 per hour. To calculate other financial parameters a discount rate of 16% was used. The economic lifetime of the project was estimated at seven years.

Cleaning Operations

The company currently uses TCE in a vapor degreaser. Finding a suitable cleaning alternative for this company is very challenging because of the high demands for cleanliness and the wide variety of substrates and contaminants. The aqueous based cleaners in the first two analyses, for example, were required to remove a relatively well-known group of contaminants from one or two substrates. An alternative cleaning system for Company A must be able to remove a large number contaminants from a variety of substrates. In addition, the sizes of parts cleaned by this company vary greatly and the new system must be large enough to accommodate the largest parts.

In recent years Company A has experienced an increased demand for cleaning. Previously the company's suppliers performed more of the initial cleaning themselves but since costs for chlorinated solvents have increased and CFCs were phased out, many of their suppliers are simply not cleaning anymore.

Based on the technical evaluation (see Chapter 2) four alternatives will be analyzed financially. The first alternative is using a plastic media blast technique for 25% of their current cleaning needs and retrofitting their TCE vapor degreaser to satisfy the other 75%. The second alternative is using fragmented CO_2 technology for 100% of their current cleaning needs. The third alternative is to use an ultrasonic aqueous cleaning tank to satisfy 25% of their cleaning needs and retrofit the TCE vapor degreaser to satisfy the other 75%. The fourth option is to purchase a new vapor degreaser, using TCE, for 100% of their cleaning needs.

Capital Costs

For the first three analyses, there will be no disposal costs for the vapor degreaser because it will be retrofitted and used for the bulk of the cleaning needs. Retrofitting requires cleaning the degreaser. For these analyses, it was assumed that one drum of TCE will be disposed of from the cleaning at a cost of $250[43]. Retrofitting the current vapor degreaser includes adding 8 inches of freeboard and a chiller at a cost of $19,000[44]. Retrofitting is necessary for the plastic blast and the ultrasonic wash alternatives. For the fragmented CO2 and the new vapor degreaser alternatives, it is necessary to dispose of the old degreaser at an estimated cost of $2,000[45]. (Disposal also requires the clean-out cost of $250.)

Capital costs for a 36" by 48" plastic blast cabinet are $8,775. Capital costs for the fragmented CO_2 system are estimated at $80,000 for a system that would be able to accommodate all of Company A's cleaning needs. A 100 gallon ultrasonics tank with oil skimmer from Blue Wave Ultrasonics in Davenport, Iowa costs $24,500. A new "closed" vapor degreaser would cost $60,000. The capital costs are summarized in Table 15.

Table 15. Company A - Capital Costs

Capital Costs	Vapor Degreaser	Plastic	CO_2	Sonics	New Degreaser
Equipment purchase	NA	$27,775	$80,000	$43,500	$60,000
Dispose of/clean old process	NA	$250	$2,250	$250	$2,250
Initial permits	NA	0	0	0	0
Building/process changes	NA	0	0	0	0
Total Capital Costs	0	$28,025	$82,250	$43,750	$62,250

Operating Costs

The operating costs are summarized in Table 16.

Chemicals and Wastes

Based on company records, the 1994 consumption of TCE was 11,152 pounds. At the current price of $0.83 per pound, the annual cost is $9,256. Two drums of contaminated TCE were sent to a reclaimer at a cost of $500[46].

Retrofitting the old degreaser will decrease the use of TCE by 50% as estimated by a representative of Degreasing Devices Company. In addition, use will be decreased by 25% by diverting this amount of the cleaning load to an alternate system. This results in a projected use of 4,182 lbs TCE at a cost of $3,471. Waste costs for the retrofitted degreaser are assumed to remain the same for this analysis.

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[43] Estimation from company representative.

[44] Estimation by representative of Degreasing Devices Company.

[45] Estimation based on similar applications.

[46] General Chemical Corporation, Framingham, MA, market price quote, August 1994.

The plastic media blast option requires the purchase of an estimated 300 pounds of plastic media at a cost of $510. Disposal of the dirty media as non-hazardous waste will cost approximately $50.[47]

It is difficult to estimate the cost of CO_2 for the fragmented system because no operating data are currently available for similar systems and applications. A rough estimate of $3,000 per year was made.

Table 16. Company A - Operating Costs

Operating Costs		Vapor Degreaser	Plastic	CO_2	Sonics	New Degreaser
Chem. Purch.	TCE	$9,256	$3,471	0	$3,471	$4,628
	plastic	NA	$510	NA	NA	NA
	CO_2	NA	NA	$3,000	NA	NA
	235	NA	NA	NA	$532	NA
Waste management		$500	$550	0	$519	$1500
Safety training/equip		0	0	incl purchase price	0	0
Insurance		0	0	0	0	0
Fees		$1,100	0	0	0	0
Filing paperwork time		$1,050	0	0	0	0
Annual permitting		$300	0	0	0	0
Maintenance	labor	$60	$420	$360	$92	$60
	materials	0	0	unknown	$24	0
Production		$30,000	$60,000	$60,000	$30,000	$30,000
Utilities	electricity	$2,600	$1,950	$2,600	$2,400	$910
	water	0	0	0	$40	0
	gas/steam	0	0	0	0	0
Total annual operating costs		$44,866	$66,901	$65,960	$37,078	$37,098

Assuming the aqueous bath in the ultrasonics tank is changed four times a year,[48] the 7% Daraclean 235 will cost $532. There are no wastewater costs associated with this option because Company A has a wastewater treatment unit that treats all the wastewater used at the facility. Waste oil skimmed from the system will be disposed of with other oily waste from the facility so it is assumed negligible.

Based on an estimation by a representative of Degreasing Devices Company, the new vapor degreaser will use an estimated 50% of the total amount of TCE currently used. This would cost Company A $4, 628 at the current demand. Based on their experience with a manually operated sand blasting process, Company

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[47] Estimation from a representative of Dawson-McDonald Company.

[48] Estimation based on similar applications.

A representatives estimated that the production costs of the plastic media blast system and the fragmented carbon dioxide system would be twice that of the vapor degreasing system.

Regulatory Costs

Because the use of TCE is above the 10,000 pound threshold set by the Massachusetts Toxics Use Reduction Act, a fee of $1,100 must be paid. In addition, planning for the reduction in use or byproduct production must also be completed. TCE is not the only chemical for which Company A currently plans. The company estimates that $750 can be attributed to each chemical for planning and continuing education time and fees. Due to the use of TCE, Company A currently files an Air Source Registration Report with the Massachusetts Department of Environmental Protection. The fee associated with this permit is $300 and the company estimates that 10 hours is necessary to complete paperwork for this permit at a cost of $300. Filing of the Air Source Registration Report would not be required with the alternative cleaning systems.

Production and Maintenance Costs

For the current system, an operator is required for 20 hours per week to operate the vapor degreaser. At an hourly rate of $30 this cost is $30,000 per year (50 week year). The operator performs other functions during the cleaning cycle. The ultrasonic system and the "closed" vapor degreaser would require the same production costs as the current system. It is estimated that the production costs of the plastic media blast system and the fragmented carbon dioxide system would double as both processes are more labor-intensive that the vapor degreasing process.

Based on company maintenance records, maintenance on the vapor degreaser is performed once per year for 2 hours at a cost of $60. This maintenance cost would be the same for the retrofitted degreaser and the new degreaser.

Maintenance associated with the plastic media blast option involves cleaning the dust bag and maintaining the gloves and glass. The vendor estimates that 12 hours per year will be required at a cost for labor of $360. When maintained properly, the dust bags do not have to be replaced.

Maintenance associated with the fragmented carbon dioxide process is changing the HEPA filters. The vendor estimates that 12 hours per year will be required at a cost of labor of $360.

There is a small amount of maintenance associated with the ultrasonic system to change the filters; this totals an estimated $32 in labor and $24 in materials[49].

Utility Costs

Vendor estimates of electricity requirements for the current vapor degreasing process are $2600. (20KW * 20 hrs/wk * 50 wk/year @ $0.13/KWH). The retrofitted degreaser would be used for 750 hours per year at a cost of $1950.

The utility costs of the plastic media blast process are negligible as 45 cfm air is all that is required. Operating costs are not currently available for the fragmented carbon dioxide system. For the purposes of this analysis, it was assumed that the electricity cost for operation of the current vapor degreaser and operation of the fragmented carbon dioxide system would be the same. The ultrasonic system will operate

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[49] Estimation based on similar applications.

50 hours per year at 18 KW (from vendor product literature) for a total cost of $450. The vendor of the new vapor degreaser estimates electricity costs for 1000 hours per year at $910.

A water cost of $40 is attributed to the ultrasonic system (400 gallons per year). This is the only alternative that uses water.

Project Outcome

None of the options evaluated resulted in a positive net present value at year seven. The net present values at year seven for the options are ($75,097) for the plastic blast and retrofitting, ($114,382) for the fragmented carbon dioxide, ($14,685) for the ultrasonic system and retrofitting and ($29,061) for the new vapor degreaser. This is due to the fact that TCE is not currently subject to taxes as in the cases of 1,1,1-TCA and CFC-113 in the previous examples. In addition, the extra cost of production for the blasting techniques made those options much less financially favorable than the other options. The financial analysis is only one part of the information necessary to make the decision to stop using TCE for vapor degreasing. There was no attempt in this analysis to estimate the cost of compliance with the Clean Air Act Amendments. Company A may decide to invest in the new technology in order to avoid future compliance costs.

Lessons Learned

- Using the TCA methodology with estimated values early in the decision making process can help narrow the choices of technically-feasible alternatives.
- Manual blasting technologies require more labor, and associated cost, than vapor degreasing.
- At its current state of regulation, TCE is relatively inexpensive to use and dispose of in quantities less than thresholds for additional regulation.

Conclusions

For Parker Hannifin Analysis One, the biggest difference between the two systems, as a percent of total operating costs, is in the waste management category. Waste management costs for the vapor degreaser have more than doubled in two years time. The majority of the cost for waste management in the vapor degreasing system is from the additional cost of disposing of oil contaminated with 1,1,1-TCA or METH and the disposal of a large volume of cooling water. In the new aqueous system, both of these costs are avoided. Again as a percent of total operating costs, the cost of maintenance is greater for the aqueous system even though the actual maintenance costs for the two systems are nearly equal (See Table 17). Although chemical purchases do not represent a large percent of total operating costs for the vapor degreasing system, prices for these chlorinated solvents have risen sharply in recent years. The costs of 1,1,1 TCA and methylene chloride have doubled in two years and five years respectively. It is known that the cost of 1,1,1-TCA will continue to rise and it is a good assumption that methylene chloride prices will rise also. Other savings result from the reduction in utilities consumption. In some situations, electricity costs are higher for aqueous cleaning systems than for vapor degreasers. However, in this case the immersion tank only operates for 20 hours per week and the vapor degreaser operated 68 hours per week.

The vapor degreaser cleaned smaller loads more frequently and the immersion tank cleans larger loads less often.

