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AN EVALUATION OF ALTERNATIVE CLEANING METHODS FOR REMOVING AN ORGANIC CONTAMINANT FROM A STAINLESS STEEL PART

Jennifer L. Boyd

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NOTICE

BETTIS ATOMIC POWER LABORATORY WEST MIFFLIN, PENNSYLVANIA 15122-0079

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ABSTRACT

AN EVALUATION OF ALTERNATIVE CLEANING METHODS FOR REMOVING AN ORGANIC CONTAMINANT FROM A STAINLESS STEEL PART

Jennifer L. Boyd, B.S.
Carnegie Mellon University

As of December 1995, the manufacture of Freon, along with many other chlorofluorocarbons (CFCs), was prohibited by the Clean Air Act of 1990 (CAA). The ban of CFC solvents has forced manufacturers across the country to search for alternative metal cleaning techniques. The objective of this study was to develop a thorough, scientific based approach for resolving one specific manufacturer's problem of removing organic contamination from a stainless steel part. This objective was accomplished with an approach that involved: 1) defining the problem, 2) identifying the process constraints,

3) researching alternate cleaning methods, 4) researching applicable government regulations, 5) performing a scientific evaluation and 6) drawing conclusions.

The research documented herein indicates that there is a wide range of alternative cleaning methods to consider. This wide range of alternatives, combined with a vast array of government environmental and safety regulations, made the selection of a new cleaning method very complex. Because of this complexity, only one small aspect of the selected cleaning problem was addressed in this study. Furthermore, the research indicates that most manufacturers have selected replacement cleaning methods in an ad hoc or subjective manner. Consequently, this evaluation met an additional challenge by developing a systematic method for ranking cleaning process alternatives. The method was modeled after the "house of quality", which is the basic design tool of the Quality Function Deployment (QFD) management approach that originated in Japan in the 1970's.

The evaluation results confirm that alternate solvent cleaning methods are the most viable short term option for removing organic contamination from stainless steel in this application. A comprehensive list of alternate solvents was generated, many of which were tested in a laboratory experiment to determine their solvency and evaporation characteristics. The top three ranked solvents, Borothene, Bioact 145 and Navy Solv 77, based on the "scores" determined by the quantified ranking method, were selected as promising candidates for the new part cleaning process. It is recommended that more extensive and equipment-specific tests be performed on the top three solvents before making a final cleaning system decision. As a long range plan, it is recommended that additional development on plasma and laser surface cleaning techniques be explored.

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1.0 INTRODUCTION

1.1 Project Background

Stainless steel parts produced in an automated fabrication line occasionally become contaminated with an organic lubricant. Because the next step in the process requires the parts to be clean, for years, they were automatically cleaned with a solvent degrease process. Each stainless steel part had been directly immersed into a degrease tank filled with a Freon based solvent. However, as of December 1995, the manufacture of Freon, along with many other chlorofluorocarbons (CFCs) was prohibited by the Clean Air Act of 1990 (CAA). This manufacturing restriction had two main effects: 1) it drastically increased the price of Freon and 2) it indicated that eventually Freon solvents would not be available for purchase. These effects prompted facility management to eliminate the Freon based cleaning process approximately three years ago.

At that time, an automated replacement process for cleaning the parts had not been developed, and was expected to require extensive investment and testing. Therefore, a search for an inexpensive, immediately available cleaning alternative was initiated. As a short term solution, the process was modified to include a manual cleaning station. Since installed, the manual cleaning station has been staffed with one operator, for three shifts a day, during product fabrication. This operator makes a visual assessment of each part's cleanliness and then wipes off the contaminant with an isopropyl alcohol (IPA) soaked cloth as needed. The cleanliness monitoring and cleaning operations for one part are completed in under three minutes so that it can be returned to the fabrication line when cued by the operating system.

The part, at the phase of production where cleaning is required, is essentially a thin stainless steel sheet. An industrial organic compound is used as a process lubricant. The organic lubricant should typically not come in contact with the part, however, the part's surface can acquire a film of this organic lubricant during product fabrication. Process modifications have been able to reduce the degree of product contamination, but have not eliminated it.

In the years since the Freon bath was phased out, the following process modifications were investigated as possible solutions: 1) replace the organic lubricant with a water-soluble lubricant, 2) eliminate cleaning of the part entirely and 3) reduce the frequency of cleaning parts (i.e. sample clean). Since the current organic lubricant is viscous, oily and difficult to solvate, replacing it with a water-soluble alternative was considered as a way to potentially make the part easier to clean. The search for an effective water-soluble lubricant was unsuccessful; none of the alternatives were able to meet the stringent process requirements.

Subsequently, a proposal was submitted to either entirely eliminate or reduce the frequency of part cleaning. This proposal was extensively evaluated by a cross-functional team consisting of representatives from design, materials, shop operations, quality and manufacturing. The results of this evaluation indicated that part cleanliness is directly linked to the quality of the end product and that any reduction in the level of part cleanliness will lead to a direct decrease in product quality. Since the end product's high quality level must be maintained, management has concluded that the current method of monitoring the part for cleanliness must continue and that a better way to clean the part must be developed for the long term.

1.2 Project Introduction

Initially, the solution to this cleaning problem seems to be a straightforward selection of another cleaning solvent. However, the problem's underlying complexity becomes apparent as current information on regulatory issues and metal cleaning alternatives is presented. This research reveals that there are many possible solution paths all of which require a high degree of interaction between business functions, as well as, different processing equipment and environmental controls. Consequently, it is unrealistic to attempt to completely resolve this cleaning problem in one experimental evaluation. As a result, the objective of this project is to perform a preliminary evaluation of alternative cleaning methods upon which subsequent more extensive and equipment-specific tests can be based.

The remaining sections of this report document the research that was conducted and the preliminary test evaluations that were performed while trying to find a better way to clean the stainless steel part. In Section 2, the cleaning problem and its design constraints are explicitly defined. Sections 3 and 4 provide an overview of the background research that was conducted on alternative metal cleaning techniques and environmental regulations. Section 5 describes the test plan that was followed and the unique cleaning option evaluation method that was developed. This option evaluation method was modeled after the "house of quality", which is the basic design tool of the Quality Function Deployment (QFD) management approach that originated in Japan in the 1970's.(1) Finally, the test conclusions and recommendations are reported in Section 6. Appendices containing product information, test procedures, raw data and the complete details of the QFD analysis are also provided.

2.0 PROBLEM STATEMENT

The initial problem statement "find a better way to clean the part" provides a good project starting point, however, it is too vague for a valid technical evaluation of cleaning alternatives. The first step taken in clarifying this problem statement was to define what is "a better way". This was primarily accomplished by examining the advantages and disadvantages of both the original automated Freon bath and the current manual wipe cleaning methods. Further problem definition was then provided by outlining all of the cleaning process design constraints. Finally, additional consideration was given to the desired level of part cleanliness, to determine what "to clean" means.

2.1 Process Comparison

The "old" Freon part cleaning process was obviously a problem because of its adverse environmental impact. However, Freon was clearly an ideal solvent for three key reasons: 1) it was easily and inexpensively incorporated into the automated process, 2) it had good solvency for removing the organic contaminant with minimal agitation and 3) it rapidly evaporated allowing the part to continue processing in under three minutes. The drawbacks and advantages of the current manual part cleaning process are not quite as apparent. The drawbacks of the manual wipe process include high labor costs, ineffective contaminant removal and potential quality problems, while the advantages are centered on minimal environmental impact, low solvent cost and simple implementation. Table 1 summarizes the comparison of these two cleaning methods, and identifies the pluses and minuses for each.

TABLE 1 - PROCESS COMPARISON

Freon Degreaser		Manual Tool Wipe	
Adverse Environmental Impact	-	Acceptable Environmental Impact	+
Easily/Inexpensively Automated	+	Entirely Manual/High Labor Cost	-
Good Solvency for Contaminant	+	Poor Solvency for Contaminant	-
No Part Contact-Immersion	+	Part Contact During Wiping	-
"Flash" Evaporation	+	Drops Evaporate in 1-2 Minutes	-

Initially, the manual part cleaning process was considered cost effective, since IPA is inexpensive and since the process can be implemented without complex equipment. However, because the overhead rate in this facility is quite high, the manual wipe process is actually extremely costly. Consequently, any new cleaning method that can be easily automated with a reasonable capital investment, as was possible with the Freon process, has the potential of generating a sizeable cost savings.

When the manual part clean station was established, IPA was selected as the wipe solvent simply because it was inexpensive, environmentally acceptable and available. However, the operators have since reported that IPA does not have good solvency for the organic contaminant. The IPA wipe actually tends to smear the contaminant rather than dissolve it. In addition, since the part is a thin stainless steel sheet it can be easily deformed if excessive force is applied. The physical contact with the part occurring during the manual wipe process may cause part deformation.

Furthermore, although IPA has a relatively rapid evaporation rate (drops will evaporate in 1 - 2 minutes), it does not "flash" evaporate in seconds as the Freon did. As a result, some solvent may still remain liquid on the part after it has been wiped. If liquid residue is left on the part the end product could be degraded. Both part deformation and liquid residue lead to an increased number of product defects and thereby reduce manufacturing yield.

2.2 Design Constraints

Several other process design constraints, beyond those highlighted above, must be considered when evaluating improvements to the part cleaning process. All of the key process design constraints are summarized in Table 2. A description of those constraints not already discussed is provided below.

As mentioned in the project background, when the fabrication process is in automatic mode, the part needs to be cleaned within three minutes. After three minutes the part must be returned to the line to support the product fabrication process. Lengthening the part cleaning cycle time would result in line stoppage and delays in product delivery dates. Furthermore, not only must the part be cleaned within three minutes, but it must also be thoroughly dry when it is returned to the processing line.

TABLE 2 - CLEANING PROCESS DESIGN CONSTRAINTS

•	Complies with government regulations
•	Effectively removes organic contaminant
•	Cost effective
•	Does not impose high mechanical loads on the part
•	Has a limited potential for leaving liquid residue on the part surface
•	Cleans and drys part in less than three minutes
•	Does not thermocycle the part
•	Does not increase the humidity of the facility
•	Has minimal explosive risk

Limiting the amount of part thermocycling is another critical design concern. The part becomes degraded if its temperature exceeds approximately 180° F. If the part reaches this temperature during fabrication, it will not assemble properly. Consequently, the part should not be exposed to elevated temperatures during the cleaning process.

The final two key process design constraints relate to the atmosphere of the manufacturing facility. First, the enclosure humidity must be controlled to a fairly low level, since the equipment is primarily constructed of tool steel components. To effectively maintain low humidity levels, the cleaning process should not promote excessive moisture build-up that could lead to accelerated equipment rusting and an increase in equipment downtime. Second, it is desired to keep all aspects of the cleaning process as inert, stable, and nonflammable as possible to limit the risk of facility damage. Therefore, explosive hazards should be avoided when evaluating cleaning process alternatives.

2.3 Cleanliness Level

Up to this point, the phrase "to clean" has been used rather loosely. However, before an accurate evaluation of cleaning alternatives could be performed, the desired level of part cleanliness had to be defined. There are a variety of methods available to assess the cleanliness level of a surface. These methods vary from visual inspections such as wipe and water break tests, up to complex supercritical fluid extraction techniques. A water break test consists of simply immersing the surface in water and observing if the retained water forms a continuous, unbroken film as the surface is tilted. Conversely, supercritical fluid extraction involves removing whatever soil might remain on the surface and then extensively analyzing the extraction by spectroscopic methods. Several commonly used cleanliness standards, listed in order of increasing sophistication, are provided in Table 3.

Although it is generally accepted that the part does not need to be atomically clean, a desired part cleanliness level is not specified in the current cleaning procedure. Furthermore, complex or extensive surface cleaning evaluations of the part have never been performed or required in the history of the process. Discussions with product design and quality assurance groups have confirmed that the main concern is to remove gross amounts of organic contamination from the part. All agreed that the part cleaning process does not need to be a precision clean operation and that acceptable removal of the contaminant can be based on visual observation. Ultimately, the consensus was that the part is clean when all visual evidence of the organic contaminant has been removed.

