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Supercritical Carbon Dioxide Cleaning Market Assessment and Commercialization/ Deployment Plan

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Summary

To meet environmental and worker safety regulations, many companies are incorporating alternative cleaning methods that do not involve hazardous chemicals such as chlorofluorocarbons. Processes using less harmful solvents and aqueous emulsion systems have been investigated and implemented for some industrial applications. However, certain environmental and health risks still exist with these methods.

Through the U.S. Department of Energy's Industrial Waste Program (IWP), work is being conducted to research, develop, and commercialize supercritical fluid cleaning for its potential as a safer technology in a wide range of industrial cleaning operations. Commercialization, which has not proceeded as quickly as expected, is being aided by the Joint Association for the Advancement of Supercritical Technology (JAAST), a research consortium made up of industry, university, and National Laboratory partners. Under the IWP, JAAST is facilitating interaction and communication among those involved in the technology and addressing specific issues slowing its growth and acceptance.

As part of the IWP/JAAST effort, Pacific Northwest Laboratory conducted a study to 1) identify and evaluate potential markets for supercritical fluids cleaning, 2) identify and address current perceptions that inhibit the acceptance of the technology into industrial cleaning operations, and 3) develop a plan that will lead to successful deployment and implementation in potential market areas. The approach to gathering the information needed for formulating the plan was to interview several individuals involved in developing, using, or commercializing the technology, specifically, supercritical carbon dioxide ($SCCO_2$), the most commonly used fluid.

Several potential markets were identified, including cleaning gyroscope and filling hardware; optical components; instrument bearings; computer disk drive components; medical devices; and fabrics, cloths, and rags. In cases where there are parts with intricate geometries, where water-based cleaning may corrode parts and materials, or where significant time and energy for drying is required, $SCCO_2$ may be an especially attractive alternative. While pursuing these applications, certain barriers still need to be overcome.

The most prevalent barriers identified from the interviews were perceived cost and an unawareness of the technology altogether. Technical barriers such as particle removal, substrate compatibility, and production rate were also noted, but these issues are already being addressed through continuing developmental work. The plan devised by PNL involves more actively familiarizing industry with the technology and putting the costs into perspective. The following activities are recommended:

Education and Awareness/Information Dissemination

1. Onsite technology demonstration using a skid-mounted portable unit

2. Case study development and documentation comparing before and after situations and taking into account lifecycle costs and environmental impacts

3. Video production to give a visual perspective

4. Brochures describing the technology and its benefits

5. Electronic network information exchanges.

Cost Issues

1. Comparative lifecycle cost analysis for meaningful economic comparisons

2. Direct discussions of costs and concerns to foster mutual understanding and continued communications.

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1.0 Introduction

Faced with the 1987 Montreal Protocol and Clean Air Act, the 33/50 Program, and other regulatory drivers, many companies are interested in cleaning methods that do not employ hazardous chemicals (such as chlorofluorocarbons). Instead, they are looking at processes involving compounds that are safer for the environment, as well as their employees.

Since 1990, the U.S. Department of Energy's (DOE) Industrial Waste Program (IWP) has been sponsoring the research, development, and commercialization of supercritical fluid cleaning technology for replacement of traditional solvent cleaning processes that contribute to stratospheric ozone depletion or have other environmental consequences. Research activities under this program have focused on development of technologies built upon years of fundamental supercritical extraction research for the practical application of supercritical fluids as an alternative cleaning process. The desired result is that commercialization and deployment of the technology be fully demonstrated by the end of FY 1995.

The Joint Association for the Advancement of Supercritical Technology (JAAST), a research consortium consisting of industry, university, and National Laboratory partners was formed to facilitate teaming and communication and to specifically address issues inhibiting the growth and acceptance of supercritical fluid cleaning. The IWP/JAAST effort has helped to stimulate the successful commercialization of supercritical fluid cleaning for very specific applications and, as a result, this technology is steadily gaining more widespread acceptance in some areas. However, it should be further demonstrated and implemented for expanded use in areas outside of these niche applications.

The study presented here was conducted by Pacific Northwest Laboratory[a] to identify and evaluate the potential markets for supercritical fluids cleaning, to identify and address current perceptions that inhibit acceptance of the technology into industrial cleaning operations, and to develop a plan that will lead to the successful deployment and implementation of this technology for industrial use in potential market areas. This report contains the findings of the study and outlines the commercialization/deployment plan. The most influential user perceptions that tend to prevent acceptance of this alternative cleaning option are discussed. Potential cleaning applications identified by industry or through recent R&D efforts are also summarized. Recommended action items cover steps to aid in providing a better understanding of the environmental and technical aspects of supercritical fluid cleaning. This report primarily involves supercritical carbon dioxide ($SCCO_2$) cleaning since it is the cleaning agent most commonly used.