For Parker Hannifin Analysis Two, the largest differences between the two systems, as a percent of total operating costs, are in the waste management and utilities categories. The price for a pound of Freon has increased by more than 400% in the last two years. Although as a percent of total operating costs, the utilities category is higher for the aqueous system (46.1%) than for the vapor degreasing system (2.5%), the actual costs for utilities for the aqueous system is much lower ($2,403) than for the vapor degreasing system ($7,234). See Table 17. Furthermore, the waste disposal costs for wastes containing Freon have increased by 50% percent. Large savings in operating costs are realized because the aqueous cleaning system does not require a full-time operator. A careful analysis of the cleaning needs allowed the company to save money on the investment by buying separate systems designed for specific cleaning needs. The alternative would have been to design the cleaning system to the highest need for cleaning and size the ultrasonic system to that need which would have increased the investment costs dramatically.

For the Market Forge analysis, as a percent of total operating costs, the vapor degreasing system is higher than the aqueous system in the categories of chemical purchases and utilities, and lower in the category of production. (See Table 17). As stated previously, the cost of 1,1,1-TCA has doubled in two years and will continue to rise due to the excise tax of $0.045/lb/yr. Therefore, chemical purchases as a percent of total operating cost would be expected to increase beyond the 36.5% calculated for 1994. The cost of chemicals for the aqueous system as a percent of total operating cost is only 8.2%. Due to the arrangement that Market Forge had with their 1,1,1-TCA supplier, the cost of waste management, as a percent of totall operating cost, is slightly (though not significantly) higher than for the aqueous system. It is expected that the cost for waste management of 1,1 1-TCA will increase as the phase-out approaches. There is a large difference in production costs, as a percent of operating cost, between the two systems. Production costs for the vapor degreaser are 37.6% and for the aqueous system are 80.9% of total operating costs though the actual annual cost for both systems is the same ($11,250). As a percent of total operating costs, the utilities category is lower for the aqueous system (4.6%) than for the vapor degreaser (23.5%).

The first two analyses in this report are clear examples of success stories of switching from chlorinated solvent cleaning to aqueous cleaning (net present values of $40,940 and $700,125 respectively). In the third analysis, the net present value is much less than in the first two analyses. However, the net present value for this investment is still positive and the cost of compliance with the CAAA and the Labeling Law was not included. If this cost was included, the NPV of this value would dramatically increase.

There are two major differences between the first three analyses and the final analysis (Company A). First, Company A has much more complex demands for the cleaning system because of multiple contaminants and substrates whereas the cleaning systems in the first three analyses remove a relatively known group of contaminants. Second, the first three analyses involved solvents that were strictly regulated whereas, TCE is not as strictly regulated because it is not an ozone depletor.

It should be noted that costs for safety equipment, training and insurance did not influence the outcome of the projects. There were no training programs that focused solely on the chlorinated solvents. Training specific to the chlorinated solvents was included with other operator training. There were no reductions in insurance cost at either company. One company was self insured and did not adjust the insurance costs because of the new cleaning system, and insurance premiums for the other companies would not be affected by the alternative cleaning system.

Additional benefits of environmentally-sound investments decisions not quantified include:

- customer satisfaction; customers increasingly demand environmentally sound products and production processes,
- public image,
- reduction in exposure to communities and workers,
- avoided future liability.[50]

These benefits were not included because they are difficult to quantify and because none of the companies in this project had attempted to quantify them.

Table 17. Cost Categories as a Percent of Total Operating Costs

Category	Parker Hannifin -1		Parker Hannifin - 2		Market Forge	
	Vapor deg.	Aqueous system	Vapor deg.	Aqueous system	Vapor deg.	Aqueous system
Chemical purchases	6.2	25.9	70.2	42.0	36.5	8.2
Waste management	60.9	0.4	5.0	0.7	0.0	5.5
Regulatory compliance	0.0	0.0	3.2	0.0	0.0	0.0
Maintenance	3.9	44.6	0.4	11.3	2.4	0.8
Production	0.0	0.0	18.7	0.0	37.6	80.9
Utilities	29.0	29.2	2.5	46.1	23.5	4.6

Environmental costs have become significant factors in investment decisions. Prices for chemicals have increased and will continue to increase because of taxes and fees on use. Waste management costs will continue to increase as regulations become more strict. Insurance companies often increase their premiums for companies with an environmental record.

All of these factors point to the need for a different perspective on investments in environmentally sound products and production processes. The goal of this report was to recognize all benefits and costs of both old and new systems. This was done by expanding the cost inventory and directing costs and benefits directly to processes and products. Often times these costs were hard to quantify because information was not easy to obtain and indirect costs had to be divided over multiple cleaning systems.

The question is whether expanding cost inventory and direct allocation of costs is enough to recognize all aspects of investments in the environment. Where relevant the time horizon of the project was increased to show long term benefits. This was feasible because the economic lifetime of investments is, for the most part, longer than its depreciation period. Net present value analysis was used because it allows for expansion of the time horizon of an investment, and it is more complete because it accounts for the time value of money.

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[50] Northeast Waste Management Officials' Organization, Massachusetts Office of Technical Assistance, "Improving Your Competitive Position: Strategic and Financial Assessment of Pollution Prevention Projects", 1994.

One disadvantage of the net present value method is that any new investment is evaluated against an alternative of not undertaking the new investment. This status quo alternative often has a significant influence on the project outcome even if it is not realistic.

The Total Cost Assessment methodology was used in three different ways in this section. It was used to prove the economic viability of projects that had already been implemented as in the two Parker Hannifin examples. It was used to estimate compliance costs in order to obtain a net present value of zero in the seventh year of the investment. This compliance cost could then be compared to company estimates of the actual cost so that a decision could be made whether to implement the alternative. And finally, the TCA methodology was used early in the decision-making process to narrow the choices of alternatives.

Chapter 5
Substitution Analysis

Introduction

Every day people in manufacturing facilities make decisions concerning their use of chemicals. These decisions are driven by many factors including the desire to develop new products, regulatory requirements, the need for improved technical and cost performance of current processes, and higher level management decisions that force changes at the production level. The ability to make informed decisions about these alternatives is important for the health and safety of the workers and the public and for the protection of the environment. While many decision making methodologies have been developed to help people make informed decisions, it is recognized that there is no generally agreed on and reliable method for evaluating the risk of alternative chemicals as a consideration in substitution decisions. As a result, the effect of these decisions on worker or public health or on the environment is rarely considered, especially by small and medium sized firms.[51]

The idea of addressing all environmental aspects of processes and products, the so-called "cradle to grave" approach, into the decision making process is over twenty five years old. Originally, these efforts were termed life cycle analysis (LCA). In 1969, Coca-Cola sponsored a study that analyzed packaging for its environmental, energy and financial impacts from cradle to grave. Since then, LCA has developed into an important decision-making tool. Much work continues to improve the effectiveness of LCA, but its use requires large investments of time and money and is, therefore, used mainly by large companies and government agencies making significant decisions.

Appendix J at the end of this report contains an annotated bibliography of many of the methodologies that have been developed for the purpose of making informed decisions concerning substitutes. Most of these methodologies, including LCA, still require an extensive amount of data and some contain elaborate ranking systems. This requires a large investment of time and money for the person faced with making a decision. For the small and medium sized business person, the luxury of time and money is not practical. In addition, many of these methodologies do not incorporate information about worker health and safety and thus have the potential to result in the shifting of risks. The goals of the substitution analysis, as described here, are 1) that it be practical for use by people in small and medium sized businesses and 2) that it include worker health and safety concerns along with the environmental and public health considerations.

In order to satisfy the goal of practicality, the substitution analysis approach must relax some standards for detail and scoring that are found in other methodologies. The thinking behind substitution analysis is that each company faced with a decision must make that decision based on their own set of circumstances and their own driving forces. This means that most of the work will have to be done by the person making the decision. Substitution analysis will provide the framework, but it will not do the work. Unfortunately, this

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[51] Gray, George M. and Jennifer Kassalow Hartwell, "The Chemical Substitution Tree", Pollution Prevention Review, Spring 1995, pp 7-17.

approach does not result in the ideal of a quick and easy software package for decision making. However, it does result in a framework that can be used to help individuals make the important decisions. One source of information for this framework comes from many hours of experience with Massachusetts Toxics Use Reduction Planners[52]. The individuals making toxics use reduction decisions, especially those in small and medium sized businesses, come from a wide variety of educational backgrounds and may not always possess adequate knowledge concerning potential hazards of alternative technologies. This framework is meant to fill in the potential gaps in the education of these individuals. The transferability to similar situations is obvious.

Substitution Analysis and the Decision Making Process

In evaluating potential substitutes, the overall decision making process has at least three components: technical evaluation, cost assessment, and environmental, health and safety and regulatory considerations. While the technical and cost assessments, addressed earlier in this report, are not simple, the third step, here termed substitution analysis, is perhaps the most difficult. First a chemical inventory must be taken (e.g., number of pounds of TCE released to the air), then potential hazards must be assessed, and finally a judgement must be made concerning the impact. When performing a substitution analysis, a statement from work on life cycle assessment must be remembered, "any interpretation beyond the 'less is best' approach is subjective".[53]

Each facility and each project may have different priorities for making decisions about whether or not to implement a particular chemical or process change. Faced with the phase-out of CFC's and 1,1,1-TCA, the technically proven excellent degreasers, companies are faced with a wide variety of options. It is possible that there are many technically feasible alternatives and it is possible that many options are also desirable economically . In this case, a substitution analysis could provide crucial information on which to base a decision. However, there may not always be so many good options. Some decisions may be driven solely by interest in improving environmental or safety performance. In this case, the substitution analysis could be performed on likely candidates even before the technical and economic feasibility studies. For the applications considered her, for example, supercritical carbon dioxide would have failed based on economic feasibility alone and perfluorocarbons would have failed based solely on their regulatory uncertainty. Other options are not so clear cut.

Parker Hannifin chose to evaluate only aqueous cleaning processes. Inspired by a management mandate, they performed a very non-systematic substitution analysis and decided to purchase the least controversial system possible. The technical feasibility and economics were important but the cost of the system was not the main driving force for change.

Market Forge, also inspired to changed by a management mandate, chose to rely on supplier information which resulted in a different potential worker health problem (i.e., the exposure of the welders to fumes) than was present with the chlorinated solvent. This experience resulted in a general distrust of all the available solvents that were potential replacements for the 1,1,1-TCA process. Had a technical assessment been conducted on the naphtha solvent, it would have failed without need for information about its economic, environmental or safety performances.

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[52] As mandated by the Massachusetts Toxics Use Reduction Act , the Toxics Use Reduction Institute trains individuals prior to certification as Toxics Use Reduction Planners.

[53] "Life Cycle Assessment: Inventory Guidelines and Principles" EPA Office of Research and Development, February 1993.

In the cleaning situation at Company A, many options appear technically feasible: plastic media blast, fragmented carbon dioxide blast and aqueous cleaning with ultrasonics. In this case, a substitution analysis of the alternatives will provide additional crucial information to the decision making process.

Performing a Substitution Analysis

In order to perform a substitution analysis, a worksheet was developed listing all of the various data that should be considered when making an informed decision about the environmental, health and safety aspects of a new process. The worksheet is included as Appendix E. The worksheet includes all of the criteria (defined in Appendix F) that the methodologies reviewed for this project suggested be taken into consideration. It was developed with the specific application of solvent substitution in mind. It is more broadly applicable, but may require some modifications for other purposes. For simplicity, the worksheet, as presented here, allows the comparison of only two alternatives. It can be expanded to allow multiple comparisons, if desired. It is the intent of this exercise to identify areas of potential concern so that companies can make informed decisions. To make this analysis more practical, raw material production, recycling and fate after disposal were not considered.