TABLE 3 - COMMON CLEANLINESS STANDARDS

Visual Observation
Cotton Swab to Probe Critical Areas
Tissue Wipe
Black Light Inspection
Water Break Test
Optical Methods (Microscope)
UV Spectrophotometer
Fourier Transform Infrared Spectroscopy
Super Critical Fluid Extraction

Incorporating the above clarifications, constraints and definitions into the problem statement results in the following revision: "Develop an alternative method to remove all visual evidence of the organic contaminant from the part, that will meet the constraints of: 1) Government Regulations, 2) Manufacturing Facility (cycle time, humidity, explosive risk), 3) Product Quality (contact, thermocycle, solvent residue) and 4) Affordability.

3.0 SURVEY OF ALTERNATIVE CLEANING METHODS

For years, chlorinated solvents offered a robust solution to the problem of removing oils and greases from metal products. Now, as a result of the Clean Air Act (CAA), chlorinated solvents have been phased out in favor of protecting the stratospheric ozone layer. Over the past decade, numerous manufacturers have sought replacements for ozone-depleting chemicals (ODCs), such as Freon, to use in various cleaning operations. For many applications, aqueous and semi-aqueous cleaners have been found to be effective replacements, however, there are still many applications where water based cleaning cannot be employed. CFCs were miracle solvents that did a remarkable job of removing all types of contaminants and leaving surfaces free of residue and essentially dry. In most cases, the relative ease of CFC metal cleaning has been replaced with a complex cleaning operation.

Six different cleaning options were identified for replacing chlorinated solvent systems. As shown in Table 4, these options range from traditional metal cleaning methods to new high technology based plasma and laser systems. The traditional metal cleaning systems include: aqueous systems, in which water is combined with a solvent or surfactant in the initial wash cycle; semi-aqueous systems, which use a pure solvent in the wash cycle, followed by a water rinse, and solvent-based systems which eliminate the use of water altogether.(2) Although universal solvents such as xylene, toluene, and acetone are available alternatives, many have health and safety problems such as flammability and carcinogenic behavior, and most are regulated as hazardous air pollutants. As a result, there has been a strong emphasis in the chemical industry on developing new solvents that meet the increasingly stringent environmental regulations and still clean effectively. Furthermore, there have been significant strides made in higher technology based cleaning methods such as laser, plasma and blasting cleaning techniques.

TABLE 4 - ALTERNATIVE PART CLEANING METHODS

Aqueous Cleaning
Semi-Aqueous Cleaning
Alternate Solvents
Blasting Techniques
Plasma Surface Cleaning
Laser Surface Cleaning

3.1 Aqueous Cleaning

Aqueous detergents are known to be environmentally friendly and are usually nontoxic or low in toxicity. In addition, aqueous products do not contribute to ozone depletion or global warming, and are not classified as volatile organic compounds (VOCs). Aqueous cleaners usually contain water, surface active agents, wetting agents, and dispersants. Typical aqueous cleaners include caustic solutions and organic formulations. Many manufacturers are using what are termed mild-mannered aqueous surfactants.

Citrosphere, for example, is an extract of orange and lemon peel that emulsifies in water and frequently replaces solvent cleaners.(3) Citrate based detergents, which have almost entirely replaced phosphates, are not only biodegradable, but are also generally recognized as safe to use. Some manufacturers have found that the latest aqueous cleaning formulations are removing contaminants which solvents were unable to remove.

Simple detergent and water cleaning solutions are well understood and require only a moderate capital investment to implement. However, in typical industrial applications, aqueous cleaning systems use hot water and detergent in an extensive four-step process: wash, rinse, dry and treat waste-water. Aqueous equipment becomes complex as the number of baths, rinse stations, and drying operations increase to achieve the necessary environmental compliance and cleaning process effectiveness. As equipment complexity increases, so does the cost. Aqueous systems can run up to $200,000 in equipment not including maintenance and water treatment. Manufacturers who have made the change to aqueous cleaning report that the conversion was more complex and time consuming than was initially projected.

Aqueous cleaning poses many handling and processing problems not previously encountered with solvent systems. The cleaning power of aqueous detergents is generally good, however, problems arise in the rinse, dry and waste-water treatment operations.

3.1.1 Rinse Operation

Aqueous cleaners require component rinsing following the clean cycle. Often this rinse operation can be as complicated as the cleaning step. Although the focus of a cleaning process is generally on removing contaminants, it is also very critical to remove all evidence of the detergent.(4) If the detergent is not entirely removed, the surface may spot. Frequently, the major cost of operating an aqueous cleaning system is the creation of high quality deionized (DI) water needed for spot-free rinsing. Even with moderate rinse water flow rates, the rinse water costs represent 20 to 25% of the total aqueous cleaning system operating expense. In addition, the rinse operation has been known to cause corrosion problems even with stainless steel parts. However, many aqueous processes have been successful at eliminating corrosion concerns by adding a rust inhibitor either in the basic cleaning chemistry or in a step prior to the drying operation.

3.1.2 Drying Operation

Without the assistance of solvents, the drying operation in an aqueous cleaning system can add significant capital and operating costs.(5) Drying can rarely be accomplished by simply allowing cleaned parts to air dry.(6) Component drying time will depend on the cleaner's evaporation rate and on the amount of cleaner remaining on the part. Generally, a drying step using hot air or compressed air is added to accelerate the drying process. Often, drying is accomplished with super hot air, forced air, infrared, high velocity air knives or vacuums.(7) Overall, drying can constitute a very high, and new energy cost and is often a key decision point after quality concerns have been addressed.

3.1.3 Waste-Water Treatment Operation

Waste water treatment is another major factor in choosing an aqueous cleaning process, even if substrate compatibility and cleaning effectiveness have been proven. Manufacturers are faced with a confusing array of federal, state and local emissions regulations that can make water treatment a time consuming issue. Industry experience has shown that many aqueous detergents have caused severe problems when introduced into waste treatment operations. Since aqueous rinse operations can use such a large amount of water, the capacity of the facility wastewater treatment system must be considered as well. Some aqueous cleaners can be selectively filtered with membranes that remove contaminants but allow cleaning components to pass through. This regeneration maintains a fresh cleaner and extends the operational life of the cleaner. (8)

Wastewater discharge can be reduced even further by employing a closed-loop no-drain water treatment operation. Membrane separation technology must be used for a closed-loop water reuse to be effective. Typically, the debris captured in the membrane is the only solid waste by-product of the cleaning process. Finally, evaporation is a another safe and economical form of water treatment that works well for both continuous rinse water streams and spent baths.

3.1.4 Industry Experience with Aqueous Cleaning

To ensure consistent precision cleaning and spot-free drying, the Aerospace Guidance and Metrology Center uses high-quality deionized water and a filtered compressed-air drying system in their repair of inertial guidance and navigation systems.(9) In their CFC replacement process the compressed air is filtered and delivered through a hand-held blowing device, while the water is recirculated through a deionizing system to prevent build-up of contaminants. Since implementing this conversion, the Center has found that their product quality has increased, while the cleaning process cost has decreased. The Kyzen Corporation also reports that, for the various aqueous cleaning chemistries evaluated in their experiments, aqueous detergents consistently cleaned better than their CFC cleaning standard.(10)

In contrast, the Ford Motor Company has found that water-based cleaning is not appropriate for many of their parts because of the corrosion potential and the long drying times associated with the water residue.(11)

3.2 Semi-Aqueous Cleaning

Organic cleaning chemistries that are not soluble in water are considered semi-aqueous products. Semi-aqueous cleaners are usually comprised of organic acids such as terpenes. This type of cleaner typically operates full strength in the bath without dilution.

In a semi-aqueous cleaning system, the parts are usually cleaned in one organic solution and then rinsed either in the same solution or in a second product with a faster drying rate. Excellent ability for removing organic contaminants with modest rinsing characteristics typify the semi-aqueous products. Since a semi-aqueous process generally needs only two process tanks and a drying stage, it takes up less facility space than a comparable full aqueous process. However, as with the aqueous cleaning systems, semi-aqueous cleaning has several disadvantages.

Operational costs for semi-aqueous systems are somewhat higher than for aqueous processes. Capital investment for semi-aqueous systems can extend up to $250,000 for an fully automatic system. Water treatment will add another $20,000 to $50,000 in up-front costs.(12) Semi-aqueous systems also have the potential for generating reactive and/or odorous emissive releases.(13) Compared to aqueous systems, certain semi-aqueous solutions may present somewhat greater concerns for toxicity, flammability, and VOCs. In addition, the parts being cleaned must be compatible with water, since it is still present in the cleaning process.

3.3 Alternate Solvents

Recent advances in solvent-based products and technologies are making the option of maintaining a solvent cleaning system more attractive. Many non-halogenated alternative solvents are currently available, as shown in Table 5. For example, aliphatic hydrocarbons and terpenes can offer a very economical process that is advantageous for metals with corrosion potential because of the elimination of water from the process.(14) However, the evaporation rates of these and other non-halogens are much slower than the traditional halogenated solvents, thereby eliciting the same drying concerns identified for aqueous cleaning. Shell Oil Company is one of the many solvent manufacturers working towards developing materials with higher flash points that are still strong solvents and quick evaporators.(15)

TABLE 5 - ALTERNATE SOLVENTS

Aliphatic Hydrocarbons	Perfluorocarbons (PFCs)
Terpenes	Hydrochlorofluorocarbons (HCFCs)
Isopropyl Alcohol (IPA)	Hydrofluorocarbons (HFCs)
Methyl Siloxanes	Hydrofluoroethers (HFEs)

Ney Ultrasonics points out that if a precision cleaning level is not needed, a solvent/solvent process can be a cost effective way to handle the in-process cleaning and drying needs.(16) The solvent/solvent approach goes back over thirty years, prior to the adoption of CFCs, when mineral spirits or some other type of organic chemical was used as a rinsing agent. This concept involves using an effective cleaning solvent, which typically has a slow evaporation rate, in the first step, followed by a rapid evaporating solvent, which is generally not a good cleaner, in the second step.

IPA is often touted as a potential replacement for CFC solvents, although it is flammable, a VOC concern, and has already been identified as not having effective solvency for removing the organic contaminant. Similarly, solvents containing methyl siloxanes are advertised as effective CFC alternatives, although they are flammable materials that require special handling and disposal. Unlike IPA, however, methyl siloxanes are quite expensive.

Perfluorocarbons (PFCs), are also marketed as prospective CFC alternatives. PFCs are effective cleaners, but their use is discouraged because of their high cost and high global warming potential. Essentially the three main disadvantages with the perfluorocarbon solvents are: 1) high cost, the least expensive range between $150 and $200 per gallon, 2) poor solvency, experience shows that they are not effective at removing oils and greases, and 3) they contribute to global warming because they can not break down in the lower atmosphere.

Despite all these disadvantages, the Ford Motor Company has been successful in their adoption of an advanced vapor degreasing system using perfluorocarbons.(18) Ford recognizes the global warming potential of these products, but believes that their system will make no measurable contribution to global warming because of the small emission potential of their new equipment. Based on recent regulatory status reports, Ford appears to be taking quite a risk. The EPA is concerned that the PFC compounds have no mechanism to break down in the atmosphere, and consequently have threatened to restrict the use of them to narrowly defined purposes.(19)

Ford's new equipment, an ultra-tight degreaser, was designed for almost complete solvent containment.(20) The system is totally enclosed so that the solvent to air interface is eliminated. It appears that the key to continued use of vapor degreasers is vapor recovery. As proven by the Ford experience, vapor degreasing with any of the currently available solvents will require extensive system modifications to control emissions.

Although hydrochlorofluorocarbons (HCFCs) were the first alternative solvents to come to the market, their use is not that prevalent. The use of HCFC solvents is limited because they are restricted by the EPA due to their ozone depletion potential, which is similar to that of Freon. Hydrofluorocarbon (HFC) solvents, another alternative, are reported by chemical manufacturers as having moderate solvency and a rapid evaporation rate. However, industry tests have shown that HFCs actually have poor solvency and only a moderate evaporation rate. The cost per gallon for HFCs rivals that of PFCs, but global warming potential is not an issue. The equipment required to economically use the HFC products ranges from $50,000 to $100,000 in a batch design.

Hydrofluoroethers (HFEs) are another type of alternate solvent. HFEs are still in development and are under safety review, but they are reported to have passed preliminary tests with flying colors.(21) Chemical manufacturers have indicated that the HFEs will have solvency properties that lie between those of the ozone depleting solvents and the PFCs. Most HFEs under consideration are also nonflammable. The HFE based product being developed by the 3M Company is expected to be in full commercial production by the end of 1996.