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2.0 Background

Alternative solvents such as perfluorocarbons, hydrochlorofluorocarbons, and other new hydrocarbon solvents, have been investigated and implemented for certain applications in industrial cleaning. However, many of these alternatives still pose environmental and/or health concerns and are likely to be significantly regulated and possibly banned in the future. Water-based cleaning has gained popularity as the alternative of choice for many applications because it is considered "environmentally friendly." However, chemicals employed with aqueous emulsion systems, such as detergents, and especially ethanolamines and terpenes, still require safety and health precautions due to known or uncertain human and aquatic toxicity associated with them. In particular, the U.S. Environmental Protection Agency (EPA) has expressed concern over the aquatic toxicity of the terpene family (Wolf 1994). In addition, water (especially for rinsing) and energy usage (especially for drying) and the treatment and disposal of spent bath and/or sludges associated with water-based cleaning add to the environmental and financial burdens.

Supercritical carbon dioxide cleaning offers several important advantages over other processes: worker and environmental safety (CO_2 is nontoxic and nonflammable); low operating costs (CO_2 is inexpensive and no drying is necessary); little or no waste treatment or disposal costs; superior levels of contaminant removal; and very short cleaning times. In addition, continuous recycling of pure CO_2 and recovery and reuse of valuable compounds removed from components, such as specialty oils and greases, are achieved easily and at a low cost. Furthermore, it is estimated that nearly all of the CO_2 used for industrial purposes today is produced as a byproduct of another process, primarily from the chemical and petroleum industries and as a natural product from geologic formations (Steiner 1993). Therefore, even if CO_2 is not recycled, this cleaning method will not affect the net contribution of CO_2 to the atmosphere with respect to global warming.

Under EPA's Significant New Alternatives Program (SNAP), the supercritical fluids technology is proposed as an acceptable substitute for ozone-depleting chemicals in metals, electronics, and precision cleaning (59 FR 13044). The concept for the technology grew out of years of research and knowledge developed on supercritical extraction, with application to cleaning being in development only within the last 10 to 15 years. A supercritical fluid is a pure compound or mixture, which is at a temperature and pressure at or above the critical temperature and pressure of the compound. A fluid in this state possesses physical properties such as density and viscosity that are intermediate between the properties of the liquid and gas states. These properties result in a fluid with very low surface tension and, consequently, the ability to penetrate small pores and crevices very effectively. In the case of CO_2, the liquid phase is also an excellent solvent but is not especially suited for penetrating small pores and crevices. Today's systems generally allow for cleaning with either the liquid or supercritical states of CO_2. Supercritical fluids are also being investigated for many other uses such as spray technology (Busby et al. 1991), soil remediation, and ultralight materials (aerogels).

Supercritical carbon dioxide is fairly well established for precision cleaning applications of parts such as gyroscopes, bearing assemblies, and machine tools but is also feasible for bulk cleaning of a variety of substrates. It has been tested and shown to be effective for a range of substrates including laser optics components, computer disk drives, and cloth rags (Wright Laboratory 1992; Novak et al. 1993; Smith et al. 1994). Metals, including stainless steel, beryllium, gold, silver, copper and others;

ceramics; and elastomeric seals such as Teflon, silicone, and epoxy potting compounds are highly compatible with $SCCO_2$ (Wright Laboratory 1992). Many contaminants, including silicones, Krytox, hydrocarbons, esters, fluorocarbons, gyroscope damping and fill fluids, and machining oils and lubricating oils, will dissolve in $SCCO_2$ (Wright Laboratory 1992). In general, nonpolar, hydrophobic contaminants such as oils dissolve well, while hydrophilic contaminants such as inorganic salts do not (Novak et al. 1993).

Although there are some questions regarding particulate removal, $SCCO_2$ cleaning has been shown to efficiently remove particulates down to 1 micron or less in size for certain applications (Bok et al. 1992; Novak et al. 1993), and much development work regarding this issue is in progress. The parts and contaminants mentioned here are not the only applications for $SCCO_2$ cleaning, as the full range of possibilities is still being defined by developers and users of the technology. The many advantages of $SCCO_2$ indicate that it is a technology that should carry industrial cleaning operations into the future.