The various categories on the worksheet allow either specific numerical values to be entered (e.g., permissible exposure limit in ppm), or a choice of alternatives (e.g., yes, no, suspect). In either case, the values entered for each alternative can be compared to determine whether, for this factor, the change to the alternate system is a positive or a negative. A column is also included to indicate whether the factor under consideration is judged to be important for this particular analysis (relative hazard high/medium/low).

Using the Worksheet

There are five steps involved in using the worksheet to assess the environmental, health and safety issues for alternative processes.

1. Inventory the chemical use and discharges for processes.
2. Decide which areas of concern these inventory results suggest.
3. Within each area of concern, find values for the criteria for both systems.
4. Decide whether a change to the new system would result in a positive or negative impact.
5. Make judgements about the relative hazard for each criteria for which values were found.

The positive and negative impacts can then be assessed for the alternate process examined. Many processes can be compared in the same manner. Each step will now be described in more detail using Market Forge's original decision between 1,1,1-trichloroethane and the naphtha petroleum distillate as an illustration. See the worksheet in Appendix G for actual values.

First, the chemical inventory must be taken. The inventory requires information about chemical use, releases and transfers. Much can be learned from this information. In this case, it is readily apparent that the discharge to air of both of these substances is the largest area of concern.

The decision maker must then evaluate the chemical use pattern in the production process to determine in which of the following areas these inventory results will most likely have significant effect (for the current process and the alternative).

- potential for inhalation
- potential for ingestion
- potential for skin contact

- potential for eye contact
- potential as a carcinogen, teratogen, mutagen, or other specific effect
- potential for exposure to physical hazards
- potential for release to air
- potential for release to water
- potential for release to land
- important physical and chemical characteristics of the material
- regulatory issues
- energy and resource information

In this case, some of the 1,1,1-TCA is captured in an exhaust system and vented to the outside, but worker exposure is still likely because it is an open system so the potential for inhalation is high. Ingestion is not likely to occur so this category can be ignored. Skin contact and eye contact are not likely, but there is potential for some exposure so this category was explored further. Physical hazards are of particular interest to the decision maker in this example. As stated earlier, the results of the inventory showed a great potential for release to air.

The potential for release to water was not included due to the very low probability of occurrence. Based on the inventory information alone, there was a potential for release to land. However, the decision maker knows that the material is being reclaimed, so this category was not explored further. It was assumed for this example that the decision maker had particular interest in other important characteristics, regulatory issues and energy and resource information. Equipped with this information, the decision maker can save time by assessing the criteria only for the issues of concern.

Under the category of potential for inhalation, there are five criteria. (The criteria are defined in Appendix F.) The only criterion for which data are available for both chemicals is the permissible exposure level or PEL. For 1,1,1-trichloroethane, the PEL is 350 ppm and for the naphtha solvent, the PEL is 100 ppm. From the definitions, a lower PEL is less desirable, so the naphtha solvent is less desirable using this criterion. Under the potential for skin contact category, it is reported that 1,1,1-trichloroethane causes dermal irritation, and naphtha solvent does not. Under the category of potential for eye contact, likewise, it is reported that 1,1,1-trichloroethane causes eye irritation and naphtha solvent does not. Under the specific effects category, 1,1,1-trichloroethane is a suspected teratogen, carcinogen and mutagen while naphtha solvent has none of these characteristics. For the physical hazards category, we are able to compare values for the LFL/UFL, values for 1,1,1-trichloroethane are 7.5/12.5% and for the naphtha solvent, 1/6%. From the definitions, the low value of 1% for the LFL of the naphtha solvent presents a greater potential hazard. From the release to air category, we see that 1,1,1-trichloroethane is a global warming material and an ozone depletor whereas the naphtha solvent has neither of these characteristics. When comparing evaporation rate in the "other important characteristics" category, it is found that naphtha solvent has a value of 6 and 1,1,1-TCA has a value of 151 (ether=1). From the definitions, higher is less desirable. Comparison of vapor pressures results in the following, 1,1,1-trichloroethane is 100 mm Hg @ 20C and the naphtha solvent is 0.5 mm Hg @ 20C. From the definitions, higher is less desirable. (i.e., 1,1,1-TCA is more volatile resulting in higher airborne concentrations.) On the issue of regulatory outlook, 1,1,1-trichloroethane is a HAP and a VOC and the naphtha solvent is neither.

The important findings from the comparative analysis are summarized in Table 18. For illustrative purposes, assume that the most significant criteria are carcinogen, teratogen, mutagen, HAP, VOC, NESHAP. The new system had positive values for each of these so that, in this case, the tradeoffs of the substitution are clear. In an actual case, the company would have to look at all of the relevant factors and decide whether the tradeoffs were worth the benefits. In this example, the positives are definitely the fact that the naphtha solvent is not a suspected teratogen, mutagen or carcinogen, has a low evaporation rate and is not currently included on any regulatory lists. However, the naphtha solvent is flammable and has a lower PEL than 1,1,1-TCA. This analysis highlights areas of concern and allows planning for minimizing the potential for problems.

A similar analysis was performed for Company A. The worksheets used for the analysis can be found in Appendix H. Because this situation is not the simple comparison of two different solvents, the worksheet was used more to highlight potential problems of each option rather than to obtain a side by side comparison. Table 19 shows the results of this comparison.

Table 18. Summary of Comparison of the Substitution of 1,1,1-Trichloroethane for Naphtha Solvent

Criteria	**1,1,1-trichloroethane**	**naphtha solvent**	**positive or negative effect of substitution**
PEL (ppm)	350	100	negative
dermal irritation	yes	no	positive
eye irritation	yes	no	positive
teratogen	suspect	no	positive
carcinogen	suspect	no	positive
mutagen	suspect	no	positive
LFL/UFL (%)	7.5/12	1/6	negative
global warming	yes	no	positive
ozone depleting	yes	no	positive
evaporation rate (ether = 1)	151	6	positive
vapor pressure (mm Hg)	100	0.5	positive
HAP	yes	no	positive
VOC	yes	no	positive

Table 19. Summary of Substitution Comparison of the Options to Replace TCE

Criteria	TCE	Plastic	CO_2	Daraclean 235 (triethanolamine, 2%)
PEL (ppm)	50	none	5000	none
TLV (ppm)	50	none	5000	5 mg/m^3 [54]
respiratory irritant	yes	no	asphyxiant	yes
dermal irritation	yes	no	yes	yes
ocular irritation	yes	no	no	no
carcinogen	suspected	no	no	no
teratogen	suspected	no	experimental	no
mutagen	suspected	no	no	no
noise generation	minimal	yes	yes	yes
high pressure	no	yes	yes	no
high temperature	yes	no	no	yes
global warming	no	no	yes	no
ozone depleting	no	no	no	no
photochemical smog	yes	no	no	no
ecological effects in water	no	no	no	possibility
HAP	yes	no	no	no
VOC	yes	no	no	no

The concerns that are highlighted by the substitution analysis for the use of TCE are that it has suspected chronic effects of carcinogenicity, teratogenicity and mutagenicity. It is an irritant to the respiratory tract, the skin and the eyes. It contributes to photochemical smog and is therefore regulated as a HAP under the CAAA.

The option of plastic media blast introduces the potential worker safety issue of a pressurized system; the current system also is pressurized. If this option was chosen, the workers would need to be trained in its use and warned of the possible dangers. This process also introduces additional noise into the workplace that must be taken into account.

When assessed as a substitute for TCE, the option of fragmented CO_2 technology also introduces the issue of a pressurized system and the potential for noise beyond the OSHA allowable level. In addition, CO_2 is an asphyxiant but with a high TLV so that the potential for over-exposure is low. CO_2 is an experimental

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[54] Note that the units for the TLV for triethanolamine are mg/m^3. This represents exposure in the liquid (droplet) form and cannot be compared to values for vapor exposure measured in ppm.

teratogen and contributes to global warming. When assessing the data gathered, the decision maker must keep the information in context. In the case of the fragmented CO_2 system, it is a closed system for the worker and the potential for worker exposure is much less than for the open vapor degreaser for instance. The CO_2 will exhaust to the atmosphere, where its concentration will be quickly diluted.

From the analysis of the aqueous system, it is learned that one of the components of the detergent is a respiratory and dermal irritant. However, this component is only 2% of the formulation. The aqueous process operates at high temperature and creates an aqueous waste where the other options do not. The detergent product literature claims biodegradability.

Limitations

A substitution analysis performed using the procedure outlines here is qualitative in nature. Two alternatives are compared using a variety of criteria, but no final "score" is calculated. In order to quantify the analysis, numerical scores would first have to be assigned to each of the criteria. For example, the PEL could be given a score of 1 if it was greater than 200 ppm, 2 if it ranged from 100-200 ppm, 3 if it ranged from 25-100 ppm, 4 if it ranged from 5-25 ppm, and a score of 5 if it was less than 5 ppm. Once each category was scored, the relative importance of each category would have to be determined. For example, it might be decided that the PEL was twice as important as the IDLH; in this case, the PEL score would be multiplied by two.

Once such a scoring scheme was developed, each alternative could be given a numerical value, and the "best" alternative could be identified. Although this quantitative approach would appear to have value, one problem is the allocation of scores and weights in a scientifically valid manner. TURI is currently pursuing research in quantitative substitution analysis.[55]

Conclusions

The substitution analysis described here is thus qualitative in nature. It allows the comparison of alternatives using many criteria, but a final decision as to the best alternative, must be made by the investigator. This approach is meant to highlight both the areas of concern for alternative substitute processes and areas where those substitutes are clearly superior to the current process. This worksheet will aid the decision maker to make informed decisions without overlooking important issues. Unfortunately the worksheet will not make the decisions and it does require work to obtain the information, but only in a perfect world could there be decisions without tradeoffs and software to make the decisions. Appendix I contains a list of useful references for obtaining the information for the substitution analysis. Appendix J contains an annotated list of relevant work on substitution analysis.

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[55] Tickner, Joel, "Development of a TUR Options Assessment Tool", TURI Research Fellow Project, 1995-96.

Chapter 6
Overall Conclusions

This project studied three principle evaluation steps that inform the decision-making process for chemical or process substitution: technical evaluation, economic evaluation, and environmental, health and safety evaluation. Each evaluation step is important in determining the viability of a substitute technology in comparison to the existing technology as well as other competing substitute technologies. The steps can be performed in any order and their relative importance can vary from project to project. The technical evaluation of a potential replacement process for an existing technically successful process is often the most important evaluative step. The success or failure of the technical evaluation determines whether the alternative process will be evaluated further. Complete technical evaluation at the lab and pilot scale levels can lead to a smooth transition into the new process. An incomplete technical evaluation can lead to unforeseen problems with the incorporation of the new process and necessitate further evaluation following installation. An economic evaluation of a technically-proven chemical or process provides valuable information affecting the decision to implement or not. Traditional financial analysis, however, often includes only the costs directly associated with production, such as labor and capital and does not include the costs (and savings) that make pollution prevention projects profitable. The Total Cost Assessment methodology used in this project is an innovative evaluative tool that examines many other important costs associated with an investment including such elements as staff time for environmental reporting, waste management costs, and permitting fees. The results of the financial assessment further inform the decision whether to adopt the alternative. However, technical and financial information together are not sufficient for decision making. Further evaluation is required to assess the environmental, health and safety issues involved with the chemicals and processes. While the technical and cost assessments are not simple, the environmental, health and safety assessment, here called substitution analysis, is perhaps the most difficult because there is no generally agreed-on and reliable method for evaluating the environmental and worker health and safety risk of alternatives.