Even though there are a multitude of new solvents available, many of which have desirable properties, alternate solvents are often not considered good replacements due to ozone depletion concerns, possible groundwater contamination, and future solvent toxicity status.

3.4 Blasting Techniques

Often blasting type cleaning techniques are recommended as CFC replacements because of their zero ozone-depletion potential, nonflammability and low toxicity.(22) However, blasting techniques such as supercritical fluid cleaning processes can only be used for parts that will not be harmed by the high temperatures and pressures applied during the process. A high pressure is required to achieve the supercritical state, which necessitates a special processing vessel and which can damage delicate parts, like the one under evaluation in this study. Furthermore, it is estimated that the initial capital investment for a supercritical carbon dioxide cleaning system is between $50,000 and $150,000. There are other blasting type cleaning methods available, such as high pressure water jet and wheat-starch crystals, but they are also judged to be too damaging for this application.

3.5 Plasma Surface Cleaning

Cold gas plasma cleaning processes use a radio frequency field to transform very small amounts of innocuous gases, such as air, oxygen and argon, into a highly chemically reactive and aggressive environment. While the energy of a plasma is sufficient to break chemical bonds in the contaminant material, the overall temperature of the process is essentially ambient. The gas particles collide and transfer energy to form free radicals, atoms and ions. These particles then bombard and interact with surface contaminants, thereby breaking them down.

Plasma surface treatment is currently being marketed as a potential dry cleaning technique to replace solvent-based processes. Plasmas have frequently been used in industry as a last step surface preparation technique prior to joining operations. The limiting factor in the usefulness of plasma cleaning is the rate at which organic materials are removed. Currently, most plasma cleaning processes are limited to removing particulate contamination on relatively small parts. It is expected that significant development will be required to adapt this process for removing bulk contamination, on large surface areas, with rapid cycle times.

3.6 Laser Surface Cleaning

Laser surface cleaning methods are another highly promising, environmentally friendly cleaning alternative. Many of the processes currently available use a laser to break the bond between the surface and the contaminant, and then use a flowing inert gas, such as argon, to sweep away the contaminants. In the simplest configuration, the cleaning process is comprised of a pulsed ultraviolet radiation source (laser), focusing optics and a gas delivery system. The energy flux in these processes is typically not sufficient to cause ablation or heating of the part surface. Also, these processes generate only minute amounts of solid waste. The removed non-toxic contaminants can be exhausted directly into the environment, while the toxic particles are trapped for proper disposal.

Similar to the plasma cleaning processes, laser cleaning has been typically used for removing microcontamination from small parts. As a result, significant process changes, with extensive development, would be necessary to provide the capability to remove thicker films, across large surface areas.

3.7 Alternative Cleaning Method Summary

In general, a wide variety of manufacturing process changes have been implemented across industry in an effort to replace the banned CFC solvents. Also, because conversion costs are so case-specific, effective cost comparisons for evaluating the affordability of the various options were hard to come by. However, after considering all identified alternative part cleaning methods, alternate solvents were judged to be the most promising short term option. Although aqueous and semi-aqueous cleaners have been successfully implemented as CFC replacements in many cases, the disadvantages related to this particular part cleaning application were found to be overwhelming. Any water-based cleaning system would require extensive evaluation to properly consider corrosion concerns, ensure spot-free drying, and provide effective waste-water treatment. Also, it is projected that developing and implementing a water-based part cleaning system for this application would involve a large capital expenditure and major renovation to an existing facility. The viability of the potentially less costly and less complex alternate solvent cleaning options should be investigated before a high level of investment is made in aqueous cleaning methods.

Furthermore, blasting techniques, due to their high pressure and aggressive nature, were deemed inappropriate for cleaning a relatively delicate part. Finally, laser and plasma surface cleaning techniques appear to be very promising for this part cleaning application. However, given that these processes are in relatively early stages of development, it is expected that several years of process development would be required to advance them to the point of providing an effective, real-time part cleaning process.

4.0 OVERVIEW OF GOVERNMENT REGULATIONS

When researching government regulations that relate to industrial cleaning processes it is important to adopt a life cycle assessment approach. In this study, life cycle assessment was used as a decision paradigm for incorporating both upstream and downstream effects. This cradle to grave philosophy assured that hidden environmental and regulatory costs were exposed for each cleaning alternative. The purpose of this research was to identify the environmental and safety regulations associated with all aspects of a cleaning process, from the production of the cleaning medium, to the disposal of the contaminant residue.

The regulatory issues surrounding an industrial cleaning process naturally fall into two categories: rules governing what goes on inside the plant and rules governing what goes on outside the plant (the environment). The Occupational Safety and Health Act (OSHA) is mainly responsible for ensuring the safety of personnel and the atmosphere inside industrial plants, while environmental problems outside plant limits are largely the responsibility of the Environmental Protection Agency (EPA). As a result, the research on applicable government regulations has been conveniently divided into two sections: inside plant regulations and environmental concerns.

Based on the conclusion that solvent cleaning is the most viable option to pursue in the short term, only those regulations that specifically relate to solvent cleaning are reported. The first step in determining what regulations are applicable to solvent cleaning was to identify the types of hazards associated with prospective cleaning solvents. To do this effectively, solvent properties and characteristics had to be well known. The product material safety data sheet (MSDS) was the key source of product information for this study. The MSDS provides information on product identification, hazardous ingredients, physical data, fire data, reactivity, health hazards, safe handling and control measures. Also, most of the information provided on an MSDS can be traced back to some form of government regulation. The regulatory discussion that follows provides insight into and understanding of the many product characteristics reported in solvent MSDSs, as well as, establishes a foundation for determining the relative importance of solvent characteristics.

4.1 Inside Plant Regulations

The safety and environmental issues inside an industrial plant are mainly governed by OSHA. OSHA was established in 1970 in an attempt to reduce the number and severity of workplace accidents by making equipment and procedures safer by mandatory means. The OSHA regulations are defined in Title 29 of the Code of Federal Regulations, Part 1910 (29 CFR 1910).(22) Various fines and penalties can be imposed if these regulations are not followed, so it is essential that they are fully understood and factored into the development of new cleaning processes. With respect to solvents, OSHA is responsible for prohibiting exposure to certain materials, setting standards limiting exposure to toxic materials and ensuring that flammable materials are properly handled.

First, it is commonly known that OSHA prohibits personnel exposure to any chemical that has been suspected of carcinogenic activity. The regulations do allow some suspected carcinogens to be employed but only in specially controlled, safe areas. Many of the traditional, highly effective solvents including: methylene chloride, perchloroethylene, and trichloroethylene, are known to cause cancer in laboratory experiments. The additional cost of special handling procedures and sophisticated containment areas required to safely use carcinogenic chemicals can be quite high. For these reasons, any suspected carcinogen was excluded from the alternate solvent evaluation.

In addition, OSHA publishes and regularly updates a list of Threshold Limit Values (TLVs). TLVs are specified primarily for toxic agents that can enter the body through the respiratory system. Since cleaning solvents typically have a high evaporation rate, respiratory exposure is quite common. The TLV indicates the average concentration of toxic agent that can be tolerated during exposure for a 40 hour week continuously in a normal working lifetime.(23) TLVs are not complete indicators of a material's relative hazard, since a highly volatile material can be more dangerous than one less volatile but more toxic. Each solvent MSDS cites the TLV for product exposure as required by OSHA. In this study, the TLVs were used mainly for comparative purposes, and to estimate the cost of preventing personnel over-exposure.

Proper evaluation of the solvent's fire potential is also required since OSHA monitors the exposure and handling of combustible materials. In the past, solvent flammability has not been a big concern since the halogen atoms (i.e. chlorine, fluorine, and bromine) in solvents like the phased out Freon give the solvent molecules stability that makes them difficult to ignite. Consequently, most of the halogenated solvents, including Freon, are non-flammable. Unfortunately, some of the same halogens that give these solvents their flame resistant properties have been shown to damage the stratospheric ozone layer. This damaging effect has led the U.S. Government to ban production and usage of these types of chemicals, and has resulted in an urgent need for effective replacement solvents. Without the stability of the halogen groups, the inverse relationship between flash point and evaporation rate becomes an issue for most replacement solvents.

A product's fire causing potential is primarily based on its combustibility, flash point and evaporation rate; all characteristics that are typically provided on the MSDS. The combustion of a solvent depends not only upon the presence of fuel, air and an ignition source, but also on their relative proportions. There exists a range between pure air and pure fuel in which there is enough fuel and enough air present for the mixture to be combustible. This is called the flammable or explosive range and the endpoints of this range are known as the upper and lower flammability limits (see Figure 1). From a safety standpoint, lower flammability limits are of much greater interest than upper limits, since they indicate the lowest concentrations at which combustion can begin. The size of the flammable range depends upon the chemical composition of the cleaning solvent.

The lowest temperature at which a liquid fuel will give off enough vapor to form a momentarily ignitable mixture with air is called the flash point. A solvent's flash point serves not only as a guideline for safe use and handling, but it also provides a rough estimate of the solvent's evaporation rate. Generally, solvents that evaporate rapidly have

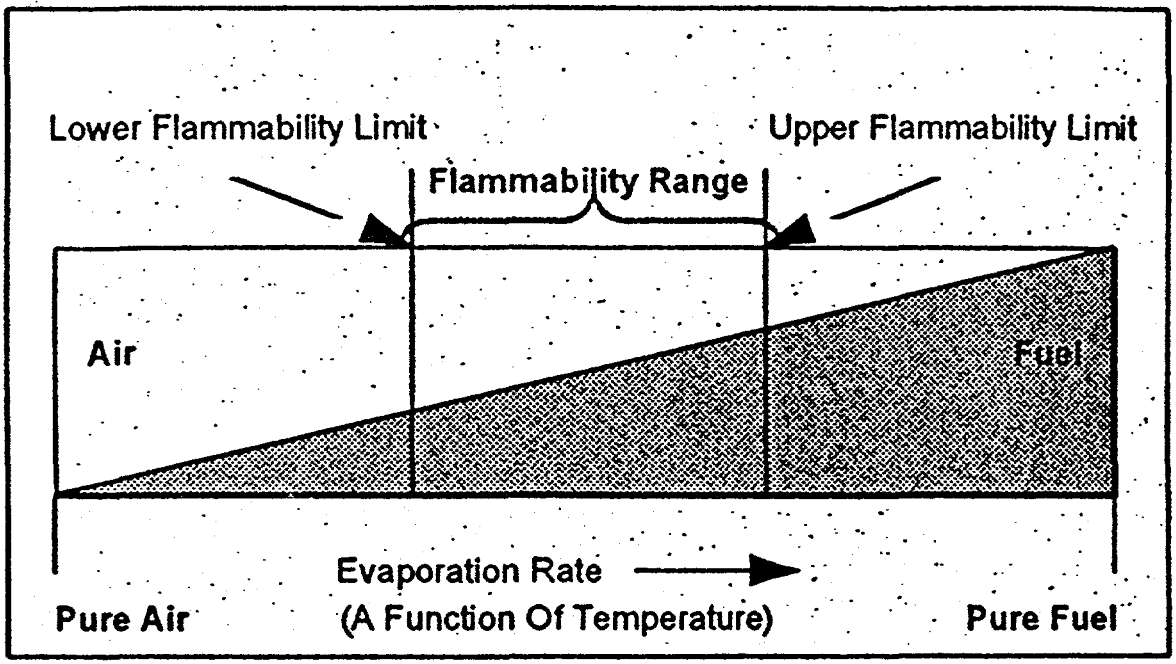

FIGURE 1 - TYPICAL SOLVENT COMBUSTIBLE RANGE

lower flash points, while solvents with high flash points evaporate slowly. Most MSDSs report the Pensky-Marten Closed Cup flash point. This is a standardized test (ASTM D93-85) in which a sample of solvent is slowly heated in a cup. The cup is covered to capture any vapor rising from the sample. After each degree of temperature increase, a flame from a special propane torch is inserted into the chamber, close to the liquid surface. The temperature at which there is a flash fire in the vapor, not the liquid, is reported as the flash point.