3.0 Approach

Given the abundance of possible cleaning operations existing in industrial manufacturing, it is not realistic to expect that $SCCO_2$ will fit the needs of every cleaning scenario. However, because the technology is relatively new and is still being tested for its full range of applications, new opportunities are likely to continue to emerge. A market evaluation for this study was conducted to help assess and predict these opportunities. The approach taken for the market assessment was to evaluate the current status of the technology, i.e., where and how it is being used; where it has potential for use; and current perceptions of the technology from the user, developer, and vendor viewpoints. This information was obtained primarily from one-on-one interviews with individuals involved in $SCCO_2$ cleaning, including industrial representatives that are either selling cleaning systems, using cleaning systems, and/or conducting research and development to support the advancement of the technology. The majority of those interviewed are very experienced in the fields of supercritical technology and cleaning in general.

The interview process involved several key questions:

- How do potential users of supercritical fluid cleaning ($SCCO_2$ in particular) view the technology?
- Are concerns valid technical barriers or misconceptions?
- What are the circumstances necessary that make $SCCO_2$ cleaning a feasible alternative cleaning method?
- What are the current and potential future cleaning markets for the technology?

Areas of industrial cleaning were then identified for which $SCCO_2$ cleaning has shown to be or is potentially an up-to-spec, cost-effective, and convenient alternative to traditional cleaning methods. From the information gathered, a plan of action was devised for actively pursuing potential markets.

4.0 Interview Results/Findings

Although responses to the interview questions were somewhat varied, the overall viewpoints were generally similar. The following paragraphs summarize the perceived barriers, the advantages of the technology and the potential markets.

4.1 Potential Barriers to Acceptance

Developers of the technology have been working to identify and alleviate potential barriers to acceptance of the technology for several years. Some of these issues appear to be valid technical issues, while others are misconceptions and require education and an increased awareness to overcome them. The most common issues identified by those interviewed are discussed here.

4.1.1 Cost

The perceived cost of the technology is considered by researcher, vendor, and user alike to be the main concern hindering expanded use of $SCCO_2$ cleaning in a range of potential market areas. They feel that if this barrier could be overcome, many cleaning applications could be proven feasible through the user and vendor working together onsite to test and fit the system to specific cleaning needs. The questions surrounding the cost of the systems need to be resolved for further deployment of this cleaning method.

4.1.1.1 Capital Costs

The actual capital cost of $SCCO_2$ systems varies, depending on the pressure and temperature rating of the extraction vessel, production capacity, and degree of control/automation support of the system. Process equipment generally consists of a cleaning vessel (extractor), separator vessel, pump, heat exchanger, and electronic support. Information from several vendors indicates that fully automated systems with capacities ranging from 4 to 60 liters are in the range of $75,000 to $400,000. For the most part systems today are still designed primarily for research purposes. These systems are designed to be highly flexible, and generally have high pressure ratings and a great deal of electronics and control support. These aspects tend to increase the manufacturing cost and hence the capital cost of units. In the future, it is expected that with the design of production-scale equipment, capital costs will decrease. In addition, as the demand for systems increases, logically, decreases in cost can be more easily justified by vendors, as is the case with other "introductory" products.

Capital costs of $SCCO_2$ and aqueous systems tend to be compared since water-based cleaning is currently the most popular alternative to organic solvent-based cleaning. Considering capital cost alone, supercritical fluid cleaning systems are commonly perceived as much more expensive than aqueous systems. However, aqueous cleaning systems having in-line capability are of comparable price and may, in some cases, have higher capital expenditures. For example, one study reports that initial investments for a standard in-line aqueous cleaning system are approximately $150,000 (Schleckser 1993).

4.1.1.2 Operating Costs

Even given a difference in capital cost between the two cleaning systems, operational costs must also be considered. In this regard, "hidden" costs such as water consumption, waste treatment and disposal, reporting requirements, worker safety issues, and future liability must be accounted for to thoroughly assess the viability of either cleaning method. Operational costs associated with aqueous cleaning, which typically include electrical, chemicals, waste disposal and process/rinsing water, are estimated at $920,000 for 2000 hours of in-line operation (Schleckser 1993). Operational costs to run a 60-liter $SCCO_2$ cleaning system for 2000 hours, which only entails electrical and CO_2 costs, are estimated to be approximately $4000 for electrical (Barton 1994) and $3000 for CO_2 if it is not recycled (based on $1/lb and 30 to 35 lb/day consumption of CO_2). Because these costs were not generated for one specific application, they should not be directly compared, but, rather, they serve to illustrate typical requirements associated with each process.

4.1.1.3 Data Requirements

There is an overwhelming consensus that meaningful economic data are urgently needed to reliably evaluate and demonstrate the true feasibility of $SCCO_2$ cleaning for specific cases. What is most desired is a comparative analysis showing lifecycle costs (i.e., including all substantial "hidden costs") of $SCCO_2$ and aqueous cleaning. It is evident that in order for vendors to identify the most sensible markets to pursue, and users to make well-informed decisions regarding alternatives, this type of information must be generated for various potential cleaning applications.