In using the three evaluative steps described above, it is important to remember that each project and facility may have different priorities for making decisions about whether to implement a particular technology. This was clearly demonstrated in this project as the participating companies had different motives for seeking substitute technologies. This, in turn, dictated which evaluative step was most important to them and indicates that the results of any one of the three can be the driving factor in a decision. Despite the emphasis being placed on one evaluative step on a given project, all three aspects must be evaluated so that valuable pieces of information are not ignored.

Parker Hannifin, for example, chose to evaluate only aqueous cleaning processes based primarily on environmental, health and safety, and regulatory reasons. Inspired by a management mandate to eliminate all chlorinated solvents for fear that, like CFC's, they might also be banned or heavily regulated, they performed a non-systematic "substitution analysis" and decided to purchase the least controversial system possible. The technical feasibility of aqueous cleaning seemed good and economics were not as much of an issue as it was a management mandate. They, of course, wanted effective cleaning for the lowest cost possible, but the cost of the system was not the main driving force for change. For this reason, the environmental, health and safety, and regulatory evaluation step was the most important for Parker Hannifin.

Market Forge, originally inspired by the Labeling Law to eliminate the use of 1,1,1-TCA, chose to rely on supplier information which resulted in a technically inadequate system with potential worker health problems. Had a technical assessment been conducted on the naphtha solvent prior to its use, it would have failed without need for information about its economic, environmental or safety performances. This experience resulted in a general distrust of all solvents that were potential replacements for the 1,1,1-TCA process; because of this, the technical assessment of aqueous cleaning was the most important piece in the decision-making process.

At Company A, many cleaning options appeared technically feasible; including plastic media blast, fragmented carbon dioxide blast and aqueous cleaning with ultrasonics. The substitution analysis of the alternatives provided additional crucial information to the decision making process. However, at the current state of regulation of TCE, the economic evaluation would perhaps most influence a decision to eliminate or decrease the use of TCE.

Many other conclusions regarding the cost of new systems, situation-specific chemicals and processes, and "drop-in" replacements can be drawn from this study. Considering the cost of new systems, the following conclusions were drawn: 1) if the aqueous systems are replacing older equipment, a savings in electricity costs may be realized, especially if hot air drying is not required; 2) depending on the cooling capacity of the vapor degreaser, the aqueous systems may actually use less water; 3) the profitability of an investment in aqueous cleaning equipment can be improved by purchasing based on cleaning needs at different stages in the production process; 4) the aggressive taxes on CFC's and TCA have made the aqueous alternatives economically feasible; and 5) the Total Cost Assessment methodology (P2/Finance Software) can be used in an iterative process to determine "costs" for unknowns by requiring a certain net present value. These "costs" can then be assessed to determine if, for example, a regulatory requirement could be met for a certain "cost" rather than actually attempting to place a value on meeting the regulatory requirement. Under the category of situation-specific chemicals and processes it was concluded that rinsing of a non-silicated cleaner is not always necessary even when a painting operation follows and aqueous immersion cleaning can be a viable option for steel and aluminum substrates either prior to nitriding or following heat treat operations. For "drop-in" replacements, it was concluded that a thorough technical evaluation of so-called "drop-in" replacements is necessary to avoid unforeseen costs and that job shops present an (as yet) unmet challenge to the vendors of "drop-in" replacements making the gradual phase-out of chlorinated solvents a possible option.

This project provided many conclusions regarding the decision making process used to evaluate alternative technologies, as well as general conclusions from the evaluations of the cleaning situations at the three participating companies. This work is part of a larger program at the Toxics Use Reduction Institute that includes laboratory assistance to companies through TURI's Surface Cleaning Laboratory, Research Fellows projects on "closed-loop" aqueous cleaning systems and further development of the substitution analysis, and the preparation of a manual "Cleaning is Greener in Massachusetts" in conjunction with the Office of Technical Assistance for Toxics Use Reduction. Through these ongoing activities the concepts and techniques developed will be further developed and disseminated.

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Appendix A
Quality Assurance, Calibration and Sampling Methods

Quantitative QA Objectives

The determination of contaminant loading was made using a Denver Instrument Analytical Balance Model A-250. The precision of the method was 0.1 mg and the accuracy was 0.3 mg. Completeness for the gravimetric measurement method was 87%. A total of eight coupons were evaluated for each cleaning trial. Seven valid determinations established the completeness objective.

Calibration Procedures and Frequency

Prior to measurements, the balance was calibrated using an internal "auto calibrate" routine using a 100 g standard. In order to verify the autocalibration procedure, external weights were used. ASTM Class 1 standards (50, 100, 150, 200 g) were weighed weekly in triplicate. The accuracy value of 0.3 mg was the allowable deviation for each standard. The allowable deviation was never exceeded during testing for this project so corrective action was not necessary. Gravimetric measurements for each coupon were recorded after a 30 second equilibration period on the balance. The reproducibility of the test coupon weight was found to be ± 0.1 mg.

Sampling Procedures

Sampling procedures and sample custody routines were followed as detailed in the Quality Assurance Project Plan for Evaluation of Alternative Surface Cleaning Methods.

Appendix B
TURI Surface Cleaning Laboratory Cleaner Performance Report

Name of Cleaning Product: W.R. Grace DARACLEAN 283 in low pressure spray wash
Contaminant: EAST FALLS Hydraulic Oil 8-32
Substrate Material: Carbon Steel
Cleaner Concentration Used: 5% by Volume
Temperature: 133 deg.F

Date: January 26 1995
Data Analyst: Donald Garlotta

Sample #/ Coupon #	Weight After Precleaning (grams)	Weight After Contamination (grams)	Contaminant Loading (mg)	Weight After Cleaning Trial (grams)	Weight of Contaminant Removed (mg)	Removal Efficiency (%)
45	133.2739	133.3026	28.7	133.2749	27.7	96.52
53	132.4365	132.4588	22.3	132.4374	21.4	95.96
58	127.7429	127.7787	35.8	127.7437	35	97.77
47	138.9952	139.0120	16.8	138.9962	15.8	94.05
25	132.8583	132.8789	20.6	132.8594	19.5	94.66
50	127.3406	127.3696	29	127.3416	28	96.55
42	162.4981	162.5246	26.5	162.4986	26	98.11
69	152.9144	152.9137*	0.7	152.9142	-0.5	
					Average:	96.231
					Std. Dev.	1.4935
					N	7

*Control

Appendix B (continued)

Name of Cleaning Product: Brulin Corporation 815-GD in a low pressure spray wash
Contaminant: EAST FALLS Hydraulic Oil 8-32
Substrate Material: Carbon Steel
Cleaner Concentration Used: 5% by Volume
Temperature: 133 deg.F
Date: January 26 1995
Data Analyst: Donald Garlotta

Sample #/ Coupon #	Weight After Precleaning (grams)	Weight After Contamination (grams)	Contaminant Loading (mg)	Weight After Cleaning Trial (grams)	Weight of Contaminant Removed (mg)	Removal Efficiency (%)
57	139.0683	139.1084	40.1	139.0710	37.4	93.27
56	162.8971	162.9274	30.3	162.8986	28.8	95.05
54	152.3015	152.3015*	0.0	152.3017	-0.2	
32	127.4974	127.5245	27.1	127.5008	23.7	87.45
46	162.9000	162.9255	25.5	162.9014	24.1	94.51
68	183.2032	183.2203	17.1	183.2048	15.5	90.64
55	156.7402	156.7579	17.7	156.7412	16.7	94.35
26	150.6293	150.6852	55.9	150.6341	51.1	91.41
49	151.3593	151.3582*	-1.1	151.3584	-0.2	18.18
					Average:	92.382
					Std. Dev.	2.7268
					N	7

*Control

Name of Cleaning Product: Oakite Products Inpro-Clean 2500 in low pressure spray wash
Contaminant: EAST FALLS Hydraulic Oil 8-32
Substrate Material: Carbon Steel
Cleaner Concentration Used: 54.59 gram/gallon
Temperature: 140 deg. F
Date: January 26 1995
Data Analyst: Donald Garlotta

Sample #/ Coupon #	Weight After Precleaning (grams)	Weight After Contamination (grams)	Contaminant Loading (mg)	Weight After Cleaning Trial (grams)	Weight of Contaminant Removed (mg)	Removal Efficiency (%)
38	146.6888	146.7412	52.4	146.6926	48.6	92.75
17	128.3814	128.4414	60	128.3857	55.7	92.83
7	147.4288	147.4659	37.1	147.4323	33.6	90.57
59	137.8544	137.9248	70.4	137.8586	66.2	94.03
19	123.1852	123.1845*	-0.7	123.1858	-1.3	
43	187.5290	187.6032	74.2	187.5349	68.3	92.05
21	140.1398	143.1390*	-0.8	140.1414	-2.4	0
63	150.8167	150.8896	72.9	150.8226	67	91.91
6	162.9305	162.9730	42.5	162.9361	36.9	86.82
					Average:	91.567
					Std. Dev.	2.3431
					N	7

*Control

Appendix C
Case Studies Documenting Success of Closed Loop Aqueous Degreasing

The following case studies are part of a TURI technical report, *Closed Loop Aqueous Cleaning*.

Company B of Newton, MA is a primary metals company which processes tantalum and niobium from the refining stage to the production of finished parts. Company B used 1,1,1-trichloroethane (TCA) in-house for part vapor degreasing, manual sheet cleaning, and as a full strength machining coolant. The mandated phase-out of TCA as an ozone-depleting substance in conjunction with the Labelling Law legislation prompted this company to begin replacing TCA in 1993. TCA was replaced with oil-based lubricants for machining processes and alkaline cleaners and non-ozone depleting solvents for cleaning processes. Another major factor prompting the switch from TCA was the issue of worker health and safety. By implementing these alternative technologies, Company B has eliminated approximately 40,000 pounds per year of TCA. In addition, the use of ultrafiltration units (spiral wound and hollow fiber) on their cleaning lines has reduced their cleaner purchases from 6,000 pounds per year to 2,000 pounds per year. The payback period for the transition from TCA to the alternative technologies was approximately 9 months.

Company C of Worcester, MA manufactures a variety of powdered metals parts. Because of environmental concerns with the use of vapor degreasing, the company worked on developing an alternative cleaning method. In late 1990, they successfully implemented an aqueous-based cleaning system that eliminated the use of perchloroethylene. In October 1994, as part of their continuous improvement activities, they purchased an ultrafiltration unit for the recovery and recycling of their aqueous cleaner. This cleaner is used primarily in part deburring as a lubricant and rust inhibitor, but also removes various contaminants. The closed loop cleaning system installed at Company C processes their used plant water, and includes a settling tank, skimmer, centrifuge, and hollow fiber ultrafiltration unit. By implementing aqueous cleaning, Company C has eliminated 24,000 pounds per year of PERC. In addition, the use of the ultrafiltration unit has decreased annual cleaner expenditures from $60,000 to about $7,500 and the daily volume of deburring effluent discharged to drain from 2,000 gallons to about 75 gallons. The payback on the closed loop system is estimated at 2 years.