The inverse relationship between flash point and evaporation rate is just one of the many tradeoff decisions that must be made when selecting an alternate solvent. Fast evaporating solvents are generally easier to use and usually allow for a more rapid pass through the cleaning step. Conversely, slower evaporating solvents require a slower pass through the cleaning step but may offer advantages in the areas of fire safety and hazardous waste generation. Tradeoffs between opposing solvent characteristics are explored further in Section 5 - Alternate Cleaning Method Evaluation and Test Plan.

4.2 Outside Plant Concerns

Three categories of environmental regulations apply to solvent cleaning: atmospheric emissions, water borne wastes and solid wastes. Overall, the Clean Air Act, the Clean Water Act and EPA hazardous waste regulations have the largest impact on the selection of alternative solvents. Each of these regulations is detailed in the following paragraphs.

The Clean Air Act (CAA) is national legislation designed to identify and control pollutants and sources of emissions that may reduce the quality of the nation's air. The objective of the CAA is to restore and maintain the chemical, physical and biological integrity of the air. Title I of the CAA defines the source requirements relative to volatile organic carbon emissions. Similarly, Title III of the act establishes emission standards for air toxins or hazardous air pollutants (HAPs), which if released could seriously threaten human health or the environment. For materials designated as HAPs the EPA specifies the controls necessary to use them in terms of Maximum Achievable Control Technology (MACTs). Both the VOC and the HAP rating are important considerations when evaluating alternate solvents. Selecting a solvent with high ratings on either of these will increase both the cost of implementing the cleaning process and the chance that subsequent policy changes will impact the process's viability.

The need for this study on alternate part cleaning methods stems from the enactment of Title VI of the CAA Amendments of 1990. This act reduced threats to the stratospheric ozone layer by phasing out production and use of CFCs and other widely used chemicals believed to contribute to global warming. The metal cleaning industry was one of the largest users of CFC based products. Consequently, almost the entire industry has been thrown into a quandary regarding the replacement of these banned solvents. To assist the industrial solvent users, the CAA requires that the EPA identify alternatives to

Class I (CFC) and Class II (HCFCs) ozone depleting substances and publish a list of acceptable and unacceptable substitutes. This formal list of solvent alternatives is called the Significant New Alternatives Policy (SNAP) Program.(24) The SNAP list was consulted for each prospective substitute for the ozone depleting Freon to ensure that they did not create environmental problems themselves.

Similarly, the Clean Water Act (CWA) is a Federal statute that addresses the quality needs of the nation's waterbodies, with regard to both human and environmental concerns. CWA subpart G lists the bulk organic chemicals that are commonly found in wastewater resulting from the use of organic chemical groups such as: aliphatics, amines and amides, aromatics, and halogens. Since these chemical groups are predominantly found in solvents such as aliphatic hydrocarbons and cyclic amines, the restrictions of the CWA must be observed prior to the release of any solvent residue. This research has revealed that reference to the CAA and CWA is frequently not provided on the solvent MSDS, so that understanding of the applicability and restrictions of these acts must be obtained via other sources such as regulatory summaries and government publications.

In contrast, the Toxic Substances Control Act (TSCA) is a regulatory act that is always cited on a solvent's MSDS. This act includes regulations and testing requirements for every chemical substance that is manufactured for commercial purposes in the United States or that is imported for commercial purposes. One of the major goals of the TSCA is to develop a test database to determine which chemical substances and mixtures present an unreasonable risk to public health or the environment.

Finally, in support of a life cycle approach, the waste disposal regulations associated with solvent-based cleaning were identified. Hazardous waste issues that apply to solvent cleaning are mentioned briefly in 29 CFR 1910 Subpart H and Z, but are primarily governed by the EPA acts. These acts include the Resource Conservation and Recovery Act (RCRA), the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and the Superfund Amendments and Reauthorization Act (SARA) Title III. (25) Each of these acts are typically referenced on the solvent MSDS if they are applicable. The RCRA's primary purpose is to control the disposal of hazardous and solid wastes generated by various manufacturing processes and the air and water pollution control devices installed for those processes. Similarly CERCLA, also called the Superfund act, regulates the clean up of environmental contaminations made before and not covered under the RCRA. SARA Title III is actually an amendment to CERCLA which defines the community right to know and provides cleanup standards and schedules. The hazardous substances and reportable quantities for the chemical compounds regulated by CERCLA are found in 40 CFR 302.4 and are listed by Chemical Abstract Services Reference Number (CASRN). The constituents of each alternate solvent considered in this study were referenced against this list.

Before a waste can be deemed a hazardous waste, it must first meet the definition of a solid waste. A solid waste is any garbage, refuse, or discarded material, including solid, liquid, semi-liquid or contained gaseous material resulting from industrial, commercial or agricultural operations. A hazardous waste is defined as any solid waste which exhibits at least one of the following characteristics: ignitability, corrosivity, reactivity or toxicity. A Hazardous Material Identification System (HMIS) rating for each of these characteristics is provided on every MSDS. These hazards are ranked on a scale of "0" to "4", with "0" being the least hazardous rating. For consistency in product comparison, the "HMIS" rating system was used throughout this evaluation. Solvents having a rating greater than "2" in any characteristic were excluded from this study to comply with a corporate mandate that requires reduction in the amount of high level hazardous waste generated on site.

4.3 Regulatory Summary

As stated earlier, the scope of this project was constrained within performing a preliminary evaluation of one of the many possible alternative cleaning methods. In a limited study, such as this one, it was difficult to perform a comprehensive safety evaluation since the majority of the system details were not yet specified. However, it is worth mentioning that once the process concept is refined, a thorough safety analysis, such as a preliminary hazard analysis or procedural analysis, should be conducted to ensure that hazards are identified and corrected early in the development process. Accident protection and regulatory compliance can and must begin as soon as the idea for a new system is defined. The most effective method of avoiding accidents and maintaining regulatory compliance is with designs that are intrinsically safe.

The government regulations that apply to solvent-based cleaning, along with key observations that pertain to this study, are summarized in Table 6.

TABLE 6 - SUMMARY OF GOVERNMENT REGULATIONS THAT APPLY TO SOLVENT CLEANING

Inside Plant Regulations			Outside Plant Regulations		
Regulation	Description	Comments	Regulation	Description	Comments
OSHA - Carcinogens	Personnel exposure prohibited	Excluded from study	CAA	Clean air, bans CFCs and HCFCs	Want low VOC and HAP rating
OSHA - TLVs	Limits for exposure to toxic materials	Used for comparison and cost estimates	CWA	Clean water, sets limits for waste water discharge	Restricts discharge of some solvents
OSHA - Flammable Materials	Limits for fire control based on flash point	Trade off: high flash point vs. slow evaporation rate	TSCA	Testing for safety and environmental compliance	Noted on MSDS
			RCRA	Waste disposal and emission compliance	Noted on MSDS
			CERCLA	Clean up not covered under RCRA	Noted on MSDS
			SARA Title III	Community right to know, standards and schedules	Noted on MSDS
			HMIS	Hazardous waste rating	Rank > 2 excluded from study

5.0 ALTERNATE CLEANING METHOD EVALUATION AND TEST PLAN

The background information, as presented in the previous sections, established a basis for an experimental study by defining the problem, outlining the design constraints, selecting a reasonable short term alternative cleaning method, and identifying the applicable government regulations. On this foundation, a plan for evaluating the selected alternative part cleaning method was developed. Given that solvent cleaning was selected as the most viable short term part cleaning option, the objective of this evaluation and test plan was to rank the available alternate solvents in terms of their ability to "solve" the problem.

The evaluation of alternate solvents involved several steps. First, a list of solvent alternatives was generated. Then, the list was sorted to exclude those products with known undesirable characteristics. Next, the remaining alternatives were tested to determine key unknown product characteristics. Finally, because of the numerous design constraints, a creative method was devised to rank the alternate solvents based on their properties and characteristics. The solvent ranking method enabled conclusions to be drawn from quantified results, as well as, identified the most effective solvents for solving the cleaning problem. The evaluation plan is summarized in Table 7.

TABLE 7 - ALTERNATE SOLVENT EVALUATION PLAN

Evaluation Plan
1. Generate list of solvent alternatives.
2. Sort list to exclude undesirable characteristics.
3. Test remaining alternatives to determine unknown characteristics.
4. Devise creative method for ranking solvent alternatives.
5. Draw conclusions

5.1 List of Solvent Alternatives

Several sources, which included published literature, industry benchmarks and cleaning equipment suppliers, were used to generate a list of solvent alternatives. Information on solvent alternatives was readily available in technical literature. CFC replacement solvents are frequently advertised in trade journals and numerous articles on replacement solvents have been written since the CAA mandate, banning CFC based solvents, was issued. In addition, the majority of U.S. manufacturers who perform metal cleaning operations have faced or are facing a similar cleaning problem. Therefore, most of the companies contacted as part of this investigation were willing to share their experiences and alternate solvent recommendations. Cleaning equipment suppliers were also good sources for solvent suggestions, since they typically have been involved in the selection of alternate solvents for many different cleaning applications. However, the industry and supplier benchmarking data were limited in that none of the manufacturers consulted had faced a cleaning problem identical to that of removing the same organic based residue from stainless steel parts. From these three sources, thirty-two Freon replacement solvents were identified.

The list of replacement solvents, provided in Table 8, identifies the product and manufacturer name, the product type and the chemical type. Note that a few water-based and semi-aqueous alternatives were included in the list. Many of the references cited in Section 3.0 - Survey of Alternative Cleaning Methods indicated that water-based cleaning offers process improvements greater than traditional solvents in both cleaning effectiveness and environmental compliance. As a result, water-based products were included in the solvent evaluation plan simply to assess their potential with regard to this specific application.

5.2 Exclusion of Undesirable Characteristics

A copy of the product MSDS for each of the thirty-two replacement solvents was obtained from the product manufacturer or distributor. The product information provided on the MSDS and in accompanying product literature was entered into a spreadsheet to allow easy comparison of key product characteristics. The selection of key product characteristics was based primarily on the solvent properties and characteristics that have been identified in Section 4.0 - Overview of Government Regulations. The following

TABLE 8 - LIST OF ALTERNATE SOLVENTS

Product Name:	Product Manufacturer:	Product Type:	Chemical Type:
1. Borothene	Tulstar Products	Solvent	Halogenated Hydrocarbon
2. NMP	BASF	Solvent	Cyclic Amine
3. Vertrel MCA	DuPont	Solvent	Hydrofluorocarbon
4. Oxsol 100	Occidental Chemical	Solvent	Chlorinated Aromatic
5. Oxsol 10	Occidental Chemical	Solvent	Chlorotoluene
6. Navy Solv 77	Navy Brand	Solvent	Napthenic Distillate
7. Formula 200	Navy Brand	Water-based	Silicates/Alkylphenals
8. Dyna Terge	Navy Brand	Water-based	Glycol Ether/Limonene
9. Terpene Clean	Aerocote	Solvent	Aliphatic Terpene
10. Aerosolv 2000	Aerocote	Semi-aqueous	Glycol Ether
11. Aerosolv CB111	Aerocote	Solvent	Petrolatum Distillate
12. DN30	Aerocote	Water-based	Organic Surfactant
13. Actrel 3338L	Exxon	Solvent	Aliphatic Hydrocarbon
14. Purasolv IPL	Purac	Solvent	Isopropyl Lactate
15. Purasolv ML	Purac	Solvent	Methyl Lactate
16. Purasolv ELS	Purac	Solvent	Ethyl Lactate
17. Purasolv EHL	Purac	Solvent	Ethylhexyl Lactate
18. Axarel 2200	Petroferm	Solvent	Aliphatic Hydrocarbon
19. Axarel 4100	Petroferm	Solvent	Aliphatic Hydrocarbon
20. Axarel 6100	Petroferm	Solvent	Aliphatic Hydrocarbon
21 Axarel 52	Petroferm	Semi-Aqueous	Hydrocarbon
22 Axarel 56	Petroferm	Semi-Aqueous	Hydrocarbon
23. Bioact 121	Petroferm	Solvent	Terpene Hydrocarbon
24. Bioact 145	Petroferm	Solvent	Aliphatic Hydrocarbon
25. Bioact 105	Petroferm	Solvent	Aliphatic Hydrocarbon
26. Opticlear	National Diagnostics	Solvent	Food Oil Distillates
27. Opticlear W	National Diagnostics	Solvent	Pyrrolidinone
28. Opticlear S	National Diagnostics	Solvent	Alkyl Hydrocarbons
29. Opticlear R	National Diagnostics	Solvent	Food Oil/Corn Alcohol
30. Methylene Chloride	Dow Chemical	Solvent	Halogenated Hydrocarbon
31. Perchloroethylene	Dow Chemical	Solvent	Halogenated Hydrocarbon
32. Trichloroethylene	Dow Chemical	Solvent	Halogenated Hydrocarbon

product characteristics were included in the spreadsheet: flammability status, lower explosive limit (LEL), upper explosive limit (UEL), cost, toxicity, vapor density, boiling point, flash point, Kauri Butanol value, vapor pressure, heat of vaporization, odor, evaporation rate, TLV, HMIS hazardous waste ranking (health, fire and reactivity), carcinogen status, water solubility, Ph, SNAP listing, hazardous waste, regulatory listing (CERCLA, SARA, and TSCA), VOC rating, and HAP rating. Most of these solvent properties and characteristics are either self-explanatory, or have been previously defined, except for the Kauri Butanol value. The Kauri Butanol value is an index of solvency for hydrocarbon based products as defined by ASTM-1133; it essentially provides a measure of a solvent's cleaning power. The complete solvent spreadsheet is provided in Appendix A.