4.1.2 Awareness of the Technology

A recent study indicates that many companies have not yet implemented alternative cleaning methods and are simply waiting for a drop-in replacement to their chlorofluorocarbon-based cleaning operations (Aronson 1993). Vendors indicate that many companies simply are not aware of the $SCCO_2$ cleaning technology. There is also indication that other companies are hesitant to invest because it is "not a well-known technology," and systems are considered to be in the "prototype stage." While this situation can be expected for any new technology, it also shows the need for strategies to publicize $SCCO_2$ as a potential alternative cleaning technology.

4.1.3 Substrate Compatibility with Pressure and CO_2

The technical feasibility of any cleaning technology depends heavily on the compatibility of the material to be cleaned and the process environment. With $SCCO_2$ cleaning, system pressures are generally within 1100 to 5000 psi, which may be harmful to certain components. For example, hermetically sealed components, such as those used in circuitboard manufacture, may implode when exposed to elevated pressures. Certain porous materials may also be damaged, as $SCCO_2$ can enter pores and cause microscale cracks or delamination of coatings upon depressurization. Likewise, certain materials may swell or be soluble in $SCCO_2$ and thus would not be compatible with this cleaning solvent. However, there are possible remedies to these situations.

Although material compatibility can limit the viability of $SCCO_2$ in a particular cleaning operation, the process conditions may be tailored for individual requirements. For example, it is not always necessary to reach the supercritical state of CO_2 to clean, and in many cases the liquid state has been shown to be more effective a solvent than its supercritical counterpart for certain contaminants (Phelps et al. 1993). In this case, the materials may be able to withstand the lower pressures of liquid CO_2. Future development of advanced materials with increased pressure resistance and compatibility with CO_2 may also increase the feasibility of this technology for specific applications.

4.1.4 Particulate Removal

There is some controversy over whether $SCCO_2$ cleaning is able to remove particulate matter from substrate surfaces, an important issue in several precision parts cleaning applications. Recent studies have shown $SCCO_2$ cleaning to efficiently remove particles down to required cleanliness levels from silicone wafers (Bok et al. 1992), computer disk drives (Novak et al. 1993), and the inside of stainless steel bottles (Bagaasen 1991). Suggested methods for enhancing particulate removal with $SCCO_2$ cleaning include the use of ultrasonication (Bagaasen 1991), co-pressure pulsation (Bok et al. 1992) and turbulent fluid flushing. Significant advances in this area can be expected in the future with the abundance of technical work currently being conducted.

4.1.5 Batch vs. Continuous Process

With current system designs, $SCCO_2$ cleaning is inherently a batch process; i.e., the parts are loaded into the extraction vessel, cleaned, and then removed. If continuous, assembly line-type cleaning is desired, $SCCO_2$ cleaning may not be considered suitable. However, if there are many parts to be cleaned at one time, current systems are capable of effectively cleaning many parts in one batch. In addition, the time necessary for loading and unloading of parts with a batch system may not be a significant issue because cleaning with $SCCO_2$ is so rapid that the time necessary for parts loading and removal can be justified.

Advances in system designs are continually being made to decrease load/unload time and emulate continuous operation. For example, multichamber systems that allow one chamber to be filling while one is cleaning and a third is unloading facilitate continuous-like processing. It is expected that future work in this area will continue to enhance production rates associated with $SCCO_2$ cleaning.

4.1.6 Existence of Aqueous Systems

Many companies have already made the decision to implement aqueous systems to replace their chlorofluorocarbon or other organic solvent cleaning operations. Because they have already invested in a safer alternative to organic solvents, many companies are resistant to considering another alternative such as $SCCO_2$ unless it is required. Consequently, $SCCO_2$ cleaning is overlooked, even in cases where it is technically superior and environmentally and economically advantageous over aqueous cleaning. Acceptance and implementation of $SCCO_2$ for replacement of existing aqueous cleaning will likely increase when the long-term economic and environmental advantages of $SCCO_2$ for specific applications become evident.

4.1.7 Defining "Clean"/Revision of Cleanliness Standards

One alternative approach to cleaning is to simply not clean at all. Although completely eliminating the process is not always possible, this raises the question of how clean a component truly has to be to function in a safe and effective manner. Many cleanliness standards are simply based on what a traditionally used organic solvent could achieve. Cleaning of a part used in defense-related operations may be governed by a military specification (milspec) that by law requires a specific type of cleaning for maintenance and repair activities. These standards often tend to restrict the use of alternative cleaning technologies for these applications.