Appendix D
Pay-back Period and Net Present Value

This appendix discusses two commonly used financial indicators: pay-back period and net present value.

Pay-Back Period

A financial indicator often used by businesses is the pay-back period of an investment. Pay back period is the cost of the initial investment (capital costs) divided by the annual savings in operating costs that will result from the investment. The outcome of the calculation will be the number of years it will take the investment to pay itself back. Most businesses have a rule-of-thumb pay-back period for investment decision making.

The use of payback period as an indicator for investment analysis has two disadvantages. First, it does not take cash flows after the pay-back period into account. Second, pay-back period does not address the time value of money. The value of a dollar today is normally greater than that of a dollar receivable or payable at a later date, for at least two reasons: (1) in periods of inflation, a dollar loses its purchasing power, so a dollar can be used to purchase more goods or services today than a year hence; and (2) a dollar held today can be invested to earn interest or some other return. For example, a dollar invested today at 6 percent interest will have a value at the end of one year of $1.06, thereby making it worth more than a dollar received at the end of that year[56].

Many accountants, financial managers, and financial planners have become aware of the importance of a thorough understanding of the time value of money concept and its application in financial planning and decision making.

Net Present Value

To calculate the effects of time on an investment, financial indicators other than pay-back period are required. Time value of money analysis (here after referred to generally as present value analysis) accounts for the effects of time on an investment opportunity. It requires that cash received in the future be valued lower than cash received today. Present value calculations convert dollars spent or saved in the future into an equivalent amount at time $t=0$ (usually $t=0$ is the present day). The unit of time for t used in this report is years.

This report shows the present value of an investment by comparing the annual operating costs of the new cleaning systems to the annual operating costs for the current cleaning systems. This comparison results in the difference in annual operating costs, the incremental cash flow. The incremental cash flows are the annual savings resulting from the new equipment that will be received over the economic lifetime of a project. The economic lifetime is the period of time over which the company depreciates the equipment.

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[56] Birrer, E.G., Carrica, J.L, *Present Value Applications for Accountants and Financial Planners*, Quorum books, New York, 1990

The incremental cash flow is further discounted over the period of the investment. The discount rate converts future cash flows to today's values. The discount rate should reflect the risk associated with the investment. Analysis of high-risk investments of a speculative nature therefore requires use of a discount rate well above the essentially risk-free rates associated with savings accounts. The equation to calculate the present value of an annuity is illustrated in equation 1. Furthermore, the discount rate should be reduced to include the effect of inflation unless inflation is considered separately. In this analysis, a discount rate that reflects the expected impact of inflation is used.

Equation 1: Calculation of Present Value of an Annuity

$$PV = CF \times \left[\frac{1}{(1+d)^n} \times \frac{(1+d)^n - 1}{d}\right]$$

Where PV is the present value, CF_1 is the incremental cash flow in the first year (CF_n in the n^{th} year), d is the discount rate and n is the number of time periods.

Present value tables provide the results of the "$(1+d)^n$" term in the equation above for different numbers of years (n) and discount rates (d).

The incremental cash flow is likely to vary over the different years of the investment due to trends in prices. For example, the effects of taxes on chemicals might result in increases in chemical purchase costs. In this case the incremental cash flows of an investment with an economic lifetime of, for example, seven years have to be discounted for each of the seven years separately. This is illustrated in equation 2. The financial analyses in this study were done using a spreadsheet program which allowed the effects of increasing taxes on ozone depleting chemicals to be included.

Equation 2: Calculation of Present Value with Differing Incremental Cash Flows

$$PV = \frac{CF_1}{(1+d)^1} + \frac{CF_2}{(1+d)^2} + \ldots \frac{CF_n}{(1+d)^n}$$

Where PV is the present value, CF is the annual incremental cash flow, d is the discount rate, and n is the number of years.

To calculate the net present value, capital costs are subtracted from the present value of the future stream of cash flows. If the net present value of a project is greater than zero, the project is financially beneficial to the company, and the higher the number the more profitable the investment. If the net present value of a project is less than zero, it is not financially beneficial to the company. If the net present value of a project is equal to zero, the project generates exactly the rate of return that is required by the company.

Depreciation and Income Tax

Most investments in manufacturing equipment have a useful life. At the end of their useful life, or economic lifetime, they may have a salvage value or they may be completely worthless. Depreciation refers to the process of allocating the purchase costs of a machine across its entire lifetime to represent the loss of value as a result of using the machine. For reasons of practicality, this analysis calculates straight-line depreciation for all options. Straight-line depreciation is calculated by simply dividing the capital cost of the equipment by the number of years of expected lifetime minus any salvage value. This results in the annual depreciation of equipment. For example, a company purchasing a $7,000 piece of equipment that has a seven year lifetime could depreciate $1,000/year on the item.

Depreciation is not a true cash flow in that no revenue transfers to the company. Depreciation is deducted from taxable income and therefore reduces the tax burden on the firm.

Taxable income, income tax and after tax cash flow are terms used to assess the effect of income tax on the savings resulting from the investment. The taxable income flow is the operating cash flow minus the annual depreciation. This is the amount over which businesses have to pay income tax. After tax cash flow refers to the amount of profit remaining after taxes have been subtracted and the depreciation is added back.

Income tax rates for corporations vary almost as much as personal income tax rates. Most businesses are reluctant to reveal their income tax rate. Therefore, in this analysis a typical income tax rate of 40% is used for all projects.

The following example illustrates the treatment of depreciation and income tax in the case studies in this report:

> In the case of a process that has an operating cost of $2,000/year, and a new alternative with an operating cost of $1,000/year, the incremental cash flow, or potential savings, of the investment will be $1,000/year. If the lifetime of the new machine is 10 years and all costs connected with purchasing it are $1,000, the depreciation per year would be $100. This amount is then subtracted from the operating costs for a total taxable income of $900. The corporation's tax rate, 40%, is applied to this balance and subtracted from taxable income to obtain the net income: $900 - $360 = $540. The annual depreciation is then added to the net income to calculate a true after tax cash flow: $540 + $100 = $640.

This example shows that the only true savings from depreciation come from the avoided tax on income generated by the equipment. These savings are generally referred to as the depreciation tax shield because the expense shields income from taxes.

Appendix E
Substitution Analysis Worksheet

Current system
Alternate system

	Typical Units	Values for Current System	Values for Alternate System
Inventory			
use	lbs/tons		
discharge to air	lbs/tons		
discharge to water	lbs/tons		
discharge to land	lbs/tons		

Areas of Concern	Criteria	Typical Units	Values for Current System	Values for Alternate System	Relative Hazard H/M/L	Change to New System +/-
	Toxicity					
☐ potential for inhalation	Inhalation LC50	ppm, mg/m3				
	PEL	ppm, mg/m3				
	TLV	ppm, mg/m3				
	IDLH	ppm, mg/m3				
	Resp. system irritation	Y/N				
	odor threshold	ppm, mg/m3				
☐ potential for ingestion	Oral LD50	mg/kg				
☐ potential for skin contact	dermal irritation	Y/N				
	absorbed	Y/N				
	corrosive	Y/N				
	pH	pH units				
☐ potential for eye contact	ocular irritation	Y/N				
	Specific Effects					
☐ potential for specific effect	carcinogen	Y/N/S				
	teratogen	Y/N/S				
	mutagen	Y/N/S				
	other specific effects					
☐ physical hazards	**Physical Hazards**					
	explosivity	1,2,3,4				
	flammability	1,2,3,4				
	flash point	F/C				
	LFL/UFL	%				
	reactivity	1,2,3,4				
	noise generation	Y/N				
	high pressure	Y/N				
	high temperature	Y/N				

Appendix E (continued)

☐ potential for release to air

☐ potential for release to water

☐ potential for release to land

Environmental

global warming	Y/N				
ozone depleting	Y/N				
ozone depleting potential	ODS units				
ecological effects	Y/N				
bioconcentration factor					
BOD half-life	min				
hydrolysis half-life	min				
NOEL	mg/kg/day				
Landfill	Y/N				
TCLP					
EPTox					
Incineration	Y/N				
Recycle	Y/N				

☐ physical/chem characteristic

Characteristics

vapor pressure	mm Hg				
vapor density	air =1				
evaporation rate	ether=1				
boiling point	F/C				
particle size	um				
solubility in water	mg/L				
specific gravity	water = 1				

☐ regulatory issues

Regulatory

HAP	Y/N				
VOC	Y/N				
NESHAP	Y/N				
degradability	Y/N				
priority pollutant	Y/N				
OSHA carcinogen	Y/N				
OSHA chem specific stds	Y/N				
RCRA Reportable Quant.	Y/N				

☐ energy & resources

Energy & Resources

non renewable	Y/N				
water use	gallons/ft3				
energy use					

Appendix F
Definitions of Criteria

Toxicity

INHALATION LC_{50}: The calculated concentration in air that is expected to kill 50% of a group of test animals with a single exposure (usually 1-4 hours). (A lower LC_{50} represents a more toxic substance.)

PEL: (Permissible Exposure Limit) The limit of allowable exposure to a chemical contaminant expressed as a time weighted average (TWA) concentration during an 8-hour work day or as a maximum concentration never to be exceeded either instantaneously or in the short term during any maximum period of 15 minutes. A lower PEL represents a more toxic substance.

> 8 HR TWA: (Time Weighted Average) The average concentration of a substance in air over the total time of exposure, in this case expressed as an 8-hour day. (A lower 8 HR TWA represents a more toxic substance.)

TLV: Threshold Limit Values are published by the American Conference of Governmental Industrial Hygienists and defined as airborne concentrations under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effects. It should be noted that a small percentage may be effected at or below these limits due to unusual susceptibility or pre-existing conditions. A higher TLV indicates that more of the substance may be present before adverse effects are caused.

IDLH: (Immediately Dangerous to Life or Health) This represents the maximum concentration from which, in the event of respirator failure, one could escape within 30 minutes without a respirator and without experiencing any escape-impairing or irreversible health effects. (A lower IDLH represents a more toxic substance.)

RESPIRATORY SYSTEM IRRITATION: A substance is given a yes if it has been found, in literature references or in practice, to be an irritant of the respiratory system.

ODOR THRESHOLD: The lowest amount of a chemical substance's vapor, in air, that can be smelled. Substances with high odor thresholds are said to have poor warning properties since they may not be detectable by those exposed to hazardous concentrations.

ORAL LD_{50}: A single calculated dose of a material administered by mouth in mg per kg of body weight, expected to kill 50% of a group of test animals. (A lower LD_{50} represents a more toxic substance.)

DERMAL IRRITATION: A substance is given a yes if it has been found, in literature references or in practice, to be an irritant of the skin.

ABSORBED: Indicates whether or not a chemical may be absorbed through the skin.