Seven of the products on the initial list of thirty-two were excluded from the study based on information highlighted by the spreadsheet. Oxsol 100 and Oxsol 10 were excluded because of their high halogen content and high VOC ratings. High ratings in these categories cause them to be sensitive to future regulatory restrictions. Methylene chloride, perchloroethylene and trichloroethylene were excluded because they are known carcinogens. Similarly, Axarel 52 and Axarel 56 were removed from consideration because of their low flash points. Costly control and handling measures are required to assure that solvent flammability is suppressed for flash points below approximately 100° F.

5.3 Testing of Solvent Alternatives

The extensive spreadsheet detailing the properties and characteristics of replacement solvents provided a wealth of product information. However, it did not explicitly provide the two solvent attributes that were of prime importance to this evaluation: solvency for removing the organic contaminant from stainless steel and evaporation rate after having removed the organic contaminant from stainless steel. Consequently, a laboratory experiment was needed to determine these attributes for each of the twenty-five remaining solvents. A summary of the experimental procedure that was used to evaluate these attributes is provided in Table 9. The detailed test procedures are provided in Appendix B.

TABLE 9 - EXPERIMENTAL PROCEDURE

Steps for Determining Solvency and Evaporation Rate
1. Submit product list and MSDS's for approval.
2. Obtain samples of approved products.
3. Make test coupons.
4. Apply organic contaminant to test coupons.
5. Immerse test coupons in each solvent to test solvency.
6. Measure the evaporation rate of each solvent after successful solvency test.
7. Summarize test results.

The list of twenty-five alternate solvents and their MSDSs were submitted to the manufacturing facility's environmental and safety groups for review. Environmental and safety approval was needed to bring new chemicals into the facility for testing, as well as, to provide assurance that adverse health and/or environmental effects were not overlooked in the initial screening. Once approval was obtained, samples of each solvent were requested. All samples were received, except for the samples of the four National Diagnostics' products, which were supposedly shipped but which were never located. Consequently, only twenty-one product samples were available for the actual testing. A sample quantity of industrial grade organic lubricant was obtained as well.

Test coupons for the experiment were made by cutting out 2 inch x 2 inch squares of stainless steel from a scrap part. An approximate 0.001 to 0.002 inch film of organic lubricant was applied to the test coupon to simulate a worst case part contamination condition. The test coupon was then immersed in a beaker of room temperature solvent to assess its solvency for the contaminant. If solvency was not observed with stagnant immersion, solvency with agitated immersion was also evaluated. If the contaminant film was not removed after a total immersion time of five minutes, the solvent was judged to be ineffective for this application.

For those products which demonstrated effective solvency for the organic contaminant, an evaporation test was also conducted. The evaporation test consisted of removing the coupon from the immersion and measuring the evaporation time of the residual solvent remaining on the coupon's surface in still room temperature air. If after five minutes the coupon did not air dry, the coupon was re-immersed in the solvent, extracted and then the time to evaporate residual solvent with the assistance of room temperature air fanned over the surface was measured. Solvents that did not evaporate within five minutes even with the assistance of fanned air were also judged ineffective for this application. This test procedure was repeated for each of the twenty-one solvent samples. The experimental raw data are provided in Appendix C.

The test results are summarized in Table 10. These results indicate that of the twenty-one solvents evaluated, seven (33.3%) demonstrated ineffective solvency for removing the organic contaminant, one (4.7%) was too slow to evaporate and thirteen (62%) were acceptable for both solvency and evaporation rate. The comments reported for the acceptable solvents include: oily residue (4/13), minimal residue (3/13), beaded residue (3/13), clean surface (1/13), and very clean surface (2/13). Oily residue indicates that the surface exhibited an oily film that could be visually observed even after the solvent had evaporated. Minimal residue means that the surface exhibited an oily film that was only apparent when wiped with a clean paper cloth. The term beaded residue was used to describe surface residue which clumped together in small spheres. A surface was judged to be clean when no residue was evident, but the surface had a hazy appearance. Finally, a surface was judged to be very clean when no residue was left and the surface was bright and shiny.

TABLE 10 - TEST RESULTS

Ineffective Solvency	Evaporation Rate Too Slow	Effective Solvency and Evaporation Rate	
		Product	Comments
Aerosolv 2000	Purasolv EHL	Actrel 3338L	Oily residue
Dyna Terge		Aerosolv CB111	Minimal residue
Formula 200		Axarel 2200	Very clean surface
Purasolv ELS		Axarel 4100	Oily residue
Purasolv IPL		Axarel 6100	Beaded residue
Purasolv ML		Bioact 121	Clean surface
Vertrel MCA		Bioact 145	Minimal residue
		Bioact 105	Very clean surface
		Borothene	Oily residue
		DN30	Beaded residue
		NMP	Beaded residue
		Navy Solv 77	Oily residue
		Terpene Clean	Minimal residue

5.4 Ranking of Solvent Alternatives

Since the part cleaning problem has numerous process design constraints, many of which can not be satisfied concurrently, and since the alternate solvents have a wide range of properties, a solvent recommendation could not be made without a ranking system or systematic selection method. Furthermore, none of the researched literature on metal cleaning methods provided a standard or scientific method for selecting an optimum cleaning alternative. In most of the cited case studies, one over-riding factor had been selected, typically either cost or environmental compliance. This factor had then been used as a basis for making an alternate solvent recommendation. Consequently, one of the challenges met by this study was to develop a systematic method for ranking the alternate solvents, based on their properties, characteristics and on the relative importance of these attributes to the cleaning problem.

A parallel was drawn between the desired solvent ranking system and the QFD management technique pioneered by the Japanese in the 1970's. The QFD technique is recognized as an effective tool for identifying and quantifying the many dimensions of "product quality" and then enabling the design to satisfy an optimum number of these dimensions.(26) The QFD method accomplishes this by generating a "house of quality", which is essentially a conceptual map whereby all design goals and priorities become visible. Since the objectives for the solvent ranking system are similar in that the many dimensions of "cleaning process quality" must be identified, quantified and satisfied, it seemed reasonable to apply a QFD-House of Quality approach to this problem. The QFD-House of Quality technique, abbreviated hereafter as QFD, is comprised of six steps, which are summarized in Table 11.

The ultimate objective of this cleaning study was to develop a new process, not to design a new product as is typically the goal of a traditional QFD analysis. As a result, there were enough differences between the needs of the part cleaning evaluation and a traditional QFD analysis that a complete house of quality was not generated. Instead the

QFD technique was used as a model for creating a systematic solvent selection method that is applicable to this and other new cleaning process problems. The complete QFD analysis is provided in Appendix D. However, a brief description of each of the six steps and how they were applied to the part cleaning problem is discussed below.

TABLE 11- QFD PROCESS

Process Steps
1. Identify the customers.
2. Determine customer requirements.
3. Determine relative importance of requirements.
4. Competition benchmarking.
5. Translate customer requirements into measurable engineering requirements.
6. Set engineering targets for the design.

The first step of the modified QFD analysis was to identify the customers of the part cleaning process. Five customer bases were identified: product designers, management, manufacturing, environmental/safety and line operators. The second step of the analysis involved determining, grouping and obtaining information on the cleaning process requirements for each of these customers. An extensive list of 53 cleaning process requirements was generated after considering all possible customer concerns. These requirements were then grouped into five categories: safety, environmental, cost, manufacturing and performance. Most of the information on the process requirements had already been obtained during the definition of the problem, the selection of a viable short term cleaning method, and the research of applicable government regulations. Therefore, this step was completed by documenting the references for each of the five categories.

The third step of the analysis was to determine the relative importance of the customer requirements. This involved identifying which of the requirements were demands and which were wishes. The eleven demands and eleven wishes identified in this step are shown in Table 12. The wishes were then ranked against each other, by assigning a "1" to the requirement with greater importance and a "0" to the requirement of lesser importance. The number of "1" rankings were then tallied for each wish, thereby enabling a relative "weight" percentage for each wish to be determined. For example, cycle time had a total of ten "1" rankings out of a possible 55, which produced a relative weight of 18.2% for this wish.

The wish "weights" were then used in conjunction with known wish values to determine a solvent rank or "score". The procedure for ranking the solvents is described on the last page of the QFD analysis in Appendix D. Since the solvent "score" represents the fraction of desired characteristics that were not satisfied, a lower score suggests a better solvent for this application.

The fourth step, perform competitive benchmarking, is typically used in a traditional QFD analysis to gain information on products marketed by the competition. Since the need for this type of information is not well correlated with the part cleaning problem, a slight modification was made. Therefore, for the purposes of this study, step four involved gaining benchmarking information from other companies that perform metal cleaning operations.

TABLE 12 - QFD DEMANDS AND WISHES

DEMANDS	WISHES
1. No carcinogens.	1. Meet/less than current cycle time.
2. Complies with government safety regulations.	2. Minimal waste generated.
3. Doesn't use "banned" chemicals.	3. Minimum residue on part.
4. Complies with government environmental regulations.	4. Minimum energy/power requirements.
5. Lower cost than current system.	5. No part degradation/rust.
6. Justifiable capital investment.	6. Easily integrated into facility.
7. Low cleaning process temperature.	7. Minimum waste disposal costs.
8. No prohibited material transfer.	8. Minimum product cost.
9. Must clean part	9. Minimum environmental/safety costs.
10. Minimal part contact.	10. Recyclable waste.
11. No liquid residue.	11. Treatable waste.

The fifth step, translating customer requirements into measurable engineering requirements, and the sixth step, setting engineering targets were combined for this study. This combined last step involved ascertaining a numerical threshold for most of the key customer requirements which included: cleaning processing temperature less than 130 °F, maximum applied force less than 0.1 lb., and cycle time = clean + dry < 3 minutes. Determination of precise engineering targets for the customer requirements which were not quantified in this preliminary evaluation was deferred until the new cleaning process has been more completely defined.

The modified QFD analysis developed for this study was successful in that it generated a list of quantified process demands and a ranked list of process wishes. These two key results thereby enabled a final solvent recommendation to be made.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The regulatory ban on the use of CFC solvents has forced manufacturers across the country to search for alternative metal cleaning techniques. The documented research indicated that there are a wide range of alternative cleaning methods to consider. This wide range of alternatives, combined with a vast array of government environmental and safety regulations, makes the selection of a new cleaning method very complex. Because of this complexity, only one small aspect of the selected cleaning problem was addressed in this study.

The objective of this study was to develop a thorough, scientific based approach for resolving the problem of removing organic contamination from a stainless steel part. This objective was accomplished by developing an approach that involved: 1) defining the problem, 2) identifying the constraints, 3) researching alternate cleaning methods, 4) researching applicable government regulations, 5) performing a scientific evaluation and 6) drawing conclusions. Since the research on alternative cleaning methods indicated that most manufacturers have selected replacement cleaning methods in an ad hoc or subjective manner, this evaluation met an additional challenge by developing a systematic method for ranking the alternate solvents.