In the case that $SCCO_2$ does not clean as well or cleans better than a solvent specified by a standard, the question of how this might affect part performance arises. In many situations the relationship between cleanliness and performance is not known, nor are there established methods of generating these data for a particular component. Many companies are attempting to develop this information to redefine cleanliness standards to facilitate the use of alternative technology such as $SCCO_2$. Milspec revision can be a much more complicated undertaking, given the intricacies of the bureaucratic process. However, as increased numbers of industry and military cleaning standards are modified to allow for alternative cleaning technology, the process of change will be easier.

4.2 Circumstances Where $SCCO_2$ Cleaning is Superior

Originally, a set of specific decision criteria on which to base the feasibility of $SCCO_2$ cleaning was to be developed as part of this study. However, as the study progressed, it became evident that the feasibility of this technology is highly dependent on the contaminant, substrate, and other circumstances specific to a particular cleaning situation and, therefore, is most accurately and fairly evaluated on a case-by-case basis. Nonetheless, several common reasons were identified that showed why $SCCO_2$ is being used and why it should be particularly advantageous over other options (specifically aqueous cleaning) in the future. Although these reasons tend to correspond to where aqueous cleaning shows weakness, considering the many advantages of $SCCO_2$, its application should not be limited to only cases when aqueous cleaning will not work.

4.2.1 Substrate with Intricate Geometry

Supercritical fluids have a low surface tension and thus an enhanced ability over other cleaning solvents to penetrate and remove contaminants from small crevices and blind holes. An interesting trend in technology development is the design of much smaller components and machines; at the extreme is nanotechnology. With this trend, it can be expected that, because of its enhanced transport properties, $SCCO_2$ (and supercritical fluids in general) will play an increasingly important role in manufacturing-related cleaning applications.

4.2.2 Water- and/or Heat-Sensitive Substrate

For applications where the materials to be cleaned are damaged by contact with water or elevated temperatures, $SCCO_2$ may provide an ideal alternative. For example, certain materials, such as those used in gyroscope assemblies and optical components, can corrode when exposed to a water-based cleaning environment. Although corrosion inhibitors may be used with water-based cleaning, there is still potential for damage given the multistep washing and rinsing used in the process. For high-performance parts, even a microscale amount of corrosion is critical and can render components unreliable and therefore inoperable.

Other materials may be intolerant to cleaning processes where elevated temperatures are necessary for effective contaminant removal and/or drying. With aqueous solutions, temperatures between 110°F and 170°F are generally required for effective cleaning (Lansky 1992; Wolf 1994). On the other hand, temperatures required for $SCCO_2$ cleaning often do not significantly exceed the critical temperature, 31°C, and no drying is necessary after cleaning.

4.2.3 Substrate Requiring Significant Drying Time

An important advantage of $SCCO_2$ cleaning is that parts are instantly dry as a result of gasification of the CO_2 upon depressurization to atmospheric conditions. For this reason, $SCCO_2$ can bring substantial energy savings and increased production rates over aqueous cleaning, especially where materials require long drying times for maximum moisture removal.

4.3 Potential Markets

The following paragraphs give an overview of market areas that are already established or have shown promise for $SCCO_2$ cleaning. This overview is not meant to limit the range of possible applications for this technology. While most of the applications discussed here fall within "precision" cleaning, there is wide interest in applying the technology to "bulk" cleaning applications. For example, removal of greases and oils from common metal parts such as gears, pumps, engine parts, screws, and bolts is not out of the realm of future possibilities. Certainly, the true feasibility of these bulk cleaning applications will depend heavily on the future cost of cleaning units and the results of detailed economic comparative analyses of $SCCO_2$ and other cleaning options.

4.3.1 Cleaning of Gyroscopes and Filling Hardware

Of all industrial cleaning operations, the gyroscope industry has implemented more $SCCO_2$ cleaning than any other industry. The $SCCO_2$ method is used primarily for cleaning specific gyroscopic parts, as well as the tooling and fixturing used to fill gyroscope assemblies with the damping fluid that is necessary for functioning. Because of the high value of the damping fluid, ($20,000 to $30,000/lb), one important goal of the cleaning process is to recover this fluid after it is removed from components.