CORROSIVE: Any liquid or solid with pH ranges of 2-6 or 12-14 that causes visible destruction or irreversible alteration of living tissue, or a liquid that has a severe corrosion rate on steel.

pH: A logarithmic index for the hydrogen ion concentration in an aqueous solution. A pH below 7 indicates acidity, and one above 7 alkalinity (@ 25°C). The pH scale ranges from 0-14, with extreme values representing a more corrosive aqueous solution. (Closer to 7 is desirable.)

OCULAR IRRITATION: Irritation caused by exposure of the eyes to a given chemical.

Specific Effects

CARCINOGEN: Any substance or combination of substances known to cause an increased incidence of benign and/or malignant neoplasms, or a substantial decrease in the latency period between exposure and onset of neoplasms in humans or in one or more experimental mammalian species as the result of any oral, respiratory or dermal exposure, or any other exposure that results in the induction of tumors at a site other than the site of administration. This definition includes any substance which is metabolized into one or more potential occupational carcinogens by mammals. A substance receives a yes (Y) if it has an IARC (International Agency for Research on Cancer) classification of 1, a suspect (S) if it has a classification of 2A or 2B, or a no (N) if it has a classification of 3 or 4.

TERATOGEN: Produces changes in the offspring of the exposed subject.

MUTAGEN: A chemical that causes mutations in the genetic material of exposed subjects.

OTHER SPECIFIC EFFECTS: Any other specific effects can be noted here, such as effects on the central nervous system, liver or kidney.

Physical Hazards

EXPLOSIVITY: The ease with which a material will detonate. Detonation is the extremely rapid, self-propagating decomposition of a material accompanied by a high-pressure-temperature wave that moves at 1000-9000 meters/second. (The DOT rates explosivity on a scale of 1-4, with a higher number denoting a greater explosion risk.)

FLAMMABILITY: The ease with which a material will ignite spontaneously either from exposure to a high temperature environment or to a spark or open flame. It also involves the rate of spreading of a flame once it has started. (The DOT rates flammability on a scale of 1-4, with a higher number denoting a greater ignition risk.)

> FLASH POINT: The temperature at which material gives off vapor sufficient to form an ignitable mixture with the air near the surface of the material. The lower the flash point, the more probability an explosion could occur under normal working conditions. (Lower is less desirable.)
>
> LFL/UFL: (Lower/Upper Flammable Limit) The lowest/highest concentration of gas or vapor (percentage by volume in air) that will burn or explode when a source of ignition is present. Substances with a low LFL, as well as those with a broad flammability range, tend to represent a greater hazard within the workplace.

REACTIVITY: Chemical reaction with the release of energy. Undesirable effects such as pressure buildup, temperature increase, formation of noxious, toxic or corrosive by-product may occur because of the reactivity of a substance to heating, burning, direct contact with other materials, or other conditions in use or in storage.

NOISE GENERATION: The amount of noise associated with the process. This category is rated yes if either: a) workers are exposed to noise levels greater than 85 dBA; or b) plant neighbors are exposed to noise levels above the ambient background level.

HIGH PRESSURE: If the process involves the handling of gases at pressures greater than atmospheric, this category is rated yes. High pressure processes pose a greater risk for accidental exposures to the chemicals under pressure.

HIGH TEMPERATURE: High temperature operations also entail a greater risk of chemical exposure, and can lead to worker heat stress. A yes is given in this category if the process involves temperatures greater than 100 F.

Environmental Hazards

GLOBAL WARMING: The substance is given a yes if it has been found to contribute to global warming.

OZONE DEPLETING & OZONE DEPLETING POTENTIAL: The substance is given a yes if it has been found to contribute to the depletion of the ozone layer. Ozone depleting potential (ODP) is reported in ODP units; scoring is relative to CFC-11 which is 1 ODP unit.

SMOG CONTRIBUTOR: The substance is given a yes if it has been found to contribute to the formation of smog.

ECOLOGICAL EFFECTS: The substance is given a yes if it has been found to exhibit ecological effects.

BIOCONCENTRATION FACTOR: Bioconcentration is a special case of bioaccumulation in which a dissolved substance is selectively taken up from a water solution and concentrated in body tissue by nondietary routes. The factor is a ratio of the rate of uptake to the rate of elimination of the substance in body tissue. (A higher factor means that the substance tends to accumulate quite readily within the body, possibly leading to adverse health effects.)

BOD HALF-LIFE: The time required for the biochemical oxygen demand (BOD) of an organic waste to be reduced to one half of its initial level. BOD is a measurement of the dissolved oxygen consumed by microbial life while assimilating and oxidizing the organic matter present in the organic waste. (A waste with a lower BOD half-life decomposes more rapidly, decreasing the time required for treatment before discharge.)

HYDROLYSIS HALF-LIFE: The time required for the hydrolysis potential of a substance to be reduced to one half of its initial level. Hydrolysis is a chemical reaction in which water reacts with the substance to form two or more new substances. (A waste with a lower hydrolysis half-life decomposes more rapidly, decreasing the time required for treatment before discharge.)

NOAEL: (No Observed Adverse Effect Level) Usually defined for fish, the experimental exposure level representing the highest level tested at which no adverse effects were demonstrated. (A lower NOAEL represents a more toxic substance.)

Release to Land

LANDFILL: The substance is given a yes if its waste is landfilled.

TCLP: (Toxicity Characteristic Leaching Procedure) The TCLP is a test to measure the leachability of a waste.

EPTOX: EP Toxicity procedure for testing hazardous waste, set forth in the Code of Federal Regulations, 40 CFR Part 261 Appendix II.

INCINERATION: The substance is given a yes if its waste is incinerated.

RECYCLE: The substance is given a yes if its waste is recycled.

Physical/Chemical Characteristics

VAPOR PRESSURE: The saturated partial pressure of a vapor in contact with its liquid form. The vapor pressure increases with temperature. Substances with higher vapor pressures at a given temperature produce higher vapor concentrations in the surrounding air, which may result in adverse health effects or explosion hazards. (Higher is less desirable.)

VAPOR DENSITY: The weight of a vapor per unit volume at any given temperature and pressure, relative to the density of air. Higher density vapors can collect near the bottom of enclosed spaces, increasing potential exposure.

EVAPORATION RATE: The rate at which a liquid converts to a vapor at temperatures below the boiling point. This rate increases with a rise in temperature since it depends on the saturated vapor pressure. Liquids with higher evaporation rates tend to be lost to the atmosphere more readily, producing both health hazards and economic losses. (Higher is less desirable.)

BOILING POINT: The temperature at which a liquid boils when exposed to the atmosphere. At this point, the saturated vapor pressure of a liquid equals the pressure of its surroundings. Substances with lower boiling points tend to evaporate more quickly. (Lower is less desirable.)

PARTICLE SIZE: The physical dimensions of a molecule or particle created by the process. Particles smaller than 50 micrometers may be inhalable (i.e., deposit in the respiratory tract). (Smaller is less desirable.)

SOLUBILITY IN WATER: The maximum number of milligrams of a substance that may be dissolved in one liter of water.

SPECIFIC GRAVITY: The ratio of the mass of a given volume of a substance to the mass of an equal volume of water at a temperature of 4°C. A value greater than 1 represents a substance more dense than water. This may be important in certain aqueous cleaning applications.

Regulatory Issues

HAP: (Hazardous Air Pollutant) Air pollutants that are not covered by ambient air quality standards but that, as defined in the Clean Air Act, may reasonably be expected to cause or contribute to irreversible illness or death.

VOC: (Volatile Organic Compound) Organic materials containing carbon and hydrogen that are subject to rapid evaporation.

NESHAP: (National Emission Standard for Hazardous Air Pollutant) Emission standard set by the EPA for an air pollutant not covered by National Ambient Air Quality Standards (NAAQS) that may cause an increase in deaths or in serious, irreversible, or incapacitating illness. Primary standards are designed to protect human health, secondary standards to protect public welfare.

DEGRADABILITY: The substance is given a yes if it degrades biologically.

PRIORITY POLLUTANT: List of 129 pollutants broken down in to the following major categories: volatile organics, acid-extractable organics, base and neutral organics, pesticides and PCBs, metals, cyanides and asbestos.

OSHA CARCINOGEN: Without establishing PELs, OSHA promulgated standards in 1974 to regulate the industrial use of thirteen chemicals.

OSHA CHEMICAL SPECIFIC STANDARDS: Chemicals for which OSHA has promulgated specific regulations.

RCRA RQ: (RCRA Reportable Quantities) A substance has a low reportable quantity when it has been rated a more significant hazard. (Lower is less desirable.)

Energy and Resources

NON RENEWABLE: The substance is given a yes if it is derived from a non-renewable resource.

WATER USE: The amount of water used in the process is entered.

ENERGY USE: The amount of energy used in the process is entered.

Appendix G
Substitution Analysis Worksheet - Market Forge

Current system	TCA degrease
Alternate system	naphtha solvent

	Typical Units	Values for Current System	Values for Alternate System
Inventory			
use	lbs/tons	7145	9765
discharge to air	lbs/tons	1246	2860
discharge to water	lbs/tons	0	0
discharge to land	lbs/tons	5899	6904

Areas of Concern	Criteria	Typical Units	Values for Current System	Values for Alternate System	Relative Hazard H/M/L	Change to New System +/-
	Toxicity					
☒ potential for inhalation	Inhalation LC50	ppm,mg/m3				
	PEL	ppm,mg/m3	350 ppm	100 ppm		-
	TLV	ppm,mg/m3				
	IDLH	ppm,mg/m3	1000			
	Resp. system irritation	Y/N	N	N		
	odor threshold	ppm,mg/m3				
☐ potential for ingestion	Oral LD50	mg/kg				
☒ potential for skin contact	dermal irritation	Y/N	Y	N		+
	absorbed	Y/N	N	N		
	corrosive	Y/N	N	N		
	pH	pH units				
☒ potential for eye contact	ocular irritation	Y/N	Y	N		+
	Specific Effects					
☒ potential for specific effects	carcinogen	Y/N/S	S	N	H	+
	teratogen	Y/N/S	S	N	H	+
	mutagen	Y/N/S	S	N	H	+
	other specific effects					
☒ physical hazards	**Physical Hazards**					
	explosivity	1,2,3,4				
	flammability	1,2,3,4				
	flash point	F/C	none	140		
	LFL/UFL	%	7.5/12.5	1/6		-
	reactivity	1,2,3,4				
	noise generation	Y/N	N	N		
	high pressure	Y/N	N	N		
	high temperature	Y/N	Y	N		

Appendix G (continued)

☒ potential for release to air

☐ potential for release to water

☐ potential for release to land

Environmental

global warming	Y/N	Y	N		+
ozone depleting	Y/N	Y	N		+
ozone depleting potential	ODS units				
ecological effects	Y/N				
bioconcentration factor					
BOD half-life	min				
hydrolysis half-life	min				
NOEL	mg/kg/day				
Landfill	Y/N				
TCLP					
EPTox					
Incineration	Y/N				
Recycle	Y/N				

☒ physical/chem characteristic

Characteristics

vapor pressure	mm Hg	100	0.6		+
vapor density	air =1		5.4		
evaporation rate	ether=1	151	6		-
boiling point	F/C	165	350		
particle size	um				
solubility in water	mg/L	0.4	negligible		
specific gravity	water = 1	1.34	0.79		