The study conclusions are drawn directly from the "scores" assigned to each of the thirteen solvents that demonstrated effective contaminant removal and reasonable drying time. The solvent "scores" are summarized in Table 13. The general conclusion that can be made is that there are alternate solvents available with the characteristics needed to satisfy the identified part cleaning process constraints. Specifically, the top three ranked solvents were selected as promising candidates to implement in a new part cleaning system. These three solvents, Borothene, Bioact 145 and Navy Solv 77 have the optimum combination of performance, cost, safety and environmental characteristics based on the extensive evaluations that were conducted. Furthermore, during this evaluation a decision was made to select alternate solvent cleaning as the most viable short term option, over aqueous based systems. Only one (DN30) of the four aqueous based products tested demonstrated even marginal solvency for removing the organic contaminant, thereby confirming that the selection of alternate solvent cleaning over aqueous based systems was the appropriate choice.

The overall recommendation is to perform more extensive and equipment-specific tests on the top three solvents before making a final recommendation on a new cleaning system. The second test phase should involve evaluating the physical equipment needs and environmental compliance measures associated with using each of the three solvents, since these concerns were too complex to include in this preliminary evaluation. Furthermore, it is recommended that the high technology cleaning methods, such as plasma and laser surface cleaning, that are not developed enough to support a short term implementation, be evaluated as possible long term solutions to this cleaning problem. These new methods have good cleaning potential in terms of their performance and even more so in their compliance with environmental regulations. Since it is reasonable to expect that environmental regulations will only become more stringent in the future, long range planning is essential.

TABLE 13 - SOLVENT SCORES

Rank	Solvent	Score
1	Borothene	0.3010
2	Bioact 145	0.3070
3	Navy Solv 77	0.3346
4	Axarel 6100	0.3485
5	Bioact 105	0.3949
6	Axarel 2200	0.4483
7	Bioact 121	0.4580
8	Aerosolv CB111	0.4615
9	DN30	0.4770
10	Axarel 4100	0.5047
11	Terpene Clean	0.5123
12	NMP	0.5364
13	Actrel 3338L	0.5402

(The solvent "score" represents the fraction of desired characteristics that were not satisfied, hence a lower "score" is better.)

APPENDIX A

SOLVENT SPREADSHEET

APPENDIX A - SOLVENT SPREADSHEET

Product Name	Product Manufacturer	Product Type	Chemical Type	Flammable	LEL	UEL	($/lb) Cost	Toxicity	Vapor Density
1 Borothene	Tulstar Products	Solvent	Halogenated Hydrocarbon	No	None	None	3.09(drum)	Slight	6
2 NMP	BASF	Solvent	Cyclic Amine	Yes	1.3%	9.5%	800/drum	Slight	3.4
3 Vertrel MCA	DuPont	Solvent	Hydroflourocarbon(HFC-43-10)	No	None	None	15	Slight	>1
4 Oxsol 100	Occidental Chem	Solvent	Halogenated Aromatic	Yes	0.9%	10.5%	2	Slight	N/D
5 Oxsol 10	Occidental Chem	Solvent	Chlorotoluene	Yes	N/D	N/D	0.4	Moderate	4.38
6 Navy Solv 77	Navy Brand	Solvent	Napthenic Distallate	Yes	0.9%	Unknown	275/drum	Moderate	6.1
7 Form 200	Navy Brand	WaterBased	Silicates/Alkylphenols	No	None	None	225/drum	Slight	N/D
8 Dyna Terge	Navy Brand	WaterBased	Glycol Ether/Limonene	No	None	None	250/drum	Slight	>1
9 Terpene Clean	Aerocote	Solvent	Aliphatic Terpene	Yes	N/D	N/D	624/drum	Slight	N/D
10 Aerosolv 2000	Aerocote	Semi-AQ	Glycol Ether	Yes	N/D	N/D	422/drum	Moderate	N/D
11 Aerosolv CB111	Aerocote	Solvent	Petroleum Distillate	Yes	N/D	N/D	224/drum	Moderate	N/D
12 DN30	Aerocote	Water Based	Organic Surfactants	No	None	None	270/drum	Slight	N/D
13 ACTREL 3338L	EXXON	Solvent	Aliphatic Hydrocarbon	Yes	1.2%	9.6%	700/drum	Slight	N/D
14 Purasolv IPL	Purac	Solvent	Isopropyl Lactacte	Yes	N/D	N/D	600/drum	Slight	4.2
15 Purasolv ML	Purac	Solvent	Methyl Lactacte	Yes	N/D	N/D	500/drum	Slight	4
16 Purasolv ELS	Purac	Solvent	Ethyl Lactate	Yes	1.5%	10.6%	550/drum	Slight	4.07
17 Purasolv EHL	Purac	Solvent	Ethylhexyl Lactate	Yes	N/D	N/D	650/drum	Slight	N/D
18 Axarel 2200	Petroferm	Solvent	Aliphatic Hydrocarbon	Yes	N/D	N/D	1000/drum	Slight	6
19 Axarel 4100	Petroferm	Solvent	Aliphatic Hydrocarbon	Yes	N/D	N/D	500/drum	Slight	6
20 Axarel 6100	Petroferm	Solvent	Aliphatic Hydrocarbon	Yes	N/D	N/D	400/drum	Moderate	6.7
21 Axarel 52	Petroferm	Semi-AQ	Hydrocarbon	Yes	N/D	N/D	350/drum	Moderate	N/D
22 Axarel 58	Petroferm	Semi-AQ	Hydrocarbon	Yes	N/D	N/D	400/drum	Moderate	N/D
23 Bioact 121	Petroferm	Solvent	Terpene Hydrocarbon	Yes	0.7%	6.1%	800/drum	Slight	>1
24 Bioact 145	Petroferm	Solvent	Aliphatic Hydrocarbon	Yes	N/D	N/D	600/drum	Slight	>1
25 Bioact 105	Petroferm	Solvent	Aliphatic Hydrocarbon	Yes	N/D	N/D	1000/drum	Slight	>1
26 Opticlear	National Diag.	Solvent	Food Oil Distillate	Yes	N/D	N/D	300/drum	Slight	4.69
27 Opticlear W	National Diag.	Solvent	Pyrolidinone	Yes	1.3%	9.5%	525/drum	Slight	3.4
28 Opticlear S	National Diag.	Solvent	Alkyl Hydrocarbons	Yes	1.3%	8.6%	600/drum	Slight	5.9
29 Opticlear R	National Diag.	Solvent	Food Oil Distillate/Corn Alcohol	No	None	None	350/drum	Slight	1.5
30 Methylene Chloride	Dow Chemical	Solvent	Halogenated Hydrocarbon	Yes	14%	22%	700/drum	High	2.93
31 Perchloroethylene	Dow Chemical	Solvent	Halogenated Hydrocarbon	No	None	None	800/drum	High	5.76
32 Trichloroethylene	Dow Chemical	Solvent	Halogenated Hydrocarbon	Yes	8%	10.5%	750/drum	High	4.53

Product Name	Boiling Point (F)	Flash Point (F)	KB Value	Vapor Pressure	Odor	Evaporation Rate	TLV (ppm)	Health Hazard	Fire Hazard	Reactivity Hazard	Carcinogen
1 Borothene	153.5	None	132	110@20	Sweet	N/D	200	Slight	Insignificant	Insignificant	No
2 NMP	399.7	195.8	>300	0.3@20	Amine	0.03	100	Slight	Moderate	Insignificant	No
3 Vertrel MCA	102	None	N/D	375@20	Aromatic	N/D	20-200	Slight	Insignificant	Slight	No
4 Oxsol 100	282	109	64	5.3@20	Yes	0.9	25	Slight	Moderate	Slight	No
5 Oxsol 10	318	123	110	2.6@20	Aromatic	0.6	50	Slight	Moderate	Insignificant	No
6 Navy Solv 77	406	160	N/D	0.2	Mild	0.1	100	Moderate	Moderate	Insignificant	No
7 Form 200	>212	None	N/D	N/D	Odorless	<1	2mg/m3	Slight	Insignificant	Insignificant	No
8 Dyna Terge	>212	>200	N/D	<17	Lemon	<1	N/E	Slight	Insignificant	Insignificant	No
9 Terpene Clean	325	140	62	5.1@100	Citrus	N/D	2mg/m3	Slight	Moderate	Insignificant	No
10 Aerosolv 2000	N/D	142	N/D	10.3@100	Citrus	N/D	270mg/m3	Moderate	Moderate	Insignificant	No
11 Aerosolv CB111	330	125	37	20.7@100	Solvent	N/D	100	Moderate	Moderate	Insignificant	No
12 DN30	N/D	None	N/D	N/D	Bland	N/D	N/E	Slight	Insignificant	Insignificant	No
13 ACTREL 3338L	309	100	>1000	2.3@20	Low Solv.	0.4	300	Slight	Moderate	Insignificant	No
14 Purasolv IPL	315	136	62	1.3@20	Mild Alcoh.	0.18	N/E	Slight	Moderate	Insignificant	No
15 Purasolv ML	291	136	>1000	2.6@20	Mild Alcoh.	0.26	N/E	Slight	Moderate	Insignificant	No
16 Purasolv ELS	309	139	N/D	1.7@20	Mild Alcoh.	0.22	N/E	Slight	Moderate	Insignificant	No
17 Purasolv EHL	476	235	>1000	0.02@20	Mild Alcoh.	0.003	N/E	Slight	Insignificant	Insignificant	No
18 Axarel 2200	303	111	N/D	3.54@20	Mild Alcoh.	<1	N/E	Slight	Moderate	Insignificant	No
19 Axarel 4100	302	104	N/D	2@20	Hydrocarb.	0.22	500	Slight	Moderate	Insignificant	No
20 Axarel 6100	360	142	N/D	0.82@20	Hydrocarb.	<0.1	500	Slight	Moderate	Insignificant	No
21 Axarel 52	N/D	99	N/D	<0.1@25	Mild	N/D	N/D	Slight	Moderate	Insignificant	No
22 Axarel 58	N/D	99	N/D	<0.1@25	Mild	N/D	N/D	Slight	Moderate	Insignificant	No
23 Bioact 121	340	117	N/D	<2@20	Citrus	<1	N/E	Slight	Moderate	Insignificant	No
24 Bioact 145	360	143	N/D	<2@20	Hydrocarb.	<1	100	Slight	Moderate	Insignificant	No
25 Bioact 105	303	105	N/D	<2@20	Mild	<1	N/E	Slight	Moderate	Insignificant	No
26 Opticlear	366	140	627	6@26	Citrus	0.4	None	Insignificant	Slight	Insignificant	No
27 Opticlear W	200	200	>200	0.29@20	Mild	0.08	100	Slight	Moderate	Insignificant	No
28 Opticlear S	374	147	27	1@20	Mild	<0.1	300	Slight	Moderate	Insignificant	No
29 Opticlear R	180	142	0	58@38	Citrus	2	1000	Slight	Moderate	Insignificant	No
30 Methylene Chloride	104	None	N/D	355@20	Irritating	N/D	50	Moderate	Slight	Insignificant	Yes
31 Perchloroethylene	250	None	N/D	13@20	Irritating	N/D	25	Moderate	Insignificant	Insignificant	Yes
32 Trichloroethylene	189	None	N/D	60@20	Irritating	N/D	50	Moderate	Slight	Insignificant	Yes