Supercritical carbon dioxide cleaning is particularly well suited for this application for several reasons. First, the damping fluid is very soluble in $SCCO_2$ and thus extraction from parts is easily achieved. With its enhanced transport properties, $SCCO_2$ is also very effective at entering and flushing microscopic voids on the parts where the damping fluid resides. Separation and recovery of the fluid from the CO_2 is efficiently accomplished upon depressurization to subcritical conditions, as CO_2 gas and damping fluid readily separate, leaving no waste. Furthermore, reprocessing of the recovered damping fluid for reuse is far less complicated and costly with $SCCO_2$ than with solvent systems. All of these factors help to justify the investment in $SCCO_2$ cleaning. In addition, many of the gyroscopic parts are very expensive, helping to further justify the investment. As mentioned previously, $SCCO_2$ is also well suited for this application over water-based cleaning because certain component materials (e.g., beryllium) are vulnerable to water-induced corrosion.

4.3.2 Optical Components

Optics encompasses a very large number of components, ranging from telescope and camera lenses to mirrors and windows used in laser applications to contact lenses. Interest in applying $SCCO_2$ cleaning to this general area of manufacturing has intensified in the past several years.

In some cases, the base materials used in optical components are water-sensitive and cannot be cleaned with water-based solutions. Many components require specialized coatings to give the final product specific optical characteristics. These coatings may be sensitive to water or require that all moisture be removed from the component base material.

In cases where water sensitivity may not be an issue, other advantages of $SCCO_2$ apply. For example, one company has switched from an aqueous detergent process to $SCCO_2$ cleaning for removal of oil from freshly manufactured fiber preforms, the precursors to fiber optics. The preforms are extremely high-valued, high precision components, and the oil to be removed is necessary for measuring optical parameters of the preform. Incentives for the change to $SCCO_2$ cleaning include less waste, increased cleaning efficacy, decreased cleaning time (primarily due to drying), and potential energy savings.

4.3.3 Instrument Bearings

Bearing assemblies have complex geometry, making $SCCO_2$ very effective in removing contaminants from blind holes within the assemblies. Furthermore, the complete assembly often includes a housing for the bearings and water cannot be completely removed from spaces inside the housing, which ultimately leads to rusting of component parts. For high-performance applications such as helicopter blade shaft bearings, prevention of this situation is critical. A third reason $SCCO_2$ is particularly desirable is the high flexibility of solvating power of this fluid, allowing for potential removal of a wide range of contaminants.

Validation testing of $SCCO_2$ for cleaning instrument bearings will be conducted this year at the National Defense Center for Environmental Excellence (NDCEE) in Johnstown, Pennsylvania. The NDCEE is funded by the U.S. Department of Defense (DoD) and has been mandated by Congress to demonstrate and validate clean manufacturing technology for application to DoD-related operations and to promptly transfer feasible technology for use in DoD and industrial operations. The Center will initially test $SCCO_2$ cleaning of instrument bearings, but also intends to investigate other potential applications within DoD-related manufacturing.

4.3.4 Computer Disk Drive Components

Users of $SCCO_2$ technology have shown it to be very effective for removal of oils and other organics from computer disk drive components. Generally, $SCCO_2$ shows superior levels of contaminant removal compared to other cleaning methods. For some applications, it is necessary to remove microparticles as well. As previously discussed, there is some controversy over the ability of $SCCO_2$ cleaning to achieve particle removal, and much work is in progress (Baagasen 1991; Bok et al. 1992; Novak et al. 1993) to provide systems capable of this function.

4.3.5 Medical Devices

A promising application of $SCCO_2$ cleaning involves medical devices such as pacemakers, prosthetic devices, and dialysis and catheter tubing. A very important problem encountered with aqueous cleaning of medical devices is the introduction of cellular matter and other particulates onto the components from the water, which can cause complications in the functioning of the device. Complete removal of chemicals from devices is also of concern, particularly with components that will be introduced into the body. For certain composite materials used in medical devices, exposure to elevated temperature can damage the materials, which would not be encountered with $SCCO_2$ cleaning. There is also interest in the possibility of utilizing a sterilizing supercritical fluid, such as neon, to combine cleaning and sterilization into one process.

4.3.6 Fabric/Cloth/Rags

Recently, there has been considerable interest in the use of supercritical fluids to clean fabric. Fabric cleaning encompasses a wide range of applications spanning from dry cleaning of consumer clothing to spot cleaning of newly manufactured textiles. One area that appears to hold promise for the use of $SCCO_2$ cleaning is in the remediation of hazardous solid waste materials such as rags, paper wipes, swabs, and coveralls that are contaminated with oils, greases, and hazardous solvents (Smith et al. 1994). An immense volume of solid waste cloth generated by cleaning operations in both the private and government sectors is rendered hazardous due to a very small amount of a hazardous component. Meanwhile the bulk of the waste is nonhazardous. The major incentive in this case is to separate the hazardous component from the nonhazardous component, resulting in an extreme reduction in the volume of material requiring disposal as hazardous waste.