☒ regulatory issues

Regulatory

HAP	Y/N	Y	N	H	+
VOC	Y/N	Y	N	H	+
NESHAP	Y/N	N	N	H	
degradability	Y/N				
priority pollutant	Y/N				
OSHA carcinogen	Y/N				
OSHA chem specific stds	Y/N				
RCRA RQ	Y/N				

☒ energy & resources

Energy & Resources

non renewable	Y/N	Y	Y		
water use	gallons/ft3	0	0		
energy use	many				

Appendix H
Substitution Analysis Worksheet - Company A

Current system	TCE degrease
Alternate	plastic blast

	Typical Units	Values for Current System	Values for Alternate System
Inventory			
use	lbs/tons	11,152	
discharge to air	lbs/tons	10,452	
discharge to water	lbs/tons	0	
discharge to land	lbs/tons	700	

Areas of Concern	Criteria	Typical Units	Values for Current System	Values for Alternate System	Relative Hazard H/M/L	Change to New System +/-
	Toxicity					
☒ potential for inhalation	Inhalation LC50	ppm, mg/m3				
	PEL	ppm, mg/m3	50 ppm			
	TLV	ppm, mg/m3	100			
	IDLH	ppm, mg/m3	1000			
	Resp. system irritation	Y/N	Y			
	odor threshold	ppm, mg/m3				
☐ potential for ingestion	Oral LD50	mg/kg				
☐ potential for skin contact	dermal irritation	Y/N	Y			
	absorbed	Y/N	N			
	corrosive	Y/N	N			
	pH	pH units				
☐ potential for eye contact	ocular irritation	Y/N	Y			
	Specific Effects					
☒ potential for specific effects	carcinogen	Y/N/S	S			
	teratogen	Y/N/S	S			
	mutagen	Y/N/S	S			
	other specific effects					
☒ physical hazards	**Physical Hazards**					
	explosivity	1,2,3,4				
	flammability	1,2,3,4				
	flash point	F/C	none			
	LFL/UFL	%	8/10.5			
	reactivity	1,2,3,4				
	noise generation	Y/N	Y			
	high pressure	Y/N	N	Y		
	high temperature	Y/N	Y			

Appendix H (continued)

☒ potential for release to air

☐ potential for release to water

☒ potential for release to land

Environmental

global warming	Y/N	N			
ozone depleting	Y/N	N			
ozone depleting potential	ODS units				
smog contributor	Y/N	Y			
ecological effects	Y/N	N			
bioconcentration factor					
BOD half-life	min				
hydrolysis half-life	min				
NOEL	mg/kg/day				
Landfill	Y/N				
TCLP					
EPTox					
Incineration	Y/N				
Recycle	Y/N	Y			

☒ physical/chem characteristic

Characteristics

vapor pressure	mm Hg	58			
vapor density	air =1	4.53			
evaporation rate	ether=1	6.39			
boiling point	F/C	189			
particle size	um				
solubility in water	mg/L	0.1			
specific gravity	water = 1	1.46			

☒ regulatory issues

Regulatory

HAP	Y/N	Y			
VOC	Y/N	Y			
NESHAP	Y/N				
degradability	Y/N				
priority pollutant	Y/N				
OSHA carcinogen	Y/N				
OSHA chem specific stds	Y/N				
RCRA RQ	Y/N				

☒ energy & resources

Energy & Resources

non renewable	Y/N	Y			
water use	gallons/ft3	0			
energy use					

Appendix H (continued)

Current system	TCE degrease
Alternate	CO2

	Typical Units	Values for Current System	Values for Alternate System
Inventory			
use	lbs/tons	11,152	
discharge to air	lbs/tons	10,452	
discharge to water	lbs/tons	0	
discharge to land	lbs/tons	700	

Areas of Concern	Criteria	Typical Units	Values for Current System	Values for Alternate System	Relative Hazard H/M/L	Change to New System +/-
	Toxicity					
☒ potential for inhalation	Inhalation LC50	ppm,mg/m3				
	PEL	ppm,mg/m3	50 ppm	5000 ppm		
	TLV	ppm,mg/m3	100 ppm	5000 ppm		
	IDLH	ppm,mg/m3	1000 ppm			
	Resp. system irritation	Y/N	Y	asphyxiant		
	odor threshold	ppm,mg/m3				
☐ potential for ingestion	Oral LD50	mg/kg				
☐ potential for skin contact	dermal irritation	Y/N	Y	Y		
	absorbed	Y/N	N			
	corrosive	Y/N	N			
	pH	pH units				
☐ potential for eye contact	ocular irritation	Y/N	Y	N		
	Specific Effects					
☒ potential for specific effects	carcinogen	Y/N/S	S	N		
	teratogen	Y/N/S	S	exp		
	mutagen	Y/N/S	S	N		
	other specific effects					
☒ physical hazards	**Physical Hazards**					
	explosivity	1,2,3,4				
	flammability	1,2,3,4				
	flash point	F/C	none			
	LFL/UFL	%	8/10.5			
	reactivity	1,2,3,4				
	noise generation	Y/N	Y			
	high pressure	Y/N	N	Y		
	high temperature	Y/N	Y	N		

Appendix H (continued)

☒ potential for release to air

☐ potential for release to water

☒ potential for release to land

Environmental

global warming	Y/N	N	Y		
ozone depleting	Y/N	N	N		
ozone depleting potential	ODS units				
smog contributor	Y/N	Y	N		
ecological effects	Y/N				
bioconcentration factor					
BOD half-life	min				
hydrolysis half-life	min				
NOEL	mg/kg/day				
Landfill	Y/N				
TCLP					
EPTox					
Incineration	Y/N				
Recycle	Y/N	Y	N		

☒ physical/chem characteristic

Characteristics

vapor pressure	mm Hg	58			
vapor density	air =1	4.53			
evaporation rate	ether=1	6.39			
boiling point	F/C	189			
particle size	um				
solubility in water	mg/L	0.1			
specific gravity	water = 1	1.46			

☒ regulatory issues

Regulatory

HAP	Y/N	Y	N		
VOC	Y/N	Y	N		
NESHAP	Y/N				
degradability	Y/N				
priority pollutant	Y/N				
OSHA carcinogen	Y/N				
OSHA chem specific stds	Y/N				
RCRA RQ	Y/N				

☒ energy & resources

Energy & Resources

non renewable	Y/N	Y	N		
water use	gallons/ft3	0	0		
energy use					

Appendix H (continued)

Current system	TCE degrease
Alternate	aqueous

	Typical Units	Values for Current System	Values for Alternate System
Inventory			
use	lbs/tons	11,152	
discharge to air	lbs/tons	10,452	
discharge to water	lbs/tons	0	
discharge to land	lbs/tons	700	

Areas of Concern	Criteria	Typical Units	Values for Current System	Values for Alternate System	Relative Hazard H/M/L	Change to New System +/-
	Toxicity					
☒ potential for inhalation	Inhalation LC50	ppm, mg/m3				
	PEL	ppm, mg/m3	50 ppm			
	TLV	ppm, mg/m3	100 ppm	5 mg/m3		
	IDLH	ppm, mg/m3	1000 ppm			
	Resp. system irritation	Y/N	Y	Y		
	odor threshold	ppm, mg/m3				
☐ potential for ingestion	Oral LD50					
☒ potential for skin contact	dermal irritation	Y/N	Y	Y		
	absorbed	Y/N	N			
	corrosive	Y/N	N			
	pH	pH units				
☐ potential for eye contact	ocular irritation	Y/N	Y			
	Specific Effects					
☒ potential for specific effects	carcinogen	Y/N/S	S			
	teratogen	Y/N/S	S			
	mutagen	Y/N/S	S			
	other specific effects					
☒ physical hazards	**Physical Hazards**					
	explosivity	1,2,3,4				
	flammability	1,2,3,4				
	flash point	F/C	none			
	LFL/UFL	%	8/10.5			
	reactivity	1,2,3,4				
	noise generation	Y/N	Y			
	high pressure	Y/N	N			
	high temperature	Y/N	Y	Y		

Appendix H (continued)

Environmental

☒ potential for release to air	global warming	Y/N	N			
	ozone depleting	Y/N	N			
	ozone depleting potential	ODS units				
	smog contributor	Y/N	Y			
☒ potential for release to water	ecological effects	Y/N	N	possible		
	bioconcentration factor					
	BOD half-life	min				
	hydrolysis half-life	min				
	NOEL	mg/kg/day				
☒ potential for release to land	Landfill	Y/N				
	TCLP					
	EPTox					
	Incineration	Y/N				
	Recycle	Y/N	Y			

☒ physical/chem characteristic

Characteristics

vapor pressure	mm Hg	58			
vapor density	air =1	4.53			
evaporation rate	ether=1	6.39			
boiling point	F/C	189			
particle size	um				
solubility in water	mg/L	0.1			
specific gravity	water = 1	1.46			

☒ regulatory issues

Regulatory

HAP	Y/N	Y	N		
VOC	Y/N	Y	N		
NESHAP	Y/N				
degradability	Y/N				
priority pollutant	Y/N				
OSHA carcinogen	Y/N				
OSHA chem specific stds	Y/N				
RCRA RQ	Y/N				

☒ energy & resources

Energy & Resources

non renewable	Y/N	Y			
water use	gallons/ft3	0			
energy use					

Appendix I
Information Resources

U.S. Department of Health and Human Services, Centers for Disease Control, NIOSH Pocket Guide to Chemical Hazards, June 1990. This publication is for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Lewis, Richard Sr., "Hazardous Chemicals Desk Reference", Third Edition, Van Nostrand Reinhold, New York, 1993.

Government Institutes, Inc. "Book of Lists for Regulated Hazardous Substances", 1994. The address is 4 Research Place, Suite 200, Rockville, MD 20850.