Product Name	Water Soluble	Ph	SNAP LIST	Hazardous Waste	CERCLA	SARA	TSCA	VOC	HAP	ODC
1 Borothene	Negligible	6.7	U/R	No	No	No	Yes	Yes(0.2)	N/D	N/D
2 NMP	Miscible	7.7	No	No	No	Yes	Yes	Yes	No	No
3 Vertrel MCA	N/D	N/D	U/R	No	Yes	Yes	Yes	U/R	Yes	No
4 Oxsol 100	35%	N/D	U/R	Yes	No	No	Yes	Yes	Yes	No
5 Oxsol 10	72 ppm	N/D	U/R	Yes	No	Yes	Yes	Yes	Yes	No
6 Navy Solv 77	Negligible	N/D	U/R	No	No	No	Yes	N/D	No	No
7 Form 200	Complete	13	U/R	No	No	Yes	Yes	No	No	No
8 Dyna Terge	Complete	9.5	U/R	No	No	Yes	Yes	No	No	No
9 Terpene Clean	Emulsifies	N/D	Yes	Yes	No	Yes	Yes	No	No	No
10 Aerosolv 2000	Soluble	7	Yes	No	No	Yes	Yes	No	No	No
11 Aerosolv CB111	Insoluble	N/D	U/R	Yes	No	Yes	Yes	No	No	No
12 DN30	Soluble	12.65	U/R	No	No	Yes	Yes	No	No	No
13 ACTREL 3338L	Negligible	N/D	Yes	Yes	No	Yes	Yes	No	No	No
14 Purasolv IPL	Complete	Neutral	Yes	Yes	No	No	Yes	No	No	No
15 Purasolv ML	Complete	N/D	Yes	Yes	No	No	Yes	No	No	No
16 Purasolv ELS	Complete	N/D	Yes	Yes	No	No	Yes	No	No	No
17 Purasolv EHL	0.03%	N/D	Yes	No	No	No	Yes	No	No	No
18 Axarel 2200	70%	N/D	Yes	Yes	Yes	No	Yes	No	No	No
19 Axarel 4100	10%	N/D	Yes	Yes	Yes	No	Yes	No	No	No
20 Axarel 6100	<0.1%	N/D	Yes	No	No	No	Yes	No	No	No
21 Axarel 62	Complete	5.6	Yes	Yes	Yes	No	Yes	No	No	No
22 Axarel 66	Complete	5.6	Yes	Yes	Yes	No	Yes	No	No	No
23 Bioact 121	Insoluble	N/D	Yes	Yes	No	No	Yes	No	No	No
24 Bioact 145	Negligible	N/D	Yes	No	No	No	Yes	No	No	No
25 Bioact 105	1%	N/D	Yes	Yes	No	No	Yes	No	No	No
26 Opticlear	Insoluble	N/D	U/R	No	Yes	No	No	No	No	No
27 Opticlear W	Miscible	N/D	No	No	No	No	Yes	No	No	No
28 Opticlear S	<0.01%	N/D	Yes	No	Yes	No	Yes	No	No	No
29 Opticlear R	Soluble	N/D	U/R	No	No	No	No	No	No	No
30 Methylene Chloride	2	N/D	No	Yes	Yes	Yes	Yes	Yes	Yes	No
31 Perchloroethylene	0.015	N/D	No	Yes	Yes	Yes	Yes	Yes	Yes	No
32 Trichloroethylene	0.1	N/D	No	Yes	Yes	Yes	Yes	Yes	Yes	No

APPENDIX B

TEST PROCEDURES

ALTERNATIVE CLEANING METHOD
TEST PLAN

1. Research and identify alternative cleaning solutions.

2. Obtain product information and MSDS.

3. Select candidates for bench testing.

4. Submit list and MSDS's of selected products for approval.

5. Obtain samples of approved products. (Store in appropriate area for chemicals and fire hazards.)

6. Cut out test coupons from a scrap part. (Approximately 2" x 2")

7. Obtain industrial sample of organic lubricant, and apply a thin (1-2 mil) film to each part coupon.

8. Perform bench tests.

9. Summarize the results of the bench tests.

10. Analyze the test results.

11. Make recommendations and outline the second phase of product testing.

ALTERNATIVE CLEANING METHOD
BENCH TEST PROCEDURE

CAUTIONS AND NOTES:

- All tests will be performed under an exhaust hood, with neoprene gloves and safety goggles.
- All tests will be performed at room temperature.
- MSDS's will be readily available at all times during tests.
- No mists will be generated during tests.
- Test products will be diluted according to the manufacturer's recommendation.
- Test products will not be mixed together.

PROCEDURE:

1. Obtain the test coupons, organic lubricant and product samples.

2. Apply a 1- 2 mil film of lubricant on one side of the test coupon, level as necessary with a straight edge.

3. Dispense approximately 200 ml of test product into a beaker.

4. Immerse the test coupon in the test product and start the timer.

5. Inspect the test coupon for film removal every thirty seconds, for up to five minutes.

6. If after soaking for one minute, lubricant removal has not been initiated, begin slight agitation.

7. If after a total immersion time of three minutes, the lubricant has not been removed, begin vigorous agitation.

8. If after a total immersion time of five minutes the lubricant film has not been removed, the product will be judged ineffective for this application. These products will not be further tested. (Continue with step 14.)

9. Once the contaminant film has been removed, as determined by visual examination, extract the test coupon from the beaker and reset the timer. Measure the air drying time for up to five minutes.

10. Allow the test coupon to air dry while suspending it on end so that excess cleaning solution may run off.

11. If after five minutes the test coupon is still not dry, re-immerse the test coupon in the test product, and reset the timer upon coupon extraction.

12. Fan room temperature air over the coupon surface. Measure the mechanically assisted drying time for up to five minutes.

13. If after a total fan assisted drying time of five minutes the test coupon surface is still not dry, the product will be judged ineffective for this application.

14. Pour the spent test product into a designated waste container, and wipe off any residue left on test coupon with a paper towel.

15. Record the following data:

    - Test product name and manufacturer.
    - Time to remove contaminant film (identify final level of agitation).
    - Time to air dry.
    - Time to dry with fan assistance (if applicable).
    - Comment on the ability of the test product to remove the contaminant film and on any other unique observations such as coupon degradation or residue.

16. Repeat steps 2 through 15 for each of the test products.

17. Dispose of spent test products as appropriate based on the MSDS.

18. Left over test product will either be stored for further use or disposed of as appropriate, based on the test results.

APPENDIX C

RAW DATA

APPENDIX C - RAW DATA

PRODUCT NAME	TIME TO REMOVE STUFF (min)	TIME TO DRY IN STILL AIR (min)	TIME TO DRY WITH FAN ASSIST (min)	COMMENTS
Borothene	2 - 3 Slight Agitation	30-45 sec.	Not needed	Left slight beads of stuff, left oily residue.
Navy Solv 77	1 - 2 Slight Agitation	> 5	4 - 5	Left oily residue.
Aerocote Terpene	0.5 - 1 Slight Agitation	5	3	Left minimal oily residue, slight agitation needed for removal < 2 min.
Aerosolv CB111	0.5 - 1 No Agitation	5	3	Left minimal oily film, no agitation needed for removal < 2 min.
Dyna Terge (mixed 4:1 with DI water)	> 5 Vigorous Agitation	N/A	N/A	After 5 min. with vigorous agitation, stuff not removed.
Form 200 (mixed 1:1 with DI water)	> 5 Vigorous Agitation	N/A	N/A	After 5 min. with vigorous agitation, stuff not removed.
Aerosolv 2000 (full strength)	> 5 Vigorous Agitation	N/A	N/A	After 5 min. with vigorous agitation, stuff not removed.
DN30 (mixed 1:1 with DI water)	5 Vigorous Agitation	> 5	3 - 4	After 5 min. with vigorous agitation had removed some stuff (visible in fluid), large beads remained but were easily wiped off.
Purasolv ML	> 5 Vigorous Agitation	N/A	N/A	After 5 min. with vigorous agitation, stuff not removed.
Purasolv ELS	> 5 Vigorous Agitation	N/A	N/A	After 5 min. with vigorous agitation had removed some stuff (visible in fluid), large beads remained, significant residue.

PRODUCT NAME	TIME TO REMOVE STUFF (min)	TIME TO DRY IN STILL AIR (min)	TIME TO DRY WITH FAN ASSIST (min)	COMMENTS
Purasolv IPL	0.25 - 0.3 (Appeared to clean but actually left significant residue on surface.) Vigorous Agitation	> 5	3 - 4	Left significant smearable residue on finished surface, even after re-exposure to solvent for up to 5 minutes.
Purasolv EHL	2.5 - 3 (Appeared to clean but actually left significant residue on surface.) Vigorous Agitation	> 5	> 5	Left significant smearable residue on finished surface, did not evaporate in under 5 minutes even with fan assist.
Actrel 3338L	1 Slight Agitation	5	2 - 3	Left oily residue.
BASF NMP	2 - 3 Vigorous Agitation	> 5	5	Left significant beads and oily residue on surface.
Vertrel MCA	> 5 Vigorous Agitation	Immediate	Not needed.	After 5 min. with vigorous agitation, stuff not removed, but dried immediately.
Bioact 121	2 Slight Agitation	5	1 - 1.5	Left minimal oily residue, clean finished surface.
Bioact 145	2 Slight Agitation	5	2 - 2.5	Left oily residue, fairly clean finished surface.
Bioact 105	1.5 - 2 Slight Agitation	5	0.75	Left minimal oily residue, very clean finished surface.

APPENDIX C - RAW DATA

PRODUCT NAME	TIME TO REMOVE STUFF (min)	TIME TO DRY IN STILL AIR (min)	TIME TO DRY WITH FAN ASSIST (min)	COMMENTS
Axarel 2200	1.5 - 2 Slight Agitation	4	1	Left minimal oily residue, very clean finished surface.
Axarel 4100	1.0 - 1.5 Slight Agitation	> 5	2	Slight oily residue.
Axarel 6100	1.5 - 2 Slight Agitation	5	4	Left beads of contamination and oily residue.

APPENDIX D

QFD ANALYSIS

APPENDIX D - QFD ANALYSIS

QFD STEP 1: IDENTIFY CUSTOMERS

- **PRODUCT DESIGNERS**

Very conservative, safety conscious engineering background.

Designers desire a consistent, effective, thorough, low temperature part cleaning method that does not degrade the part, leaves minimal residue and does not physically contact the part. Ideally they would like to see every part cleaned.

Critical Concerns that relate to final product quality:
  Part must be cleaned.
  No wet residue (i.e. puddles) can be left.
  Cleaning process temperature must not be elevated.
  Physical part contact must be avoided to prevent distortion.

- **MANAGEMENT**

Very cost conscious, want equal or better quality at less cost.

Management desires a quick, low cost, low maintenance, reliable part cleaning method that requires minimal facility modifications. Ideally they would like to see the minimal number of parts cleaned, i.e. only those parts that "must" be cleaned.

Want to maximize product yield, unit produced/time period.

- **MANUFACTURING PROCESS**

An automated, highly synchronized fabrication line.

The process needs an integrated, reliable part cleaning method that meets the current cycle time, with minimal process changes and without part degradation.

- ENVIRONMENTAL AND SAFETY DEPARTMENT

Faced with increasingly stringent environmental and safety regulations, with a high degree of regulatory oversight.

Environmental and Safety desires a part cleaning method that meets all government regulations, generates minimal waste, involves minimal "special" safety requirements and does not expose workers to hazards.

- LINE OPERATORS

Skilled, union personnel.

Operators desire a part cleaning method that minimizes their effort, maximizes their skills, involves no hazardous exposure and is easy to maintain, access, run and service.