Supercritical carbon dioxide is very effective at extracting many oils and greases from the contaminated fabrics and does not generate extra waste in the process. Furthermore, recovery and reuse of the clean rags is possible and should be implemented to minimize waste sent to the landfill. Based on the work of Smith et al. (1994), DOE's Kansas City Plant plans to implement a full-scale system in FY 1996 for treatment and recovery of solid waste oily rags. The concept of waste remediation and material recovery using $SCCO_2$ cleaning could also be expanded to many applications in the rapidly growing industry of solid waste recycling.

Another application being considered is to use $SCOO_2$ in place of organic solvents and water-intensive cleaning and rinsing processes for removing oils, greases, and other process chemicals from newly manufactured fabric. Work is currently in progress to investigate this application as part of the American Textiles (AMTEX) initiative, a collaborative effort between the DOE National Laboratories and the U.S. Textiles Industry.

A third area of interest in fabric cleaning is the replacement of perchloroethylene with $SCCO_2$ for dry cleaning applications. For cleaning clothing, the solvent must be able to effectively solubilize and remove contaminants such as food stains, bodily oils, and dirt. Work is currently under way to develop solvent systems using supercritical fluids that can handle such compounds.

5.0 Recommendations for Proceeding with Commercialization and Deployment

Based on the interviews and discussions, the following actions are recommended to help enhance awareness and understanding of the $SCCO_2$ cleaning technology from the potential user's standpoint, along with ways to address cost issues. As previously discussed, developmental work is currently under way to address technical issues such as particle removal, substrate compatibility, and production rate; these issues are not covered here.

5.1 Education and Awareness/Information Dissemination

Many of the barriers to acceptance of $SCCO_2$ cleaning stem from a lack of awareness or understanding of the technology. It is evident that a proactive approach to disseminating accurate information regarding $SCCO_2$ cleaning will stimulate increased interest in potential market areas and will help to overcome misconceptions. Several effective strategies for information dissemination and education that should be taken in the near future are presented here.

5.1.1 Onsite Technology Demonstration

The Superscrub User Test Facility developed under the IWP program (Boston 1994) has allowed a number of potential users of $SCCO_2$ cleaning to visit and bring parts to the facility for feasibility testing. However, a greater impact could be made by taking the technology directly to the user and demonstrating the process in a specific manufacturing environment. Onsite demonstrations would show how the technology could be tailored to individual requirements. A portable system would also increase the opportunity to reach a wide range of industrial sectors, regardless of bulk or precision parts operations, and would include small, medium, and large companies.

It is recommended that a portable (e.g., skid-mounted) supercritical $SCCO_2$ cleaning unit be developed to take to as many facilities as possible for onsite testing. This unit should be an easy-to-use, yet flexible, system that is relatively simple for the user to understand and operate. The system should have a moderate capacity, 20 liters, for example, to allow cleaning of a wide range of part sizes and shapes, and should be capable of CO_2 recycling to demonstrate the benefits of minimizing solvent waste and consumption.

5.1.2 Case Study Development and Documentation

Case studies are powerful tools for demonstrating the feasibility and impact of an alternative technology. The most influential case study compares the "before" and "after" situations and takes into account all of the lifecycle costs and environmental impacts associated with both cases. Documentation of these comparisons is essential in making potential users aware of an option and demonstrating the environmental and financial benefits of implementing a new technology.

Although partial economic data exist, thoroughly documented economic comparisons of $SCCO_2$ use and other cleaning technologies (aqueous, in particular) simply do not exist to a significant extent.

As part of the commercialization and deployment plan, it is recommended that a side-by-side evaluation of $SCCO_2$ cleaning and a comparable alternative be conducted for one, if not several, potential market areas. These data should be generated in an actual production facility, rather than in a laboratory, to provide the most relevant data to the industrial manufacturing sector. Since $SCCO_2$ and aqueous detergent cleaning tend to "compete" as "environmentally friendly" alternatives, it is especially important to develop comparative evaluations of these two options.

Wide dissemination of these case studies in a timely manner is critical to the influence they will have in educating potential users. The studies should be distributed to reach both private and government sectors through organizations such as state and federal pollution prevention offices; environmental and trade journals such as Pollution Prevention Review and Precision Cleaning Magazine; non-profit organizations such as the Northwest Pollution Prevention Research Center; and information exchange systems and networks, such as the EPA's Pollution Prevention Information Exchange System (PIES), the Great Lakes Technical Resource Library, and DOE's Pollution Prevention Information Clearinghouse (EPIC) system.