Appendix J
Annotated List of Substitution Analysis References

"Chemical Hazard Evaluation for Management Strategies: A Method for Ranking and Scoring Chemicals by Potential Human Health and Environmental Impacts" Center for Clean Products and Clean Technologies, University of Tennessee, EPA Document EPA/600/R-94/177, June 1994. *This model uses risk-based chemical ranking an scoring combining the toxic effects of chemicals and the potential for exposure to those chemicals. The report ranks 140 TRI chemicals based on 99% of total releases. The method does not include secondary global impacts such as ozone depleting and global warming. Potential uses of the methodology are: priority setting for regulatory action, for business decisions and to set priorities for pollution prevention. The model does not include safety issues in its analysis.*

TURI

"The Role of Risk in Chemical Substitution Decisions" George Gray and Jennifer Hartwell, Harvard Center for Risk Analysis, Harvard School of Public Health, prepared for TURI, July 1994. *Outlines a risk-based substitution decision-making framework, the chemical substitution tree (CST). Suggests looking at both the application exposure and the disposal exposure for potential effects on the environment, workers and the public. Gives some ideas of the actual chemical characteristics to consider and where to find relevant information. The model seeks to identify areas of potentially high risk so that companies can make informed decisions on how to reduce the risk.*

"Blanket Wash Technology Study: An Evaluation of Commercially Available Blanket Washes" TURI Technical Report No. 16, 1994. *This study gives comparative information on the perfomance, environmental, health and safety characteristics of blaket washes commonly uised in sheetfed offset lithography. Each attribute was given a good, fair or poor score. The attributes scored that did not have to do with performance included VOC content, flash point, health hazard and potential regulatory impact. For determining a score for the health hazard, mixtures were given the highest score of any ingredient and data were obtained from REPROTEXT. For determining the potential regulatory impact, chemicals were given scores based on how many times they appeared on nineteen regulated chemical lists.*

EPA

"Life Cycle Assessment: Inventory Guidelines and Principles" EPA Office of Research and Development, Feb 1993, EPA/600-R-92/245 *1) Goal Definition 2) Scoping - must be constantly reviewed and redefined when necessary 3) Assumptions must be clearly stated. 4) Any interpretation beyond the "less is best" approach is subjective. 5) Generic data may mask technologies that are more environmentally burdensome or may not allow opportunities to identify specific facilities operating in a more environmentally sound manner. Three components of a life cycle assessment: 1. Inventory Analysis - the identification and quantification of energy and resource use and environmental releases to air, water, and land. 2. Impact Analysis - the technical qualitative and quantitative characterization and assessment of the consequences on the environment. During this analysis, linkages are established between products* *and potential impacts (sulfur dioxide and the loss of biodiversity) 3. Improvement Analysis - the evaluation and implementation of opportunities to reduce environmental burdens Raw material acquisition, Materials Manufacture, Product Fabrication, Consumption, Waste Management, Transportation*

"Background Document on Clean Products Research and Implementation" EPA Office of Research and Development, Oct 1990, EPA/600/2-90/048
Criteria that have been used to evaluate products:
recycled content
recyclability/reusability
degradability
hazardous/toxic material content
water pollution impacts
soil pollution impacts
air pollution impacts
noise pollution impacts
production processes used
use of resources (including energy)
other criteria
    use of more benign products/processes
    general requirement of safety, usability
    amount or type of packaging
    provision of information for the consumer
    overall corporate reputation
    effect on rainforest
    longer lasting or repairable products
    weight or volume contribution to landfills or waste streams
    disposal problems

Methodologies that have been used to evaluate products:
product life cycle analysis
matrix approach
weighting systems

EPA, OPPT, Cleaner Technologies Substitutes Assessment - Screen Printing Industry: Screen Reclamation, EPA document # EPA744R-94-005, September 1994. *This is an in-depth risk-based assessment of the environmental impacts, energy use, health and safety issues of the alternatives for screen reclamation in the printing industry. This work is based on earlier work by the University of Tennessee Center for Clean Products and Clean Technologies. This document is not intended to easily enable small-medium sized businesses to choose among alternatives.*

EPA, ORD, "Development of a Pollution Prevention Factors Methodology Based on Life-Cycle Assessment: Lithographic Printing Case Study", EPA document # EPA/600/R-94/157, January 1994. *This report discusses a P2 factors methodology that can be used as a screening tool to provide direction in selecting P2 activities that provide the most environmental improvement. The tool uses a scoring criteria using numbers 1-9. Scorings were tabulated for the following categories: energy use, airborne emissions, waterborne emissions, photochemical oxidant creation potential, inhalation toxicity, ozone depleting potential, global warming potential. The tool was used for two specific situations in this report:*

solvent substitution in blanket and press wash and waterless versus conventional dampening fountain system printing.

Stephen, David, Robert Knodel and James Bridges, "A "Mark I" Measurement Methodology for Pollution Prevention Progress Occurring as a Result of Product Design Decisions", USEPA RREL, November 1994. *This is a methodology for assessing progress in pollution prevention that results from product redesign, reformulation or replacement. Impacts assessed are: human health, use impairment (for each media) and disposal capacity. Note that amounts of pollutants only are assessed, not risk. (Risk may be included in future versions.)*

EPA Region III, Air, Radiation and Toxics Division, "Environmental Targeting Systems", EPA/903/B-94/001, December 1994. *This document reviews several existing targeting systems including five systems for analyzing comparative risk. The following models are described: Comparative Risk Analysis, Cross-Media Comparative Risk Assessment Model, Graphical Exposure Modeling System, Integrated Environmental Management Program, Region VI Human Health Risk Index.*

SETAC

"A Technical Framework for Life-Cycle Assessment", SETAC, January 1991.
Inventory, Impact, Improvement
Energy, material, environmental release data AND ecological impacts, site selection, habitat alteration, community relations, public perceptions, good management practices, worker health concerns, public health and accident risk.

"A Conceptual Framework for Life-Cycle Assessment", SETAC, March 1993. *Presents framework for assessing ecological and human health impacts and resource depletion using an impact analysis matrix. The matrix uses scores from -1 to +1 and -- and ++ for accenting positives and negatives.*

Tellus

Shapiro, Karen, "To Switch or not To Switch: A Decision Framework for Chemical Substitution" Pollution Prevention Review, Winter 1993-94. *This article outlines a method for assessing chemical substitutes designed for use by businesses and regulators. This decision framework is to be used as an organizing tool for assessing the desirability of substitutes. The model takes into account technical, economic, environmental, health and safety effects. No detail is provided on how to assess the environmental, health and safety effects or how to compare alternatives.*

RTI, North Carolina & Battelle

Weitz, Keith et al. "Developing a Decision Support Tool for Life-Cycle Cost Assessments", Total Quality Environmental Management, Autumn 1994, p 23-36. *This method is intended to enhance life cycle assessment by adding cost information. It contains a concise history of LCA. It defines three life cycle cost categories: conventional, liability and environmental. The authors suggest including such environmental costs as global warming and ozone depletion. It contains a table of the costs considered by various costing methodologies. It discusses a "top-down" approach to modeling to facilitate cost effective decision making, (ie. begin by viewing the project in a generic life-cycle context before gathering cost and environmental data and adding detail as needed.)*

Institute for Research and Technical Assistance

Wolf, Katy, "The Generic Classification System: A Simplified Approach to Selecting Alternatives to Chlorinated Solvents" Pollution Prevention Review, Winter 1993-94, p 15-29. *The author sets up a generic classification system for choosing alternative to a chlorinated solvent. The properties/classifications of PEL, VOC, HAP, flash point, evaporation rate, solvent strength, ozone depleting potential, global warming potential and toxicity are covered. Good reference for data on the available solvent alternatives. Methodology is practical but very specific to solvents alternatives.*

Air Force, Navy, DOE

Tiley, Jaimie, "Solvent Substitution Methodology using Multiattribute Utility Theory and the Analytical Hierarchical Process", Department of the Air Force, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH. *This thesis presents a multicriteria decision making methodology for ranking alternatives to solvent cleaning. It compares Multiattribute Utility Theory and the Analytical Hierarchical Process. The cleaning situation studied is general cleaning of aircraft engine components. There were problems associated with both decision models including independence constraints and scaling issues. The author used group decision making scoring (1-7) in four areas: environmental impact, health/safety, process compatibility, cleaning effectiveness. Important attributes within each category were chosen by survey. Interesting to note which attributes were chosen in the environmental impact and health/safety categories (p 46.)*

"Hazardous Material Life-Cycle Cost Model" L.A. Hermansen et al., Naval Health Research Center, Technical Document 93-4D. *This is a user's manual for the software. The model includes five phases: r&d, acquisition, construction, maintenance/repair and final disposition and looks at the probability for no exposure, above PEL for personal exposure, and unacceptable environmental exposure. The following cost factors are used: claims and compensation, disposal, engineering controls, fines and penalties, medical surveillance, medical treatment, permits and certification, personal protective equipment, procurement, spill containment andcleanup, storage, training, and workplace monitoring.*

Booth, Steven, Linda Trocki and Laura Bowling, "A Standard Methodology for Cost-Effectiveness Analysis of New Environmental Technologies", Los Alamos National Laboratory, June 22, 1993. *This methodology is used to assess the cost-effectiveness of environmental technologies under development. The steps of the methodology are: define the technologies, define the system, characterize the performance (minimum exposure to hazardous materials is included here) and develop life-cycle cost of alternatives. Uncertainty and environmental risk are included. Tailored for use on evaluation of remediation technologies. Not practical for small-med business decision making use.*

Other

"The Haze Around Environmental Audits" Technology Review, April 20, 1992.
Environmental audits - cradle to grave analyses
"it makes more sense to do the studies within a given industry an limit analysis to which product or process uses less material and energy and, therefore, is environmentally more benign.'

Pekelney, David, "Analyzing Environmental Policies for Chlorinated Solvents with a Model of Markets and Regulations", A RAND Graduate School Dissertation, November 1990. *This report presents a model of chlorinated solvent markets and regulations. The model gives possible outcomes of specific policy decisions concerning the solvents. Good background of solvent market at that time.*

Keoleian, Gregory A. "Pollution Prevention Through Life-Cycle Design" Industrial Pollution Prevention Handbook by Harry Freeman McGraw-Hill, Inc. 1995.
Product Life Cycle can be organized into the following stages:

Raw material acquisition
Bulk material processing
Engineered and specialty materials production
manufacturing and assembly
Use and service
Retirement
Disposal

Environmental requirements should be developed to minimize:

Use of natural resources (particularly nonrenewables)
Energy consumption
Waste generation
Health and safety risks
Ecological degradation

Jacobs Engineering Group, "Source Reduction and Recycling of Halogenated Solvents: Life-Cycle Inventory and Tradeoff Analysis", 1992. *This report examines the tradeoffs of the substitution of aqueous cleaning for vapor degreasing and supercritical CO2 paint spraying for traditional airless paint spraying. First a lifecycle inventory was taken then the results used to develop a framework for impact comparison and tradeoff analysis. This report describes the Impact Analysis Matrix which is defined by five categories of resource utilization and emission parameters (material inputs, energy inputs, atmospheric emissions, aqueous wastes and solid wastes) and seven categories of environmental impact or risk areas (global warming, ozone depletion potential, non-renewable resource utilization, air quality, water quality, land disposal and transportation effect). Results of the analyses are dependent on the scope of the lifecycle inventory.*

Grimsted, Bradley, et al., "A Multimedia Assessment Scheme to Evaluate Chemical Effects on the Environment and Human Health" Pollution Prevention Review, Summer 1994, pp. 259-268.
This article presents a model for calculating a common unit of measure - the Pollution Unit - that allows comparisons of potential relative effects of chemicals on different environemental media. The scheme that is presented incorporates environmental and human health factors (using ambient standards and regulatory criteria) but can be adjusted to stress one over the other or may be developed to incorporate occupational standards if worker health is of primary concern. Authors boast easy to use, technically defensible and versatile as words to describe the model. Ease of use must depend on the sophistication of the person using it. The model does not seem practical for small businesses.

Baumann, Henrikke and Tomas Rydberg, "Life Cycle Assessment: A Comparison of Three Methods for Impact Analysis and Evaluations" Journal of Cleaner Products, Volume 2, Number 1, 1994, pp. 15-20.
This paper evaluates three methods for impact analysis and evaluation for comparing different types of emissions: the exological scarcity method, the environmental theme method and the environmental priority strategies in product design method. The goal of each method is to set a one dimensional value on resource use and emissions in order to calculate the total environmental impact of a product.