QFD STEP 2: DETERMINE CUSTOMER REQUIREMENTS

A. IDENTIFY REQUIREMENTS

- Minimal operator effort
- Maximize operator skills
- No operator hazardous exposure
- Easy to maintain
- Easy to access
- Easy to operate
- Easy to service
- Easily integrated into facility and process line
- Requires minimal process changes
- Meets/less than current cycle time
- No part degradation
- Reliable cleaning system
- Generates minimal waste
- Meets environmental regulations
- Waste recyclable
- Waste treatable
- Minimal "special" safety requirements

A. IDENTIFY REQUIREMENTS (Continued)

- Consistent cleaning method
- Quick drying
- Leaves minimal residue
- Minimal physical part contact
- Clean every part
- Clean part
- Low cost system
- Low maintenance requirements
- Quick to implement/install
- Minimal facility modifications
- Minimal number of parts cleaned (i.e. only those that "must" be cleaned).
- Minimize product defects related to part
- Minimize power/energy requirements
- Dual purpose/can be used for other applications
- Product support/replacement hardware easy to get
- Fits into currently available facility space
- Minimal facility impact
- Generate minimal humidity
- Minimal number of processing steps
- Not rust part
- Reasonable capital investment
- Low maintenance costs
- Minimal environmental compliance costs
- Minimal waste disposal costs
- Low operating costs
- Low product cost
- No prohibited materials transferred to product
- No major safety hazards
- Minimize spill/containment issues
- No carcinogens
- Has process monitoring capability
- Upgraded/expandable
- Short equipment lead time
- Minimal material handling requirements
- Sufficient equipment/product availability
- Cleaning processing temperature not elevated

B. GROUP CUSTOMER REQUIREMENTS

SAFETY:

1. No carcinogens
2. Complies with government safety regulations
3. Minimal "special" safety requirements
4. No worker exposure to hazardous chemicals or processes
5. No extreme safety hazards

ENVIRONMENTAL:

1. Generates minimal waste
2. Complies with government environmental regulations
3. Waste is recyclable
4. Waste is treatable
5. Minimal spill/containment problem

COST:

1. Lower cost than current system
2. Minimize energy/power requirements
3. Justifiable capital investment cost
4. Low maintenance costs
5. Minimal environmental compliance costs
6. Minimal waste disposal costs
7. Low operating costs

MANUFACTURING/ASSEMBLY/MAINTENANCE:

1. Easy to maintain and service
2. Easy to access
3. Easily integrated into facility/process line
4. Quick to install/minimal facility downtime
5. Equipment and product support/replacement hardware easy to get
6. Short acquisition/lead time
7. Sufficient equipment/product availability

PERFORMANCE:

1. Cleaning process temperatures not elevated
2. Minimize material handling requirements
3. Process monitoring capability
4. No potential for prohibited material transfer to product
5. Will not degrade/rust part
6. Minimal part changes required
7. Size to fit into available facility space
8. Dual purpose/use for other applications
9. Minimize product defects related to part
10. Clean every part (design)
11. Clean only those parts that "must" be cleaned (management)
12. Clean part
13. Minimal physical part contact
14. Minimal residue on part
15. Quick drying
16. Does not leave wet residue
17. Consistent cleaning
18. Reliable system
19. Meets/less than current cycle time
20. Minimal process changes
21. Easy to operate
22. Maximize operator skills
23. Minimal operator effort

C. OBTAIN INFORMATION ON CUSTOMER REQUIREMENTS

SAFETY:

- Obtain and review product MSDS, check TLV's, personal protective equipment required, flammability, toxicity, carcinogens.
- Review shop/laboratory safety guidelines.
- Review CFR Vol. 29 on OSHA requirements for TLV's, PEL's, ventilation, protective equipment and storage requirements.
- Review final system for spill prevention and containment.
- Conduct an overall safety analysis of final system.

ENVIRONMENTAL:

- EPA literature (SNAP list, CERCLA, SARA, TSCA)
- Product literature, MSDS, product data sheets.
- Contact disposal companies.
- Research recycling/treatment of different wastes.
- General research of current guidelines.

COST:

- Estimate the current system operating cost/yr for labor and material, plus the loss of product quality must be quantified.
- Current power requirements - none.
- Capital investment must be justified by the savings within 3 years.
- Research environmental cost estimates.
- Obtain rough estimates from product and equipment suppliers:
  - Maintenance
  - Disposal
  - Operating

MANUFACTURING/ASSEMBLY/MAINTENANCE:

- Estimates
- Product literature
- Talk to other users.
- Mostly hard to quantify until the final system is specified.
- May need to do more testing at a later date.
- Would need to pull together a cross-functional team.

PERFORMANCE:

- Part limiting temperature approximately 180 °F, set part cleaning temperature at least 50 °F below this.
- Current part cleaning cycle time < 3 minutes.
- No wet residue that could run or drip off is allowed, some slight oiliness may be allowable.
- Apply no more than 0.1 lb. of force to part.
- Level of cleanliness, atomically clean surface is not required, basically a visual cleanliness is all that is needed, judge by a wipe test.
- Product defects related to: wet residue, part deformation and dirty parts.
- Current available facility space 12 ft. x 10 ft.
- Obtain list of prohibited materials.
- Effective process monitoring would inspect and clean only those parts that are contaminated, also would monitor temperature, humidity, recontamination as needed.
- May require long term testing to effectively evaluate rust potential, rely in the short term on product manufacturer data and industry product experience, also investigate rust inhibitors and humidity mitigation.

QFD STEP 3: DETERMINE RELATIVE IMPORTANCE OF CUSTOMER REQUIREMENTS

<u>DEMANDS:</u>

No carcinogens
Complies w/govt safety regulations
Doesn't use "banned" chemicals
Complies w/govt environ. regulations
Lower cost than current system
Justifiable capital investment
Low cleaning process temperature
No prohibited material transfer
Must clean part
Minimal part contact
No wet residue

<u>WISHES:</u>

Meet/less than current cycle time
Minimal amount of waste generated
Minimum residue on part
Minimum energy/power requirements
No part degradation/rust
Easily integrated into facility
Minimum waste disposal costs
Minimum product cost
Minimum environmental/safety costs
Recyclable waste
Treatable waste

(Many other wishes are possible, but most can not be easily evaluated until the cleaning system has been further defined.)

Determination of Wish "Weights"

	CT	MR	RH	EI	PC	DC	EC	PR	TW	RW	WA	Total	%
Cycle Time	X	1	1	1	1	1	1	1	1	1	1	10	18.2
Minimum Residue	0	X	1	1	0	0	0	1	0	0	1	4	7.3
No rust/Humidity	0	0	X	1	0	0	0	0	0	0	1	2	3.6
Easy Integrate	0	0	0	X	0	0	0	0	0	0	0	0	0.0
Product Cost	0	1	1	1	X	0	0	1	1	1	1	7	12.7
Waste Disp. Cost	0	1	1	1	1	X	1	1	1	1	1	9	16.4
Envir./Safety Cost	0	1	1	1	1	0	X	1	1	1	1	8	14.5
Power Req.	0	0	1	1	0	0	0	X	0	0	1	3	5.5
Treat Waste	0	1	1	1	0	0	0	1	X	0	1	5	9.1
Recycle Waste	0	1	1	1	0	0	0	1	1	X	1	6	10.9
Waste Amount	0	0	0	1	0	0	0	0	0	0	X	1	1.8
Total:												55	100%

(1=more important, 0=less important)

QFD STEP 4: COMPETITIVE BENCHMARKING

Consulted with other businesses that do metal cleaning to see how they have responded to the increased regulatory restrictions. These manufacturers include:

- MedRad, Pittsburgh, PA
- General Motors - Delco Moraine, Dayton, OH
- GE Aircraft Engine - Cincinnati, OH
- Several cleaning equipment suppliers

QFD STEP 5: TRANSLATE CUSTOMER REQUIREMENTS INTO ENGINEERING REQUIREMENTS AND QFD STEP 6: SETTING ENGINEERING TARGETS

DEMANDS:

- No carcinogens.
- Complies with government safety regulations.
- No banned chemicals.
- Complies with government environmental regulations.
- Operating cost < Operating cost + Quality cost of today's process.
- Capital investment < 3 X annual operating cost savings.
- Processing temperature < 180°F - 50°F = 130°F.
- No prohibited material transfer.
- No visible contamination.
- No applied force > 0.1 lb.
- No wet residue after 3 minutes.

WISHES:

- Cycle time = clean + dry < 3 minutes.
- Minimal residue - as judged by wipe test.
- No rust/humidity - is water used, if so what percentage.
- Easily integrated - compatible with automated system, general size of equipment, special demands (i.e. vacuum, heat, air).
- Product cost - $/drum.
- Waste disposal cost - number of restrictions, hazardous waste.
- Environment and Safety costs - special safety needs, TLV level, toxicity, flammability and reactivity ratings.
- Power requirements - demands for heat, vacuum, fan.
- Treatable waste.
- Recyclable waste.
- Quantity of waste generated.

PROCEDURE FOR RANKING SOLVENTS

			WISH VALUES														
	WISH WEIGHTS:		18.2% 0.182		7.3% 0.073		3.6% 0.036	0% 0	12.7% 0.127		16.4% 0.164	14.5% 0.145		5.5% 0.055	9.1% 0.091	10.9% 0.109	1.8% 0.018
SOLVENT	RANK	SCORE	CT	NCT	MR	NMR	RH	EI	PC	NPC	DC	EC	NEC	PR	TW	RW	WA
Borothene	1	0.3010	3	0.33	3	0.75	0	0	700	0.70	0	2	0.67	0	0	0	0
Navy Solv 77	3	0.3346	7	0.78	3	0.75	0	0	275	0.28	0	1	0.33	1	0	0	0
Terpene Clean	11	0.5123	4	0.44	2	0.50	0	0	624	0.62	1	2	0.67	1	0	0	0
CB111	8	0.4615	4	0.44	2	0.50	0	0	224	0.22	1	2	0.67	1	0	0	0
DN30	9	0.4770	9	1.00	4	1.00	1	0	270	0.27	0	2	0.67	1	0	0	0
Actrel	13	0.5402	4	0.44	3	0.75	0	0	700	0.70	1	2	0.67	1	0	0	0
NMP	12	0.5364	8	0.89	4	1.00	0	0	800	0.80	0	3	1.00	1	0	0	0
Bioact 121	7	0.4580	3.5	0.39	1	0.25	0	0	800	0.80	1	1	0.33	1	0	0	0
Bioact 145	2	0.3070	4.5	0.50	2	0.50	0	0	600	0.60	0	1	0.33	1	0	0	0
Bioact 105	5	0.3949	2.75	0.31	0	0.00	0	0	1000	1.00	1	1	0.33	0	0	0	0
Axarel 2200	6	0.4483	3	0.33	0	0.00	0	0	1000	1.00	1	2	0.67	0	0	0	0
Axarel 4100	10	0.5047	3.5	0.39	3	0.75	0	0	500	0.50	1	2	0.67	1	0	0	0
Axarel 6100	4	0.3485	6	0.67	4	1.00	0	0	400	0.40	0	1	0.33	1	0	0	0
Descriptions: (Norm. means that the values have been normalized to a scale of 0 to 1 for comparison.)		Solvent Score	Cycle Time	Norm. Cycle Time	Minimum Residue	Norm. Minimum Residue	Rust/ Humidity	Easy Integrate	Product Cost	Norm. Product Cost	Dispose Cost	Environ. Cost	Norm. Environ. Cost	Power Req.	Treat Waste	Recycle Waste	Waste Amount
Comments: N/A: Data not available for limited study.		Lower is better	Max time to remove + dry time with fan as tested		very clean =0 clean=1 min. residue=2 oily residue=3 beaded residue=4 Test comments		Water=1	N/A	Cost $ per 55 gal drum approx.		Hazard Waste = 1	1 for each: CERCLA SARA TSCA VOC HAP ODC		1 if cycle time > 3 min. would require drying	N/A	N/A	N/A

A description of the solvent ranking procedure and a sample calculation is provided on the following page.

Solvent Ranking Procedure

1. Identify representative values for each wish, for all solvents being evaluated.

   - Cycle Time: used the results from the solvency and evaporation experiments (i.e. Maximum time to remove stuff + drying time with fan assist.)
   - Minimum Residue: used the comments recorded during the solvency and evaporation experiments. (Assigned a scale of 0 to 4, with 0 representing the least residue.)
   - Rust/Humidity: if water was needed for the process assigned a "1", otherwise assigned a "0".
   - Easy to Integrate: unable to estimate at preliminary stage.
   - Product Cost: used the approximate solvent cost per 55 gallon drum.
   - Disposal Cost: if the product would produce a hazardous waste assigned a "1", otherwise assigned a "0".
   - Environmental Cost: used the number of environmental regulations that apply to using the solvent. (Assigned a "1" for each regulation, CERCLA, SARA, TSCA, VOC, HAP, and ODC, that applied.)
   - Power Requirements: used the results of the solvency and evaporation experiments. (If the total cycle time for cleaning and drying exceeded the current cycle time of 3 minutes, it was assumed that some form of accelerated drying would be needed, and would potentially require substantial power input.)
   - Treat Waste, Recycle Waste and Waste Amount: unable to estimate at preliminary stage.

2. Normalize all wish values to obtain numbers between 0 and 1 for comparison purposes.

3. Calculate a score for each of the solvents by multiplying each wish value by its respective wish weight, and adding up the results.

Sample Calculation:

Borothene Score:

$$NCT(0.33)*18.2 + NMR(0.75)*7.3 + RH(0)*3.6 + NPC(0.7)*12.7 + DC(0)*16.4 + NEC(0.67)*14.5 + PR(0)*5.5 \;=\; 0.30086$$

(Did not include the wishes that did not have estimated values in the calculation.)

4. Determine a rank for each of the solvents based on the calculated scores. Since the solvent score represents the percentage of desired characteristics that were not satisfied, a lower score is better.

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