5.1.3 Video Production

Film is also a very powerful tool for demonstrating the applicability of a technology to specific user needs. Given that $SCCO_2$ cleaning is somewhat of a departure from traditional solvent or aqueous cleaning, witnessing the process in action can help simplify the complex nature of the process. Because video can be widely distributed via satellite telecast, it provides a convenient and cost-effective method for familiarizing and educating potential users.

Contacts have been established with the Office of Industry-Education Partnerships at the Lawrence Livermore National Laboratory (LLNL) regarding their efforts to transfer DOE-developed or -advanced manufacturing related technology to small- and medium-sized businesses. As part of LLNL efforts in technology transfer, satellite-linked telecasts have been produced for technologies such as "Fluxless Soldering," Environmentally Conscious Manufacturing," and "Cleaning Solvent Substitutions." Programs are telecast at community colleges throughout California, as well as at NIST Manufacturing Technology Centers to reach business people from localities throughout the nation. The general format of the telecast is 1 1/2 hours of pre-taped technical programming and a 1-hour live question-and-answer session, where questions are phoned in for response on the air. Technologies that are "environmentally friendly" are looked upon very favorably for support under this program. Preliminary arrangements have been made to pursue production of a satellite telecast on $SCCO_2$ cleaning early in FY 1995, and it is recommended that this opportunity continue to be pursued and supported.

5.1.4 Brochure Development and Dissemination

It is recommended that a brochure on the $SCCO_2$ cleaning technology and JAAST be produced in the near future. While members of JAAST have been discussing brochure development for some time, this is a critical time to take action given the pressing need to increase awareness of the technology and its capabilities. Dissemination of an information brochure on the technology would not only increase awareness on a broad scale, but would also serve to open JAAST membership to small- to medium-sized companies that would benefit from the technology.

The brochure should include a brief description of the technical aspects of the process, where it has been successfully applied, and possible future applications. A description of the purpose and activities of JAAST and procedures for becoming involved in the organization should also be included. Intense dissemination of the brochure is critical and should be carried out through state and federal pollution prevention offices nationwide, conferences, universities, and U.S. trade organizations.

5.1.5 Involvement in Information Exchange Networks

Electronic networks can be very effective in connecting individuals of a common interest and allowing efficient and smooth information sharing and transfer. Although JAAST exists to facilitate communication among members regarding supercritical technology, the primary medium for communication is through biannual meetings and phone calls, which can be fairly inconvenient relative to electronic communication in today's world. Development of a network that provides electronic mail communication, updates on development work, and posting of other useful files would enhance both JAAST external and internal communication and, in turn, help to advance the technology.

The Best Manufacturing Practices Network (BMPNET) is an existing electronic network that facilitates communication and information transfer among DoD, Navy, DOE, and industry, regarding proven alternative techniques and technology used in government- and industry-related manufacturing operations. The BMPNET, funded by the Office of the Assistant Secretary of the Navy, has many useful features including electronic mail, file and photo transmission capabilities, and Special Interest Groups (SIGs). The SIGs are especially useful in that they allow users to investigate potential solutions to their manufacturing problems by joining a group of individuals with the same problem.

Preliminary arrangements have been made to develop a SIG for supercritical fluid cleaning technology on the BMPNET. It is envisioned that while JAAST members will be the initial members of the SIG, the nature of the topic will encourage more individuals to join the SIG. Not only will the development of a SIG allow increased communication among those interested in the technology, but it will also uncover opportunities in defense-related operations, an area that may hold many more potential applications for $SCCO_2$ cleaning.

5.2 Cost Issues

Many companies may be motivated to consider $SCCO_2$ if it is shown to be an economical asset. Two activities are recommended below as a beginning approach for bringing $SCOO_2$ costs into perspective.

5.2.1 Comparative Lifecycle Cost Analysis

As discussed previously, the need for accurate and meaningful economic comparisons of $SCCO_2$ and aqueous cleaning is apparent. Currently, efforts are being taken at IBM research division to acquire data for the "Cost of Ownership Model" (Semitech Corp.) to compare aqueous and $SCCO_2$ cleaning. The PNL study has involved assisting IBM; however, information is not yet available to present a meaningful cost comparison in this report. Work with IBM is continuing. Beyond these efforts, extensive case study documentation, as discussed above, should also be pursued.

5.2.2 Direct Discussion of Cost Issues

There is much interest among those involved in $SCCO_2$ cleaning to understand the exact nature of the cost barriers, especially with regard to capital expenditures. As a result of this interest, the next JAAST meeting (Washington D.C., August 1994) will include a workshop to facilitate frank discussions of current system costs and brainstorming of future strategies. These workshops and other open discussions should be continued to promote information exchange, problem solving, and direct interactions.

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